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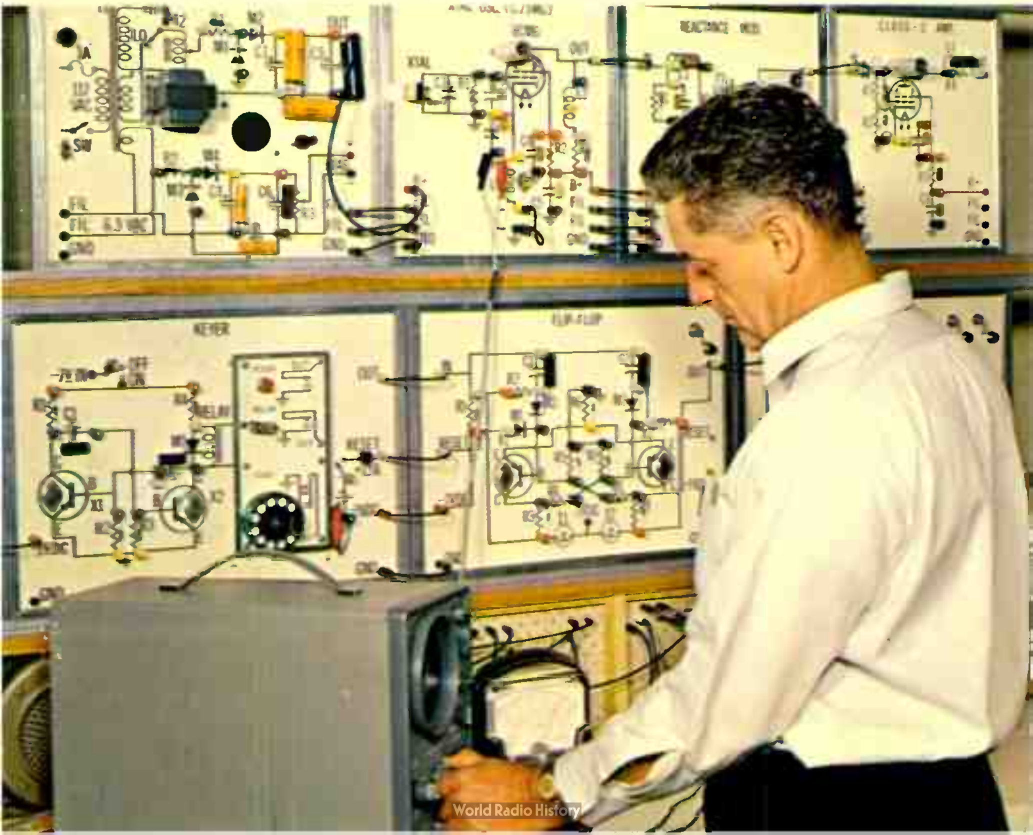
BASIC ELECTRICITY/ELECTRONICS

A Programmed Learning Course

VOLUME 2

- Series Circuits
- Parallel Circuits
- Alternating Current
- Resistance
- Capacitance
- Inductance

HOW AC & DC CIRCUITS WORK



HOW AC & DC CIRCUITS WORK

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BASIC

ELECTRICITY/ELECTRONICS

VOLUME 2

HOW AC & DC CIRCUITS WORK

By Training & Retraining, Inc.

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®

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SEYMOUR D. USLAN, *Editor-in-Chief,*
Training & Retraining, Inc.

Introduction

This second volume in the series shows how the basic principles of electricity apply to the behavior of AC and DC circuits, the building blocks from which all electrical and electronic equipment is made. As the principles of circuit operation are presented, they are related to familiar applications to help you understand both the principle itself and how it can be put to practical use. Thus the learning process is made easier, and your interest in the subject is maintained. In this volume you will progress beyond basic generalities and begin to learn specific facts of greater practical importance. After studying this volume, you will be able to apply your knowledge of circuit fundamentals to the analysis of how electrical and electronic devices work.

WHAT YOU WILL LEARN

This volume explains how the relationship between voltage and current in a circuit depends on the arrangement of components in the circuit. You will learn about these components (resistors, inductors, capacitors, transformers, etc.) and study the basic ways in which they can be connected. Methods of calculating the combined effect of several resistors, inductors, or capacitors connected in a circuit are also discussed. The text explains reactance—how inductors and capacitors produce different results for AC than they do for DC. You will discover how reactance and resistance produce a combined effect called impedance. Special combinations of capacitance and inductance that produce a condition called resonance are presented, and you are shown how this condition can be put to use in tuning radio and television receivers, as well as in many other applications. The meaning of phase and the use of vectors when studying the actions of AC in a circuit are explained. You will become familiar with time constants and be introduced to the fundamentals of pulse circuits. Finally, you will study about transformers, how they work, and how and why they are used.

WHAT YOU SHOULD KNOW BEFORE YOU START

Before studying this text it is desirable, but not absolutely necessary, that you have a general familiarity with the basic principles of electricity and electronics (such as is provided by Volume 1 of this series). However, the only essential prerequisites for learning about AC and DC circuits from this text are an ability to read and a desire to learn. All terms are carefully defined. Enough math is used to give precise interpretation to important principles, but if you know how to add, subtract, multiply, and divide, the mathematical expressions will give you no trouble.

WHY THE TEXT FORMAT WAS CHOSEN

During the past few years, new concepts of learning have been developed under the common heading of programmed instruction. Although there are arguments for and against each of the several formats or styles of programmed textbooks, the value of programmed instruction itself has been proved to be sound. Most educators now seem to agree that the style of programming should be developed to fit the needs of teaching the particular subject. To help you progress successfully through this volume, a brief explanation of the programmed format follows.

Each chapter is divided into small bits of information presented in a sequence that has proved best for learning purposes. Some of the information bits are very short—a single sentence in some cases. Others may include several paragraphs. The length of each presentation is determined by the nature of the concept being explained and the knowledge the reader has gained up to that point.

The text is designed around two-page segments. Facing pages include information on one or more concepts, complete with illustrations designed to clarify the word descriptions used. Self-testing questions are included in most of these two-page segments. Many of these questions are in the form of statements requiring that you fill in one or more missing words; other questions are either multiple-choice or simple essay types. Answers are given on the succeeding page, so you will have the opportunity to check the accuracy of your response and verify what you have or have not learned before proceeding. When you find that your answer to a question does not agree with that given, you should restudy the information to determine why your answer was incorrect. As you can see, this method of question-answer programming insures that you will advance through the text as quickly as you are able to absorb what has been presented.

The beginning of each chapter features a preview of its contents, and a review of the important points is contained at the end of the chapter. The preview gives you an idea of the purpose of the chapter—what you can expect to learn. This helps to give practical meaning to the information as it is presented. The review at the completion of the chapter summarizes its content so that you can locate and restudy those areas which have escaped your full comprehension. And, just as important, the review is a definite aid to retention and recall of what you have learned.

HOW YOU SHOULD STUDY THIS TEXT

Naturally, good study habits are important. You should set aside a specific time each day to study in an area where you can concentrate without being disturbed. Select a time when you are at your mental peak, a period when you feel most alert.

Here are a few pointers you will find helpful in getting the most out of this volume.

1. Read each sentence carefully and deliberately. There are no unnecessary words or phrases; each sentence pre-

sents or supports a thought which is important to your understanding of electricity and electronics.

2. When you are referred to or come to an illustration, stop at the end of the sentence you are reading and study the illustration. Make sure you have a mental picture of its general content. Then continue reading, returning to the illustration each time a detailed examination is required. The drawings were especially planned to reinforce your understanding of the subject.

3. At the bottom of most right-hand pages you will find one or more questions to be answered. Some of these contain "fill-in" blanks. Since more than one word might logically fill a given blank, the number of dashes indicates the number of letters in the desired word. In answering the questions, it is important that you actually do so in writing, either in the book or on a separate sheet of paper. The physical act of writing the answers provides greater retention than merely thinking the answer. Writing will not become a chore since most of the required answers are short.

4. Answer all questions in a section before turning the page to check the accuracy of your responses. Refer to any of the material you have read if you need help. If you don't know the answer even after a quick review of the related text, finish answering any remaining questions. If the answers to any questions you skipped still haven't come to you, turn the page and check the answer section.

5. When you have answered a question incorrectly, return to the appropriate paragraph or page and restudy the material. Knowing the correct answer to a question is less important than understanding why it is correct. Each section of new material is based on previously presented information. If there is a weak link in this chain, the later material will be more difficult to understand.

6. In some instances, the text describes certain principles in terms of the results of simple experiments. The information is presented so that you will gain knowledge

whether you perform the experiments or not. However, you will gain a greater understanding of the subject if you do perform the suggested experiments.

7. Carefully study the review, "What You Have Learned," at the end of each chapter. This review will help you gauge your knowledge of the information in the chapter and actually reinforce your knowledge. When you run across statements you don't completely understand, reread the sections relating to these statements, and recheck the questions and answers before going to the next chapter.

This volume has been carefully planned to make the learning process as easy as possible. Naturally, a certain amount of effort on your part is required if you are to obtain the maximum benefit from the book. However, if you follow the pointers just given, your efforts will be well rewarded, and you will find that your study of electricity and electronics will be a pleasant and interesting experience.

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1

Understanding Basic Principles

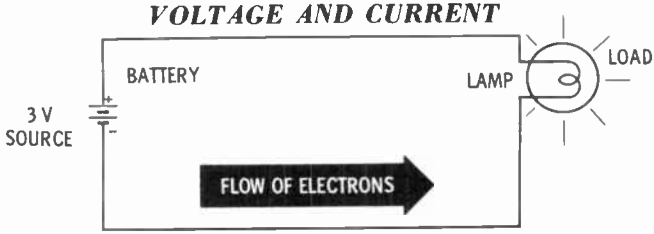
What You Will Learn

It is important that you learn to visualize and describe electron flow and be able to define the difference between conductors and insulators. In this chapter you will learn to identify and describe the six methods for developing electricity. You will determine the effect of resistance and voltage on current flow and become familiar with actual devices.

WHAT IS ELECTRICITY?

Electricity is voltage and current. Voltage is electrical pressure, and current is the flow of charged particles.

VOLTAGE AND CURRENT

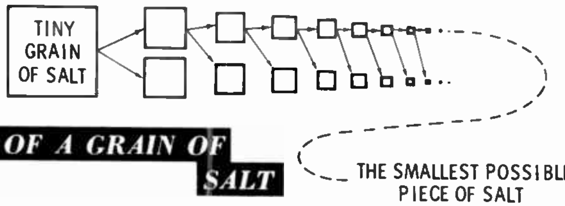


Voltage (electrical pressure) is an excess of negatively charged particles at one terminal of a source with respect to the other terminal.

Current is the movement of these charged particles from the negative terminal of the source (battery), through the load (lamp), and back to the positive terminal of the source.

THE MOLECULE

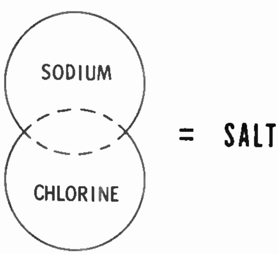
To establish a mental picture of these charged particles and their movement, you must visualize how all matter is put together. First, consider the smallest grain of salt you can see. Assume that we break it in half and then break



DIVISION OF A GRAIN OF SALT

one of the halves in half, continuing the process until we have the smallest piece of salt possible. This piece cannot be seen, even with the most powerful microscope. This breakdown to the smallest possible piece of salt would require several million of the ½-of-½ steps.

The smallest possible piece of salt is called a **molecule.** It consists of two elements—chlorine and sodium. A molecule, by definition, is the smallest particle of a substance that still retains the same physical and chemical characteristics



SALT MOLECULE

of the substance. A molecule of salt is made up of two elements—one part chlorine and one part sodium—chemically bonded, or "welded," together. Water is composed of two parts hydrogen and one part oxygen.

THE ATOM

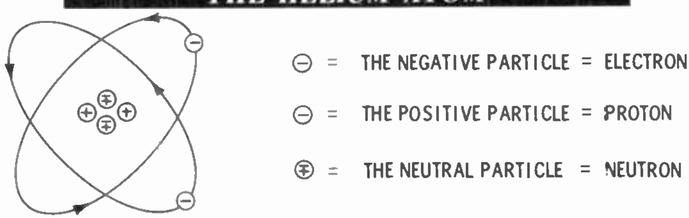
The elements that are bonded together to form the molecule are called **atoms.** The atom, by definition, is the smallest portion of an element which exhibits all properties of the element. An **element** is one of a class of substances (of which more than 100 are now recognized) which cannot be separated into substances of other kinds. The atom is made up of even smaller particles called **protons, electrons,** and **neutrons.** There are other tiny particles in an atom, but these three are all that will be discussed.

EQUATIONS FOR SALT AND WATER

ONE MOLECULE OF SALT	=	ONE ATOM OF SODIUM + ONE ATOM OF CHLORINE
ONE MOLECULE OF WATER	=	TWO ATOMS OF HYDROGEN + ONE ATOM OF OXYGEN

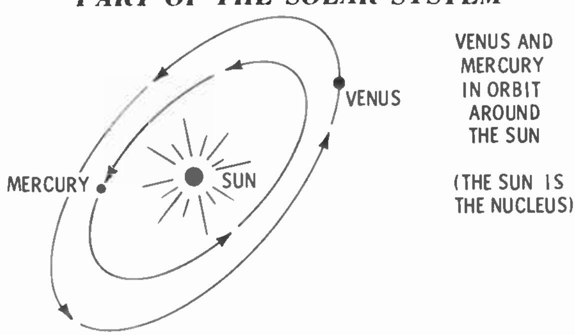
The helium atom has two electrons in orbit around a nucleus of two protons and two neutrons. An electron has a negative charge that is equal to but opposite in polarity

THE HELIUM ATOM



to the positive charge of a proton. The atom is very similar to the solar system in structure.

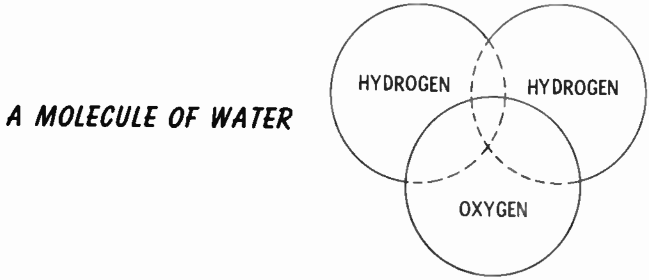
PART OF THE SOLAR SYSTEM



Q1. Of what would the smallest particle of water be made? Draw a diagram similar to the one for a molecule of salt on a separate sheet of paper.

Your Answer Should Be:

A1. The smallest particle of water would be made of **two parts hydrogen and one part oxygen.**

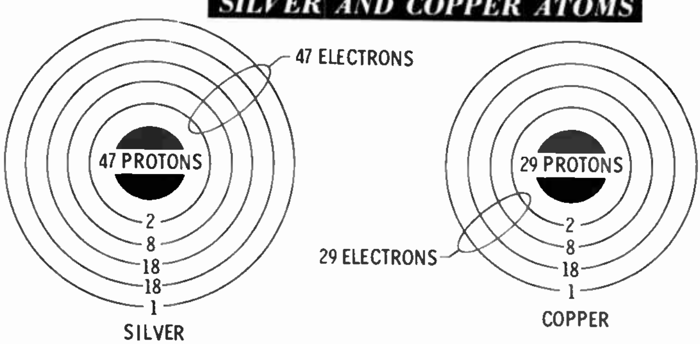


FREE ELECTRONS

If the proper amount of energy in the form of heat, light, electrical pressure, etc., is concentrated in an atom, it can cause the atom to give up or take on electrical particles. Elements differ from each other by the number of electrons in orbit and how many protons and neutrons are in the nucleus.

Normal atoms have the same number of protons in the nucleus as they have electrons in orbits.

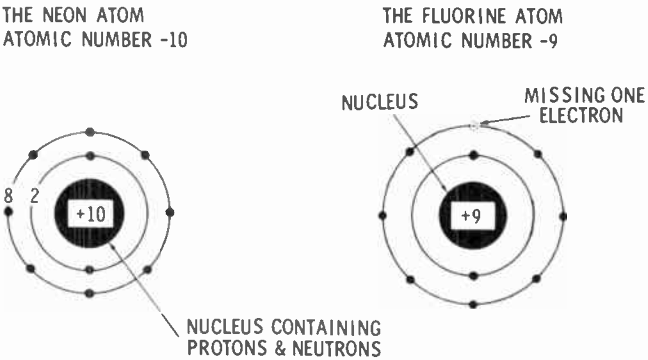
SILVER AND COPPER ATOMS



Electrons do not all move in the same direction around the nucleus. They travel in many different orbit paths (as many paths as there are electrons). Counting from the nucleus outward, the greatest number of electrons that can exist in the first and second orbit zones are 2 and 8, respectively. Subsequent zones may be filled by 8, 18, or 32 electrons. When the outer orbit zone is not completely filled, the element (atom) has the ability to release **free electrons** when voltage is applied.

Silver and copper atoms have only one electron in their outer orbit zone. The amount of energy needed to move these electrons to a nearby atom will be less than if the outer orbit zone were completely filled.

Some elements have all of their orbit zones completely filled. These elements are called **inert** because they will neither give up nor accept an electron from another atom. The neon atom is a good example of this concept. Its atomic number is 10—it has 10 electrons in orbit around a nucleus containing 10 protons. As can be seen in the illustration below, the outer orbit zone contains 8 electrons, thus it is completely filled. By contrast, the fluorine atom has only 7 electrons in its outer orbit. This makes chlorine an active element rather than an inert element.



Q2. An atom, like the solar system, is mostly ______.

Q3. Could a molecule be a single atom? (Review each definition carefully.)

Q4. The electrons go from the negative terminal, through the load, and to the positive terminal of the source. What path do they follow inside a battery?

Q5. Name the particles in the nucleus and assign the proper charges. Assign the proper charge to the particles which orbit about the nucleus.

Your Answers Should Be:

A2. The atom, like the solar system, is mostly **space.**

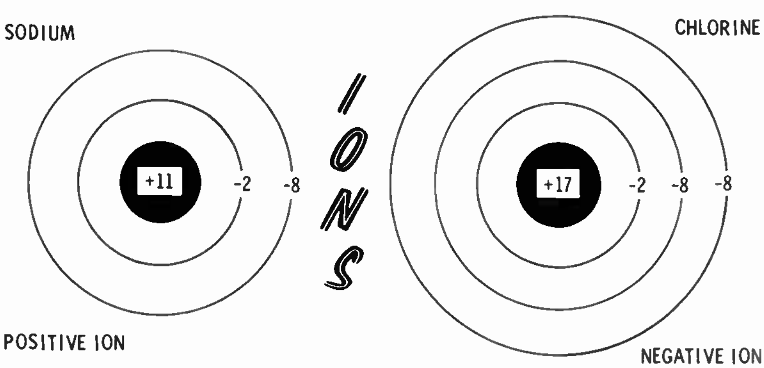
A3. **Yes,** if the substance in question is one of the 103 elements.

A4. The electrons, or the flow of negative charges, must move **from the positive terminal of the battery through the battery to the negative terminal.**

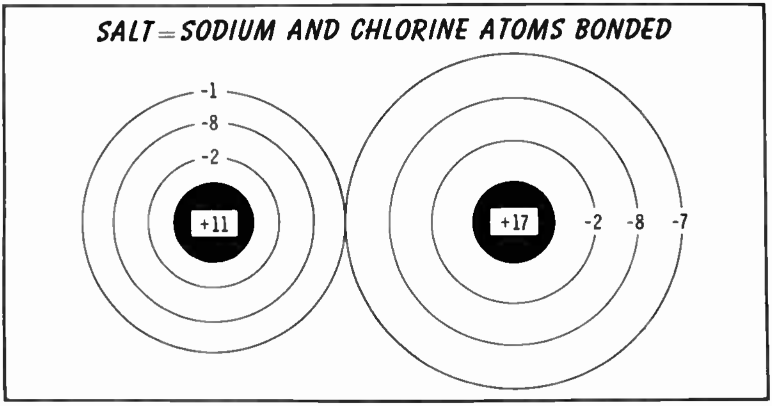
A5. The nucleus contains **protons** (a proton has **one unit of positive charge**) and **neutrons** (a neutron has **one unit of positive and one unit of negative charge**). Electrons are in orbit around the nucleus. The **electron** is assigned **one unit of negative charge.**

THE ION

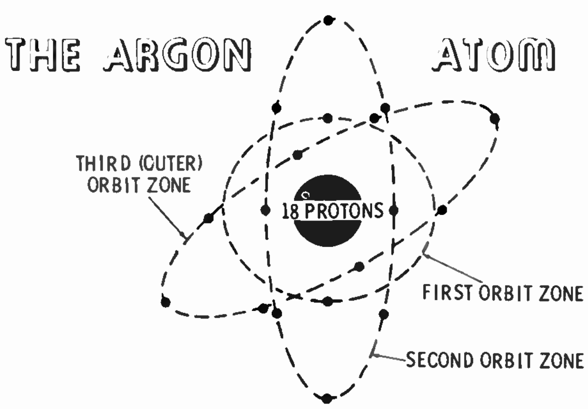
If enough force or energy is applied to an atom it is possible to add or take away an electron or two. If this happens, the atom will have an unbalanced electrical charge (unequal number of electrons and protons). This unbalance will cause the atom to have either a negative or positive charge. When an atom is charged (either negative or positive), it becomes an **ion.** A negatively charged atom is called a **negative ion,** and a positively charged atom a **positive ion.**



It was shown earlier how the sodium and chlorine atoms were bonded to form common household salt. This bonding is not a difficult thing to understand if you consider that the sodium positive ion shares its outer electron with the chlorine negative ion so that the two bond together to form balanced outer-orbit zones. That is, the sodium atom shares its outer electron with the chlorine atom, which permits the chlorine outer-orbit zone and the sodium outer-orbit zone to be effectively filled.



This sharing process establishes a stable combination (a molecule of salt) which is difficult to break. In the combination (molecule), you could consider the sodium atom capable of being a positive ion and, at the same time, the chlorine atom capable of being a negative ion if either should become isolated.

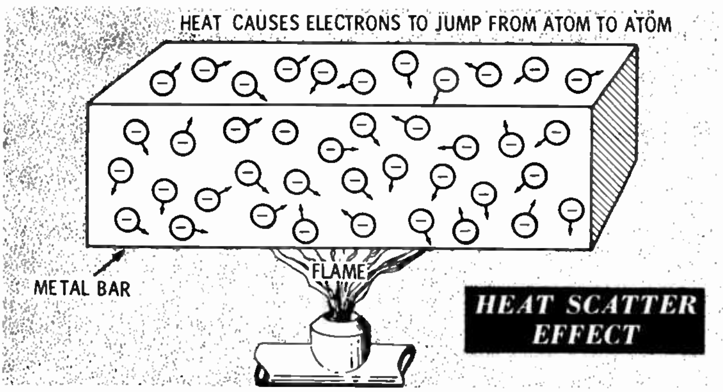


Q6. Could argon, with an atomic number of 18 (18 electrons and 18 protons), be considered a free-electron type element? Why?

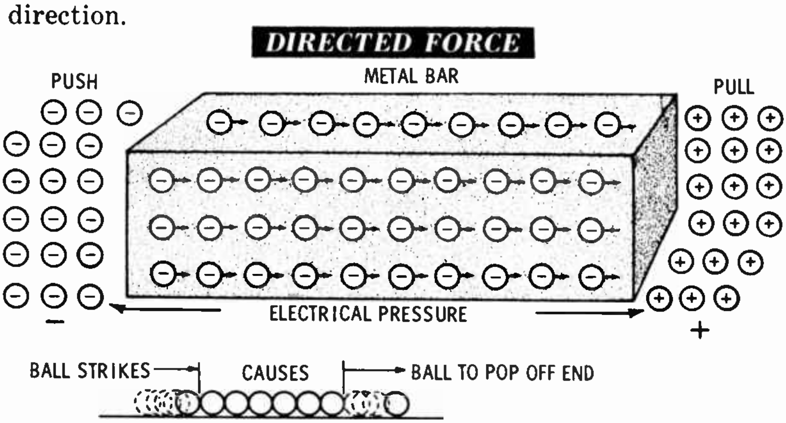
> **Your Answer Should Be:**
>
> **A6. No. Argon has all orbit zones completely filled.** Each argon atom has 2, 8, and 8 electrons in its three orbit zones, making it inert.

FORCE AND FLOW

To have electrical movement, energy must be applied to the atoms in a material. For the electrical movement to be



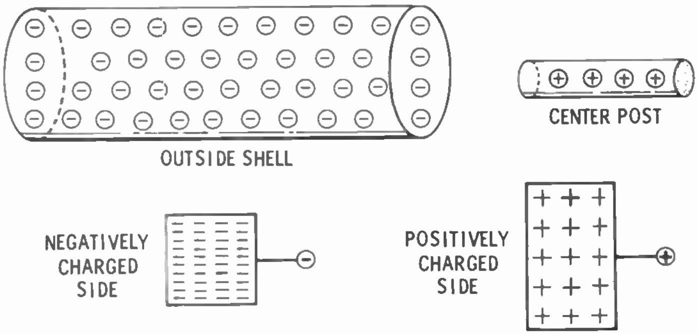
of value, the energy must be applied in such a manner as to move a relatively large number of electrons in the desired direction.



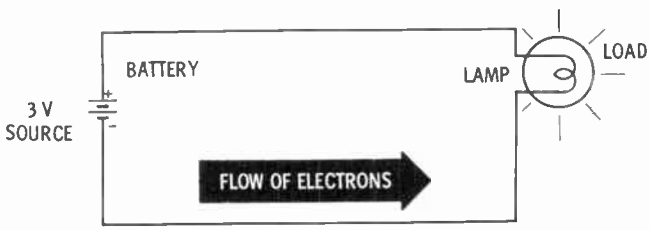
Electrical pressure is the most common form of control. This electrical pressure, or force, is made available by many forms of voltage sources.

A voltage source is an excess accumulation of negatively charged ions in one area with respect to another area.

A FLASHLIGHT CELL



A battery is one such form of voltage source. It has an excess of negative charges on one terminal and a lack of negative charges on the other terminal. When the two battery terminals are applied properly to other elements, a complete path from one terminal to the other is formed. The more negative terminal gives off negative charges that pass through the other elements to the positive terminal.



This process continues until the charges on the two terminals are equal. This does not mean the terminals have to be so completely neutralized that no electrical charge exists on either terminal. Under this condition, the battery is discharged (run down).

Many processes in electricity are described in terms of electrical charge. Not only must you be concerned with the amount of electrical charge, you must also be concerned with the polarity (negative or positive).

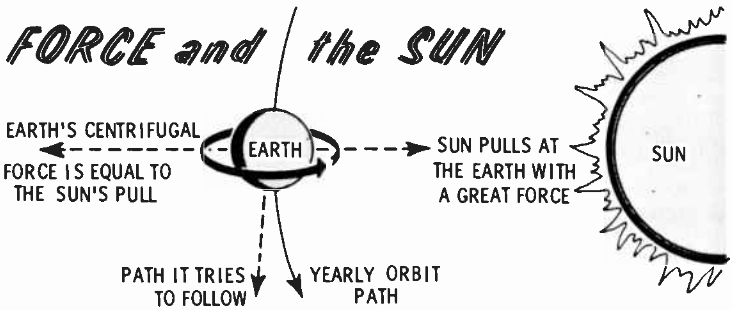
Q7. Consider the salt molecule. Could the effect of electrical charges, one atom to the other, hold it together?

> **Your Answer Should Be:**
>
> A7. **Yes.** Electrical charges do affect the bonding of the two atoms, one to the other.

Electrons and Ions

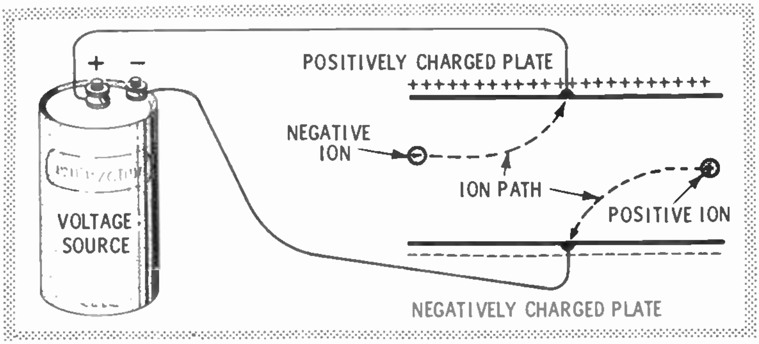
One atom is constantly trying to steal an electron from another atom so that the last orbit zone will be completely filled. This results in the production of two ions (if they are considered separately)—one negative and the other positive. The two atoms are thus held together because of the unlike charges attracting each other.

Why is it the earth does not go crashing into the sun? These two bodies are attracted to each other. If this attraction did not exist, the earth would not revolve around the sun in its yearly orbit. Instead, the earth would go rambling off into space. If you swing a ball in a circle at the end of a string, the ball tends to pull away from you. If you pull back with an equal force, the ball remains the same distance from you. The same is true of the earth and the sun. If the earth were to speed up (go faster in its orbit about the sun), it would slowly move farther and farther away from the sun. If it were to slow down, it would finally collide with the sun.

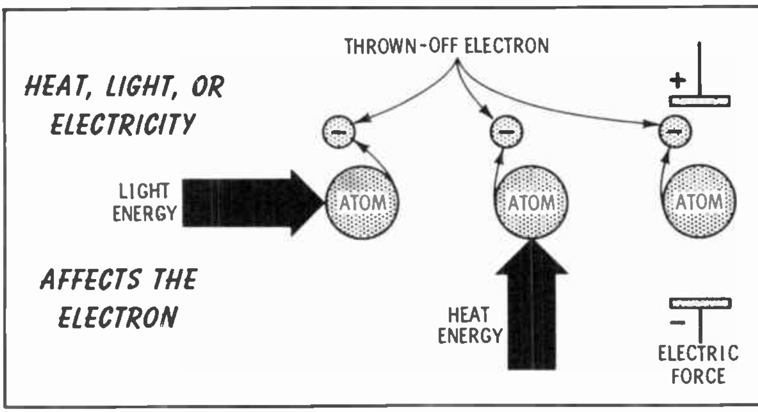


With respect to the ratios of size and weight indicated between the earth and the sun, how do the particles in the tiny atom compare? First, the electron is many times lighter than the proton. Second, the proton is slightly lighter than the neutron. With nearly all the mass or weight in the center (nucleus) of an atom and the lighter particle moving about it in an orbit, the electron is the most likely particle to be disturbed by some external force. However, the entire

THE ION PATH



atom may be moved. How about the ion, could it be caused to travel in a directed line? Yes. If positive, it will be repelled by another positive force or attracted by a negative force.



Q8. What happens in the atom, with reference to the description of forces on the earth? Draw the atom to include the nucleus and the orbiting electrons.

Q9. Could the earth be made to move in a straight line?

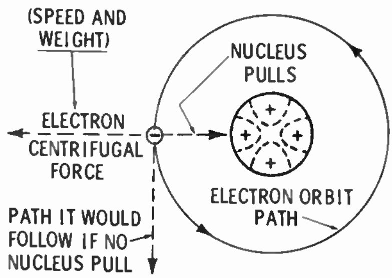
Q10. Show by an illustration what effects positive and negative forces have on a negative ion.

Q11. Draw a lithium atom, atomic number 3. Label the free electron.

Q12. What effect do the neutrons within an ion have on the movement of the ion?

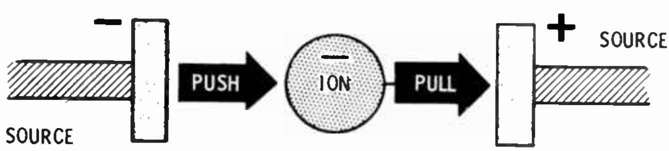
Your Answers Should Be:

A8.

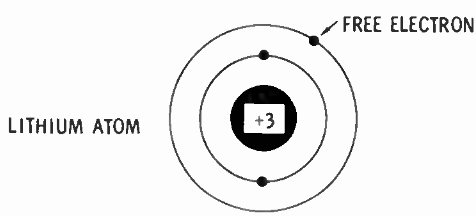


A9. Yes, if enough force were applied from some source that had a much greater pull than that applied by the sun.

A10.



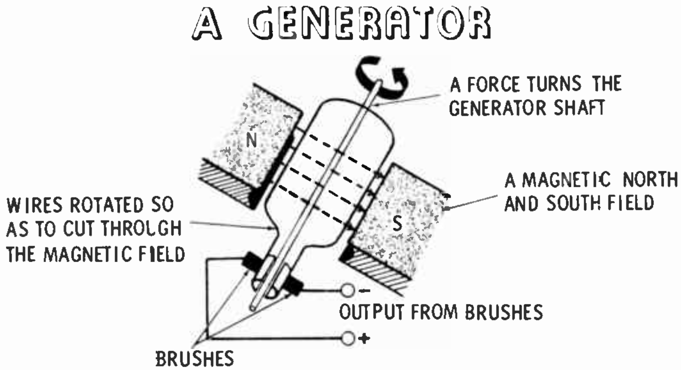
A11.



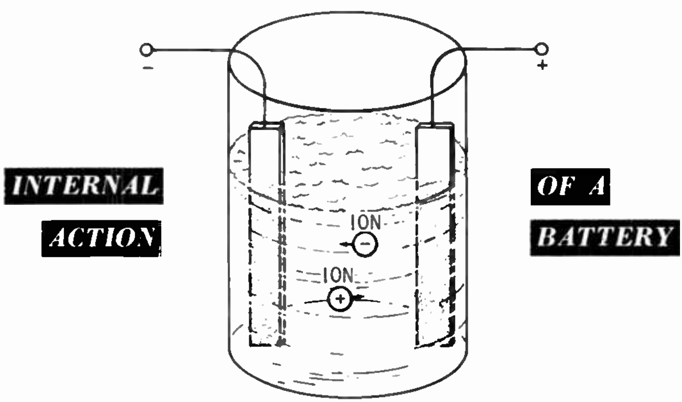
A12. They have the effect of **slowing down the movement of the ion** because of their mass. Without the neutron the ion could be moved more easily.

PRODUCTION OF ELECTRICITY

Electricity is produced by a movement of charges between two terminals. One terminal collects negative charges and the other positive charges. Electricity can be the movement of free electrons from one point to another. A DC generator, a device for producing a constant voltage, moves an excess of electrons in one direction through a series of windings. The electron movement is caused by the loops of wire cutting magnetic fields.



Electricity can also be a movement of positive ions in one direction and, at the same time, a movement of negative ions in the other direction.



In order for electricity to be produced, there must be a way to transfer charges from one place to another. This transfer of charges is made possible by the use of **conductors.**

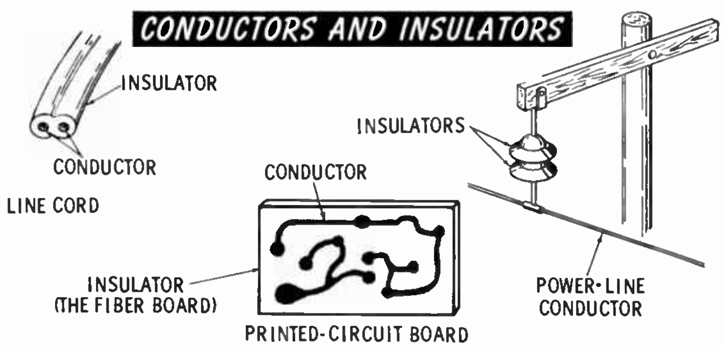
Q13. What is the source of electricity called?

Q14. How is the source of electricity made available to other locations?

> **Your Answers Should Be:**
>
> **A13. A voltage source.**
>
> **A14.** Electric charges are transferred from one location to another by **conductors.**

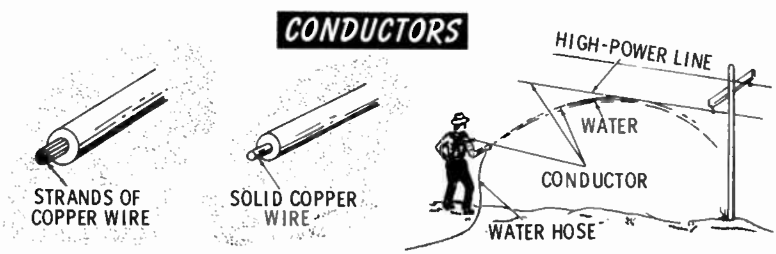
CONDUCTORS AND INSULATORS

The use of a conductor as the path by which electrical charges are transferred from one point to another is demonstrated in automobiles, homes, aircraft, ships, and almost anything else you can name. Examples of insulators are the large glass shields used to support wires and the rubber or plastic coverings along the surface of the conductors.



Conductors

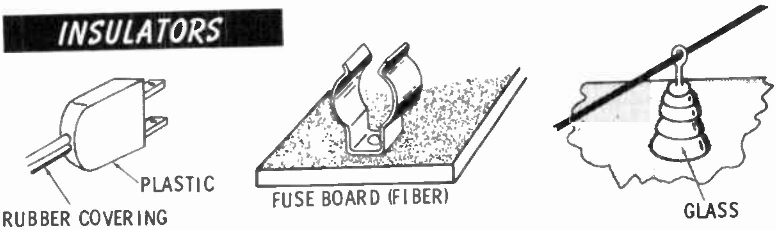
A conductor is a free-electron material which serves as a path for electric current.



Some materials are better conductors of electricity than others. The availability of more free electrons in silver and copper, for example, makes them better conductors than iron or steel.

Insulators

An **insulator** is a material through which electric current will not flow easily; thus, an insulator may be used to separate conductors from each other. An insulator may also be a covering over each conductor, permitting two or more conductors to be positioned near each other without danger of current following an undesired path between the conductors. In all cases, the insulator, to be effective, must present a path of high opposition to electron or ion flow.



Any insulator, however, will become a conductor of electric current if subjected to a sufficiently high voltage. This is true because of the atomic structure of all elements. The insulators in the following list will remain insulators under normal values of house voltage (120 volts).

Conductors	Insulators
silver	glass
gold	porcelain
copper	plastic
lead	rubber
tin	mica
brass	ice and snow (pure)
aluminum	nylon
bronze	bakelite
nickel	paper
iron and steel	wood
cadmium	paraffin
graphite	quartz
mercury	dry air

Q15. With respect to the orbit zones, how should an atom in an insulator be constructed?

Q16. With respect to the orbit zones, how should an atom in a conductor be constructed?

Your Answers Should Be:

A15. Each atom should have **completely filled** orbit zones.

A16. Each atom should be a **free-electron type element.**

STATIC ELECTRICITY

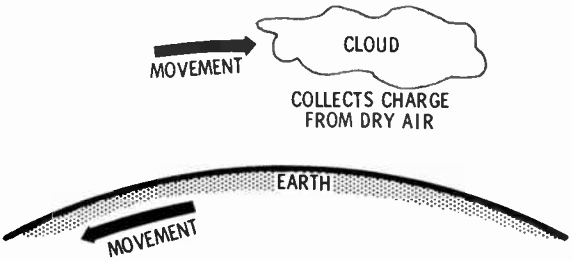
Static electricity is the production of a difference in electrical charges between two materials as a result of friction. Rubbing one type of material against another, each of different orbit-zone construction, causes electrically charged particles to be transferred from one material to the other.

CHARGING A BALLOON

Lightning is an example of static electricity, and is the result of an accumulation of charges caused by friction between cloud layers or between clouds and the earth. When the charge becomes great enough, it breaks down the insulating air. The resulting discharge produces the familiar lightning flash.

The sparks that jump from your fingers to metal objects or to other persons is another example of static electricity. The sparks are the result of your body becoming charged by walking across a rug and discharging to an object having a neutral charge.

CHARGING A CLOUD

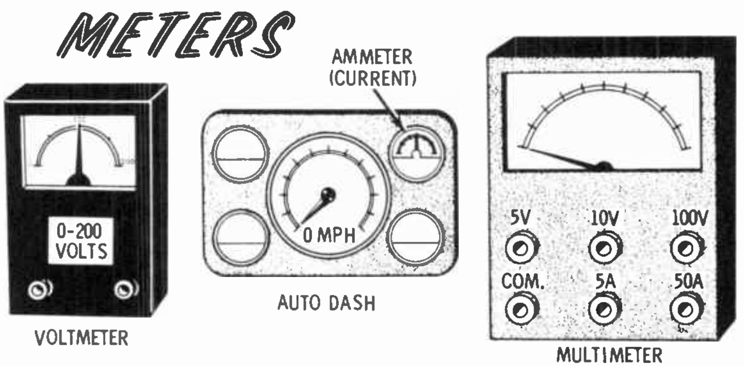


Electrical Charge

Electrical charge is founded on a basic electrical principle. The **electron** is considered to be a **negative particle**, and the **proton** is considered to be a **positive particle.** These are the two elementary electrical particles on which all other expressions of electrical charge are based.

An ion is another example of a negative or positive charge. Whether the ion is positive or negative depends on the number of electrons in the outer orbit and the number of protons in the nucleus. If the electrons outnumber the protons, the atom is a negative ion. If the protons outnumber the electrons, the atom is a positive ion. It is very difficult to determine if a single atom is an ion, and whether it is positive or negative even after it has been found to be an ion.

There are ways to measure the overall effect of an accumulated charge. The most common method is with a meter, such as a voltmeter, ammeter, or a combination unit known as a multimeter.



These devices indicate an approximate measurement of charges. Yet, these measurements are sufficiently accurate to serve as standards on which electrical and electronics personnel base their evaluations.

Q17. The electron is a _________ particle.

Q18. The proton is a _________ particle.

Q19. What two factors determine whether an ion will be charged positively or negatively?

Q20. How could you measure the overall effect of an accumulated charge?

Your Answers Should Be:

A17. The electron is a **negative** particle.

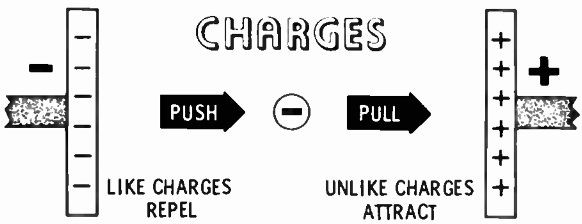
A18. The proton is a **positive** particle.

A19. The number of electrons in the outer orbit and the difference in number between electrons and protons in the atom.

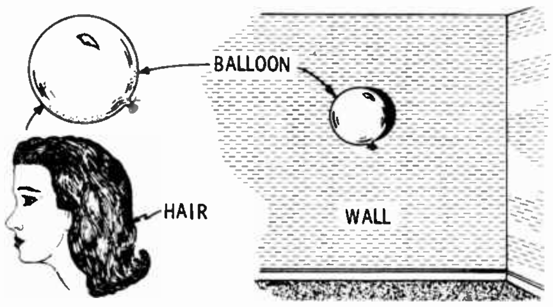
A20. You can measure the overall effect of a charge by the use of a **meter.**

Like and Unlike Charges

Another principle on which all other concepts of electricity are founded is the fact that **like charges repel** and **unlike charges attract.**



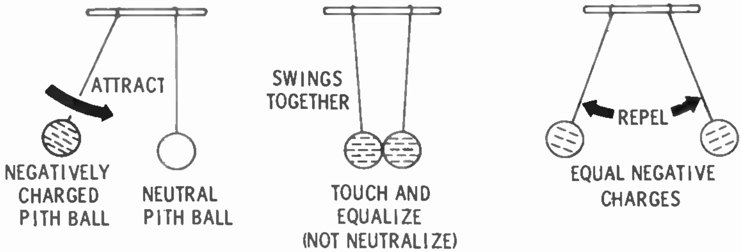
A negatively charged body placed near a positively charged body produces a force of attraction between them. One body tries to contact the other in an attempt to neutralize, or balance, the charges. You can try a simple experiment to demonstrate this principle. Inflate a rubber balloon and rub it on your hair. (Make certain your hair is dry and clean.)



BALLOON AND STATIC CHARGES

Now place the balloon near a wall. The balloon clings to the wall because of the negative static charge it accumulated.

When a charged particle comes in contact with a neutral particle, the charge will be equalized (divided equally) between the two particles. If the original charge is great enough, both particles will then acquire a like charge and repel one another. This can easily be seen if a pith ball is given a negative charge and allowed to come in contact with a neutral pith ball.

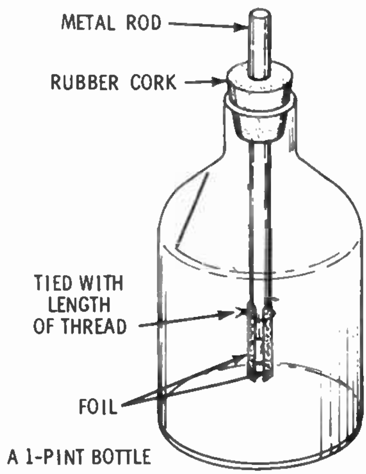


You can perform another experiment using an electroscope to illustrate the principle of attraction and repulsion between static charges.

What you will need to build an electroscope:

1. One clear glass bottle (1 pint) and a rubber cork to fit.
2. One metal rod, approximately ¼ inch in diameter.
3. Two thin pieces of aluminum foil (1 inch × ¼ inch).

AN ELECTROSCOPE



Q21. Why was the balloon attracted to the wall?

Q22. What charge was left on your hair?

Your Answers Should Be:

A21. Because **the wall has a neutral charge** and **unlike charges attract** one another.

A22. A positive charge.

Electroscope Demonstration

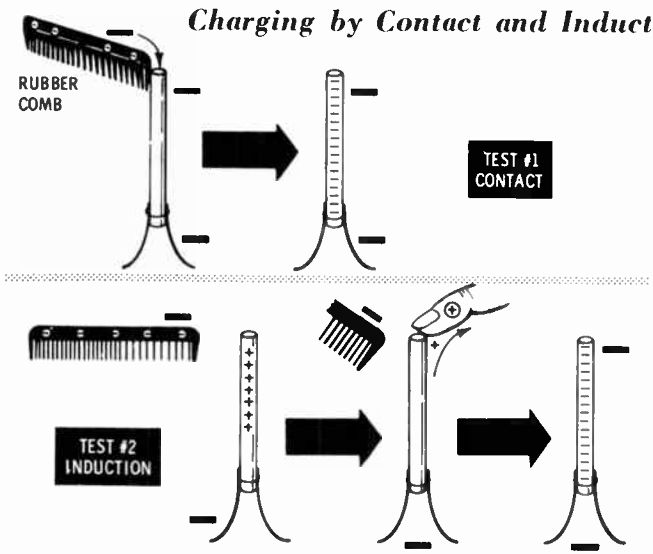
Testing the electroscope:

1. Rub a rubber comb with fur.
2. Touch the metal rod with your finger.
3. Touch the metal rod with the charged comb.
4. The pieces of foil should repel one another.

Next test:

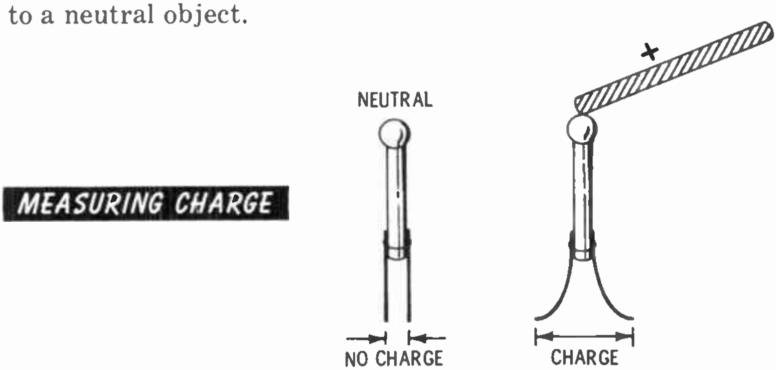
1. Touch the metal rod with your finger.
2. Charge the comb using the fur.
3. Bring the comb near the rod (do not touch the rod). Now touch the rod with a finger from your other hand.
4. Remove your finger from the rod.
5. Remove the comb from the vicinity of the metal rod.
6. The foil strips should repel one another.

Charging by Contact and Induction

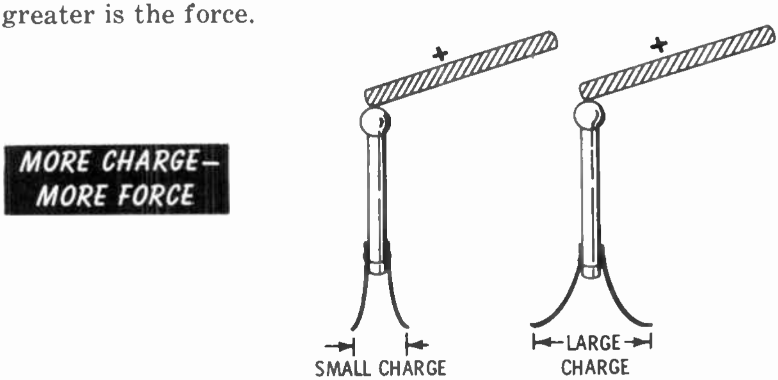


Forces Between Charged Objects

You can visualize the effects of charged bodies on one another and on neutral bodies. First, what is the effect called which caused the foils to be repelled, or the pith ball to be attracted or repelled? The answer is **force.** How do you determine just how much force and what caused it to exist? The answer is **charge.** The amount of charge determines the amount of force. How can the charge be measured? Each object must be measured separately with respect to a neutral object.



Multiply the numerical value of charge on one object by the numerical value of charge on the other. The product gives the total charge. The greater the total charge, the greater is the force.



Q23. What is the charge condition on the metal rod and the comb at the completion of the first test?

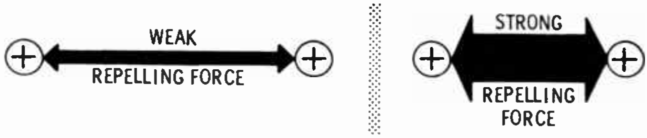
Q24. What is the charge condition on the metal rod and the comb at the completion of the second test?

Your Answers Should Be:

A23. Equal and negative, because the comb took electrons from the fur and transferred them to the metal rod.

A24. The metal rod is negative because the comb repelled electrons away from the tip of the rod and the excess positive charges were removed via the finger. The comb retains a **negative charge.**

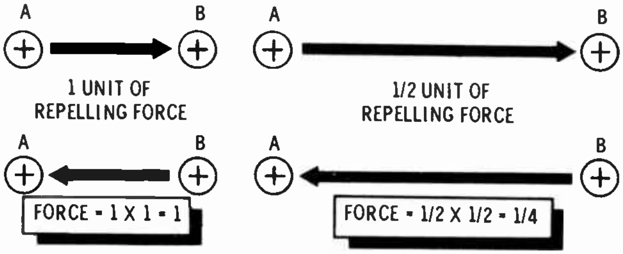
Does the distance between the objects have any effect on the force between them? Yes. The greater the distance, the less effect one body will have on the other.



Less Distance—More Force

There is one very important concept you must understand before the mathematical expression which fits all of these ideas can be determined. This concept states that the distance is not a direct measurement factor. For instance, if the distance is doubled between the two objects, the force effect between them will not be half as great, as might be expected, but only a fourth as great. Why is this?

Consider the effect that only one charge has on the other. If this charge is moved twice the distance away from the other, it will have one half the effect as before. By the same reason, the other charge will have one half the effect as before. Therefore, one half times one half is one fourth.



The Effect of Distance on Force

Now that the reasoning has been established, take a look at the shorthand statement in a mathematical form.

$$F = \frac{Q_1 \text{ times } Q_2}{d \text{ times } d} = \frac{Q_1 \times Q_2}{d^2}$$

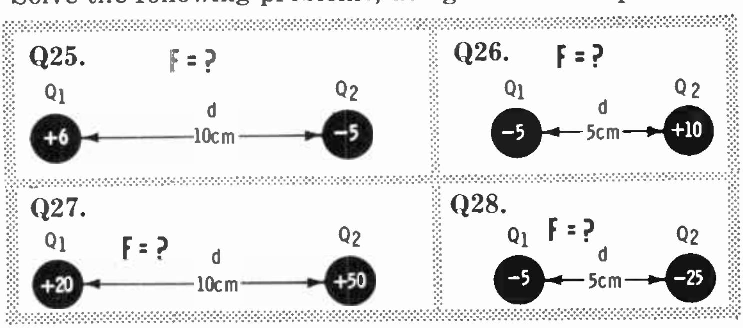
where,

F is the force exerted between two charged bodies,
Q_1 is the charge on the first body,
Q_2 is the charge on the second body,
d is the distance between the two bodies.

The force will be in dynes, if the Q's are given in electrostatic units and the distance is measured in centimeters (cm). An **electrostatic unit** is defined as the charge required to repel an equal charge 1 centimeter away, with a force of 1 unit. The unit of force is the **dyne.**

What is a dyne? First, what is force? One way of reasoning is to think of the effect you have on the speed of a toy wagon by pushing it. It requires more effort on your part to get it started. After it starts, you need only push with a small effort to keep it at a constant speed. What if the push against the wagon is always just as much as that with which you started? The speed of the wagon will increase and the force of your push must increase accordingly. The speed of the wagon and the force of your push will increase until the limit is reached where you cannot push any harder. At this point the force against the wagon decreases and the speed will no longer increase. If the pushing force decreases below the amount required for a steady speed, the wagon will slow down.

Solve the following problems, using the force expression.



Your Answers Should Be:

A25. F = (6 × 5) ÷ 100 = **0.3-dyne attraction.**

A26. F = (5 × 10) ÷ 25 = **2-dyne attraction.**

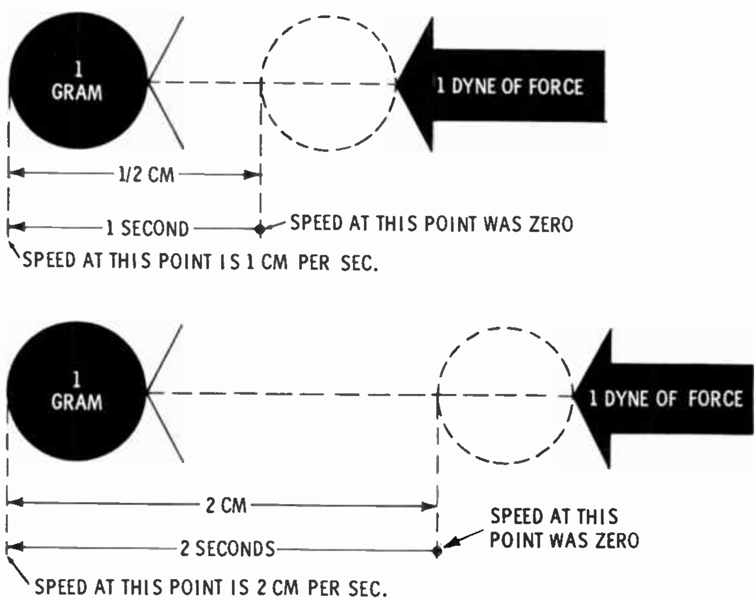
A27. F = (20 × 50) ÷ 100 = **10-dyne repulsion.**

A28. F = (5 × 25) ÷ 25 = **5-dyne repulsion.**

Application of Force

A dyne is the force required to cause a 1-gram mass to travel a distance of ½ centimeter (cm) when the force has been applied for 1 second. If this same 1 dyne of force is continued for another second, the gram of mass will be 2 cm from where it started. At the end of the first second it will be traveling at a speed of 1 cm per sec. At the end of the second second it will be traveling at a speed of 2 cm per sec.

FORCE - MASS - SPEED



A force of one dyne produces an **acceleration** of 1 centimeter per second per second on a 1-gram mass.

One gram of matter is the measurement of how much resistance a collection of matter offers to a change of motion. One dyne of force applied to a 1-gram mass results in the following speeds and distances traveled:

TIME seconds	0	1	2	3	4	5	6	7
SPEED cm per sec.	0	1	2	3	4	5	6	7
DISTANCE centimeters	0	½	2	4½	8	12½	18	24½

Graphical Representation of Forces

There are many methods used to represent the force between two charged bodies. These methods attempt to make the idea of force between the two bodies easier to understand or visualize. The following diagram is not one of the classical representations. Instead it emphasizes the potential difference from one plate to the other. Notice that the force is equally distributed throughout the entire area between the two plates.

FORCE EXERTED BY TWO CHARGED BODIES

Q29. What is the electrostatic unit of force?

Q30. One ____ is the force required to cause a one ____ mass to travel a distance of ½ __ when the force has been applied for one ______.

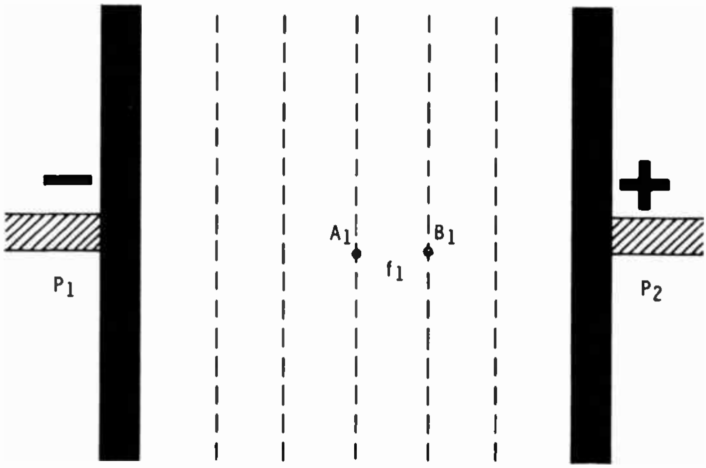
Your Answers Should Be:

A29. The **dyne.**

A30. A **dyne** is the force required to cause a one-**gram** mass to travel a distance of ½ **cm** when the force has been applied for one **second.**

Electric Fields

In addition, there are other potential differences existing between imaginary points located somewhere between the two charged plates.

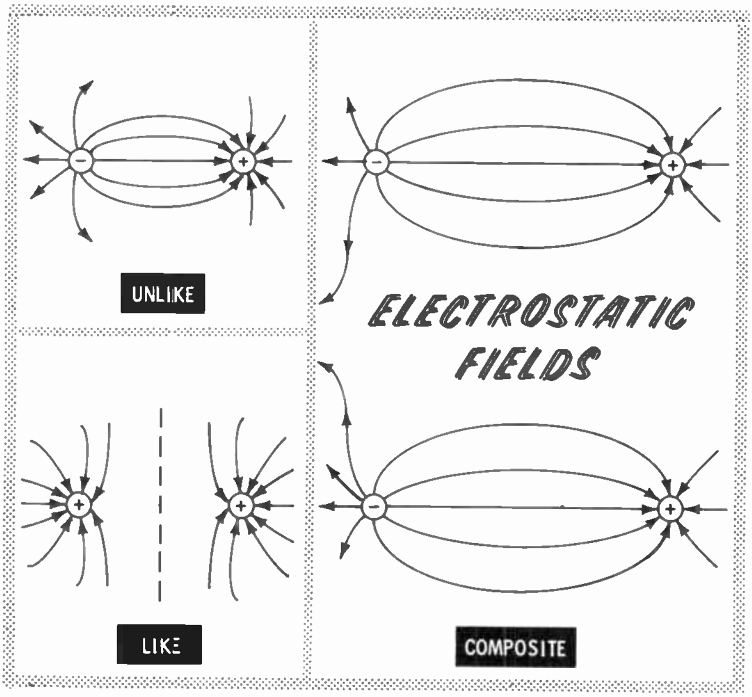


POTENTIAL DIFFERENCE BETWEEN CHARGED PLATES

Because of the distance between P_1 and P_2 and the amount of charge on each, there is a specific force between the two plates. The force in this case is an electrical attraction of one plate to the other.

If a charged particle is placed at point A_1, a force acts on the particle. For example, an electron placed at point A_1 would be urged toward plate P_2. Similarly, a force acts on a charged particle placed at point B_1 or any other point between the two charged plates. In the case of two parallel charged plates, the amount of force acting on a charged particle is the same for any position of the particle between the plates.

The region around the charged body is referred to as the **electrostatic field of force.** The lines represent the path a free electron would follow.



This area therefore contains electrostatic lines of force between two charged bodies. There is an electrostatic field around each charged body. When two positively or two negatively charged particles are placed near each other, their electrostatic fields repel each other. However, when a positively charged particle is placed near a negatively charged particle, their electrostatic fields attract each other. **Like charges repel**, and **unlike charges attract.**

Q31. What two factors must be considered in determining the force exerted between two charged bodies?

Q32. The area surrounding a charged body is called a(an) _______________ ______ __ ______.

Q33. Like charges ______, and unlike charges ________.

Your Answers Should Be:

A31. The **distance** and the **potential difference** between the two charged bodies.

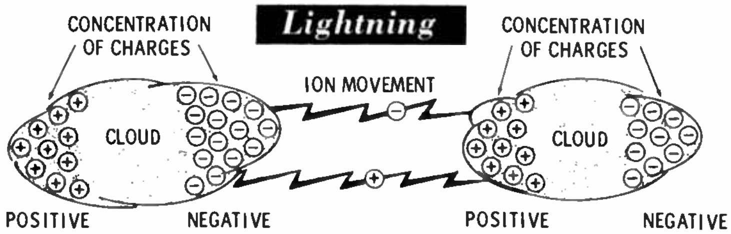
A32. The area surrounding a charged body is called an **electrostatic field of force.**

A33. Like charges **repel,** and unlike charges **attract.**

ELECTRIC CURRENT

Electric current is the movement of electrical charges from one location to another. This is normally considered as the flow of current (electrons) through a conductor. It can also be the movement of charged particles through a battery or any other electrical component.

Even lightning is the result of the movement of charges from one location to another. It is ion movement, primarily, with positive ions moving in one direction at the same time negative ions are moving in the opposite direction. The movement is very fast and involves a tremendous number of ions. This results in a very intense light which is the result of a high concentration of forces discharging from one cloud to another, or from a cloud to the earth, and causing a large number of ions to flow.



Moving Charges

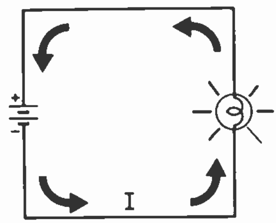
Charges in motion, then, are actually the movements of either free electrons or ions from one location to another. This constitutes current flow, or **electric current.** Some people describe the electrical flow of charges in terms of the electron theory and others describe electrical flow in terms of ions. Those that propose current to be a flow of electrons employ the **electron-current theory.** When current is considered to be positive ions, the theory explaining its flow is called **conventional current flow.**

Current is defined as the **movement of electrons through a conductor.** Current is also the **movement of ions through a material.** The most important factor you must remember from discussions on the subject is the application of **electron** and **conventional** current theories.

Electron Current Theory

Electron current is said to flow through a circuit when electrons are repelled by the negative terminal of a voltage source and are attracted by the positive terminal. Inside the source, electrons travel from positive to negative.

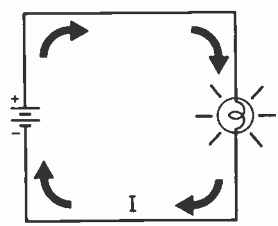
ELECTRON CURRENT FLOW



Conventional Current Theory

When current is explained as leaving the positive terminal of a source and flowing through a circuit to the negative terminal, the **conventional current-flow theory** is being used.

CONVENTIONAL CURRENT FLOW



Q34. Why can't electron current be the only theory employed?

Q35. Will the movement of negative ions produce the same electrical effect as the movement of electrons?

Q36. Can electrons be in motion from atom to atom in the opposite direction to the motion of positive ions?

Q37. Can both negative and positive ions be in motion when current is said to flow?

Your Answers Should Be:

A34. Because the movement of electrons **can create ions which will also move.**

A35. Yes. The negative ions will be caused to move by the same force that moves the electrons.

A36. Yes. The same force which causes positive ion motion in one direction has exactly the opposite effect on the electron.

A37. Yes. This will be clearly demonstrated later in this chapter.

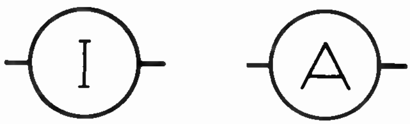
Current Units and Symbols

Just as there are measurement units for height, weight, time, force, etc., there is also a measurement unit for current. If this were not true, you could not measure current, determine current from other known factors, or describe a quantity of current to others. The unit of measurement for current is called an **ampere.**

An ampere is the effect of 6,250,000,000,000,000,000 electrons passing any point in an electrical circuit in 1 second. It is easy to remember this number as 6.25 million, million, million electrons, which can be written as 6.25 MMMe. It is difficult to use such a figure continuously, so the term **coulomb** is used in its place. That is, a coulomb is 6.25 million, million, million electrons.

To measure electric current in a circuit, you must measure how many charged particles pass any point in the circuit per unit of time. The shorthand symbol assigned to represent current is **I.**

CURRENT-METER SYMBOLS



I IS EQUAL TO A NUMBER OF AMPERES

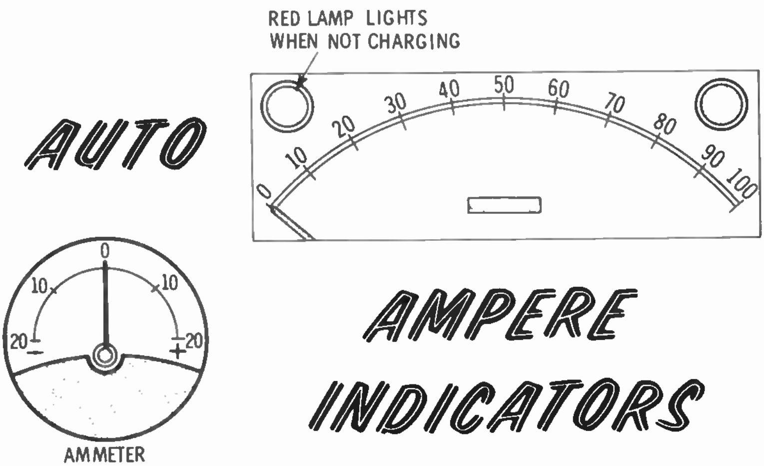
An ampere is the standard unit of measure for current (I) in a circuit. However, there are methods for describing very small or very large currents.

Magnitude or Strength of Current

Feet and inches are smaller units than yards, a measurement of length. The measurement unit for current, an ampere, can likewise be subdivided. A **milliampere,** for example, is 1/1000 (one thousandth) of an ampere. A **microampere** is 1/1,000,000 (one millionth) of an ampere. **Amp, milliamp,** and **microamp** are accepted abbreviations of ampere, milliampere, and microampere.

An ammeter often employs the smaller units of current measurement. Meters must be capable of measuring different values of current and, in some cases, revealing the direction of current flow.

An ammeter is a device having scales calibrated in amperes, milliamperes, or microamperes, used for measuring the total current flow in a circuit.



Q38. The unit of measure for current is the ______.

Q39. A(an) _______ is 6.25 MMM electrons.

Q40. The shorthand symbol for current is ____.

Q41. How can you measure the current in a circuit?

Q42. What is an ammeter?

Q43. How should an ammeter be connected to a circuit?

Your Answers Should Be:

A38. The unit of measure for current is the **ampere.**

A39. A **coulomb** is 6.25 MMM electrons.

A40. The shorthand symbol for current is I.

A41. You can measure the current in a circuit with an **ammeter.**

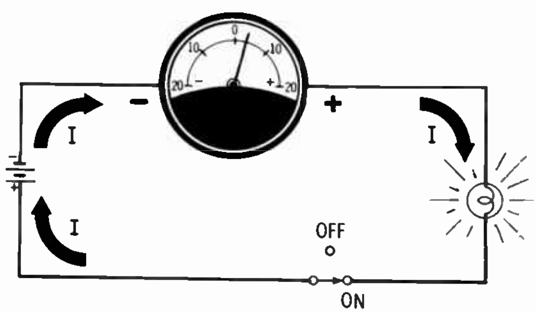
A42. An ammeter is an electrical device, having scales calibrated in amperes or portions of an ampere, placed in an electrical circuit in such a manner as to indicate how much current is flowing.

A43. It must be placed in the circuit so as to monitor all of the current in the circuit.

Current Measurement

An ammeter in an automobile indicates both minus and plus charges (amperes). If the meter indicates minus, the auto is using electrical power from the battery. If the meter

AMMETER IN A CIRCUIT



indicates plus, the auto is getting electrical power from the generator and, at the same time, the battery is being charged. Therefore, a minus meter reading indicates the battery is being used, and a positive meter reading indicates the battery is being charged. Before the days of long trips and dependable voltage regulators on the automobile, the operator had to watch the ammeter very closely.

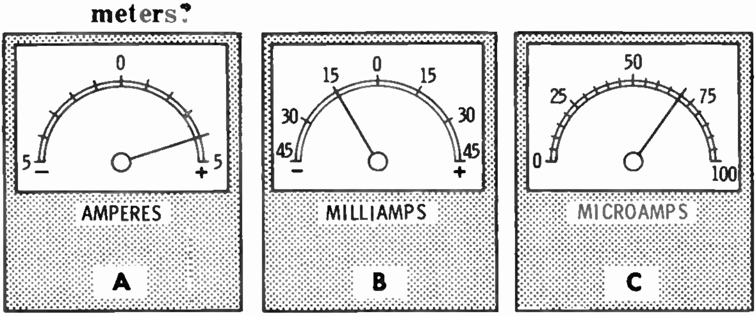
The reason for the close observation was not only to insure a well-charged battery for starting purposes, but also to prevent an overcharge of the battery. Overcharge could damage the battery, and undercharge could require manual cranking or a push to start the engine. Even close observation was not entirely satisfactory because it was a hit-and-miss arrangement, and did not give the accuracy required for long life and good dependability. Thus, the voltage regulator was developed, and man did not have to know quite so much to operate his "horseless carriage." The automobile mechanic, however, had to know more and more about electricity.

The requirement for electrical knowledge by a mechanic is even greater today. Electrical devices in the automobile are becoming more complex. This means a mechanic must be better qualified in the use of electrical tools, electrical systems, and the fundamental knowledge of electricity so that he can identify maladjustments, failures, and any number of other problems which need his attention if the automobile is to perform properly. The use of an ammeter is important to many others, for the automobile is only one application of electrical devices.

Ampere symbols and their meanings are shown below.

Current Designation	Meaning
I	symbol for current
1 ampere (amp)	1 coulomb per second
1 milliampere (ma)	$\frac{1}{1,000}$ ampere = 0.001 amp
1 microampere (μa)	$\frac{1}{1,000,000}$ ampere = 0.000001 amp

Q44. How much current is indicated on the following meters?



Your Answers Should Be:

A44. (a) +4 amps (b) —15 ma (c) +70 μa

VOLTAGE

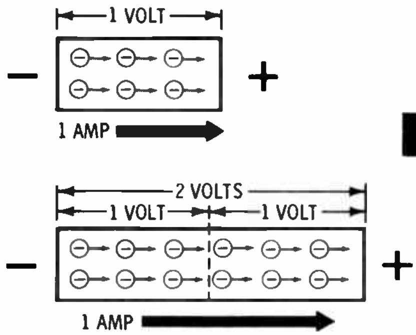
Electrical pressure required to move current through a circuit is called voltage. It is the accumulation of negative electrical particles on one terminal with respect to positive electrical particles on the other terminal of a voltage source. It is the force that causes the movement of electrical particles through a circuit. Voltage, as a pressure, is often called **electromotive force.**

Electromotive Force

The abbreviation for electromotive force is **emf.** This is the force which causes electricity to flow when there is a difference in electrical charge between two terminals.

Potential

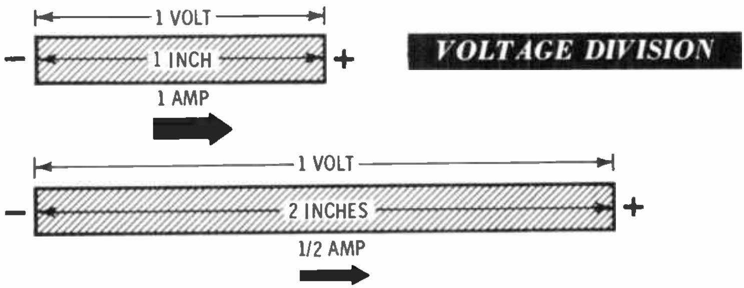
Potential is another term associated with electrical pressure, emf, and voltage. All of these terms are used interchangeably. The term potential generally denotes, however, that voltage (emf or pressure) is available but not necessarily being used to cause current flow. Voltage may be described as a **potential drop, potential difference,** or **voltage potential.**



VOLTAGE POTENTIAL

You can see that current will be the same through a conductor (with a specific voltage applied) as it is through a similar conductor twice as long but with twice the voltage applied. In each case, you could describe the voltage applied as a potential difference between the two ends of the conductor. What happens if the conductor is twice as long and the same potential difference is applied?

As in the previous illustration, the conductors are of the same material and cross-sectional area. The second conductor is twice the length of the first and thus offers twice as much material for current to flow through. Twice the length of material means that current will encounter twice as much opposition.



Voltage Definition

Voltage is **electrical pressure.** It is the force which causes current to flow. Voltage can be described as the **potential difference** between any two points.

Voltage Units and Symbols

The standard unit of measurement for electrical pressure is the **volt.** The volt may also be described in smaller or larger units. These other units are used for convenience of expression in the same manner that milliamps and microamps are used to define small quantities of current.

E is the letter symbol for voltage, and is used to represent pressure in volts when working with electrical circuits.

Q45. Electrical pressure is called _______.

Q46. The unit of measure for electromotive force (emf) is the ____.

Q47. What is voltage?

Q48. When 1 volt is applied across a 1-inch conductor, 1 amp of current is produced. How much current will flow if 1 volt is applied across a 2-inch conductor of the same material?

Your Answers Should Be:

A45. Electrical pressure is called **voltage.**

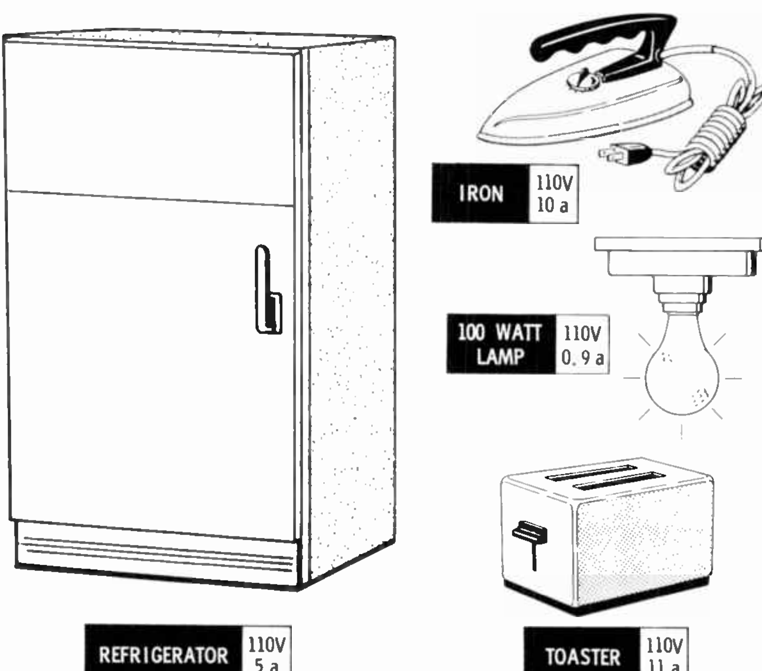
A46. The unit of measure for electromotive force (emf) is the **volt.**

A47. Voltage is **the force that causes current to flow.**

A48. Only **0.5 amp** of current will flow.

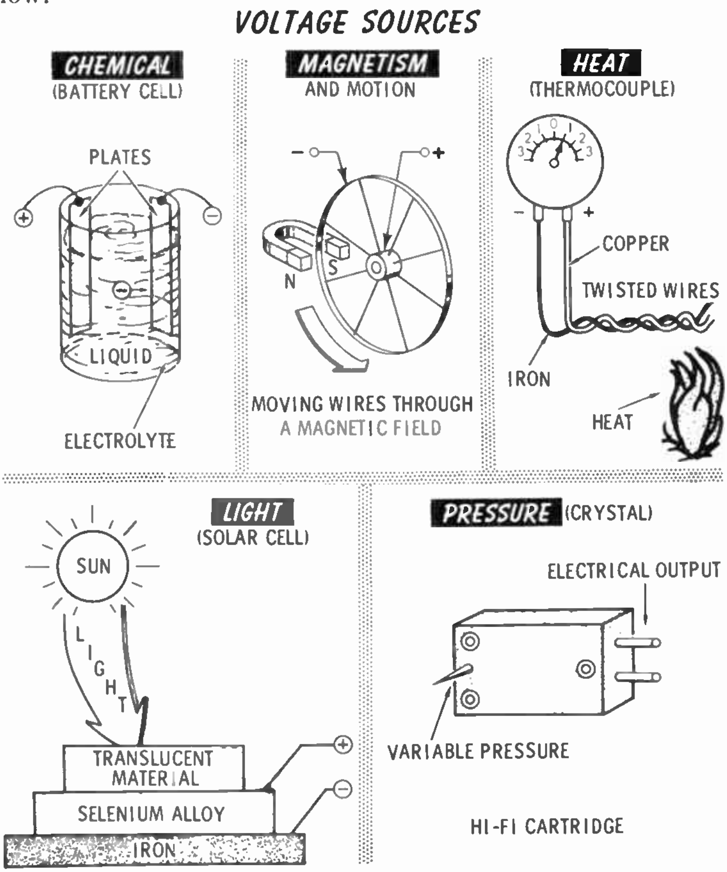
Comparison of Voltage and Current

There are many values of voltage and current. For example, voltages in a flashlight range from 1.5 to 9 volts or higher; corresponding current in flashlights varies from a few ma to 2 amps. Voltage in an automobile may be 6 or 12 volts; current varies from a few ma for small lamps to several hundred amps for the starter. Voltages in a home vary from 16 to 440 volts, depending on where you live and what electrical devices are installed; and currents range from a few ma to 20 amps or more.



CHEMICAL VOLTAGE SOURCES

There are many ways to produce electricity, but there are only six fundamental methods used to change another form of energy into electrical energy. Five of them are shown below.



A battery or cell is a voltage source in which chemical action is used to develop a voltage potential. The cell is the basic unit. A battery consists of two or more cells placed together, end to end. For practical, uniform application, a dry cell is considered to be a 1.5-volt source. A lead-acid cell is a 2-volt source.

Q49. What is the method of producing electricity not shown above? What is it called?

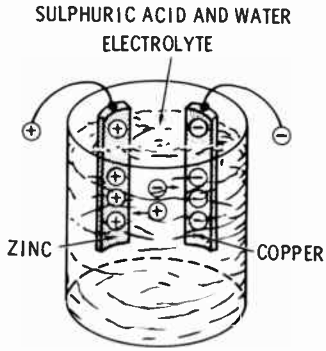
Your Answer Should Be:

A49. The other method is **friction.** It is called **electrostatic electricity.**

The Dry Cell

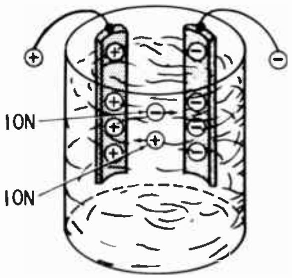
The most common form of a cell is the flashlight cell. The most common form of a battery is the automobile battery.

The cell is made with an outside protective covering which is an electrical insulator and, at the same time, is a mechanical support for all the other elements. Within this outer shell there are two electrodes separated and surrounded by an **electrolyte.** An electrolyte is any substance which, in solution, breaks down chemically into ions, thus allowing electric current to flow through it.



A SIMPLE CELL

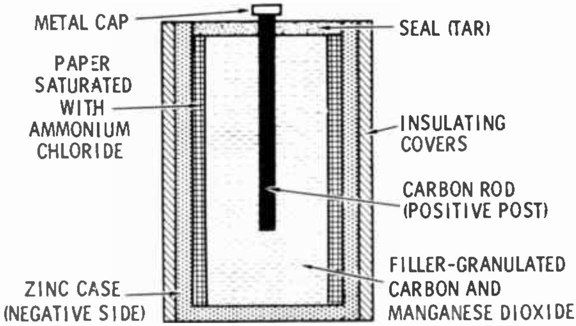
The electrodes are generally made of two unlike metals. Ionization of the electrolyte causes current to pass between the two plates, or electrodes, in such a manner as to charge one positively and the other negatively.



CURRENT FLOW IN THE CELL

The dry cell is the most common type of DC-voltage source. It is constructed with an outside shell of zinc, a center rod of carbon, and a paste form of electrolyte which is a solution of ammonium chloride.

Cutaway View of a Dry Cell



The zinc and the electrolyte are gradually "used up" as the dry cell supplies electricity. A dry cell is called a **primary cell** for this reason. The consumption of material in the cell is a result of chemical action between the zinc and the electrolyte. When the zinc case and the electrolyte have been used for some time, the chemical action which created the ion movement will decrease to a point where the cell is considered run-down (discharged).

Q50. How does a cell produce voltage and current?

Q51. How would a dry cell be affected if the center rod were made of zinc and the outer shell of carbon?

Q52. How would a battery of 9 volts be constructed using dry cells?

Q53. What advantage is there to connecting the terminals of two cells in parallel (positive to positive, negative to negative)?

Q54. Why is a simple cell considered a primary cell?

Q55. How many lead-acid cells are in a 12-volt car battery?

Q56. If it takes the same amount of power (I × E) for the starter to turn the engine in an automobile, in which system (6-volt or 12-volt) would more current have to be furnished to the starter motor?

Your Answers Should Be:

A50. By **chemical action.**

A51. The cell would use the zinc more rapidly than in a normal cell.

A52. A 9-volt battery consists of **six 1.5-volt dry cells in series.**

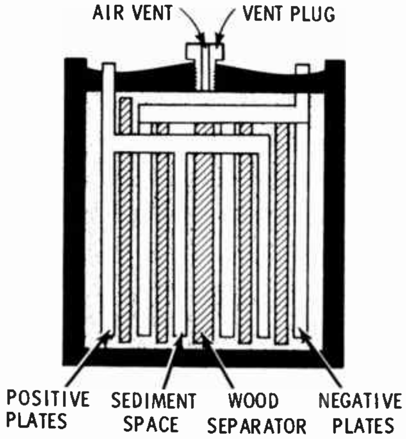
A53. Two cells in parallel provide the same voltage but **supply twice** as **much current** as a **single cell.**

A54. A simple cell is a primary cell because **it is used up over** a **period of time** or arrives at a condition where there will be no more chemical action between the zinc and the electrolyte.

A55. A 12-volt car battery contains **six lead-acid cells.**

A56. **A 6-volt system** would have to furnish more current.

When a dry cell is discharged, it must be replaced. There are some discharge conditions in which a cell can be recharged, but these are very unreliable.



A LEAD-ACID CELL

The Lead-Acid Cell

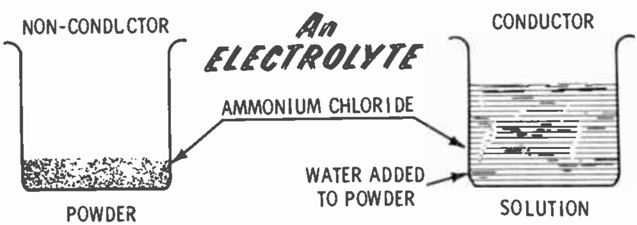
The lead-acid cell is the type used in an automobile battery and has a normal output of approximately 2 volts. Since it can be recharged, a lead-acid cell is called a **secondary cell.**

A lead-acid battery must be constructed of a material that will not be eaten away by the highly corrosive electrolyte. For this reason, rubber or glass is normally used for the case that contains the cells and solution.

Maintenance Precautions

The maintenance of lead-acid cells requires the observance of certain safety and maintenance precautions to prevent injury and damage. Reasons for such care include: (1) the presence of dangerous sulphuric-acid electrolyte that will eat through clothing and skin, (2) generation of explosive fumes while battery is charging, (3) build-up of corrosion on connections and vent caps.

The level of the electrolyte must be checked regularly to insure maximum effectiveness of the cell. This is a very



important monthly check for the automobile battery. If the electrolyte is permitted to get too low, the battery may become permanently damaged. The following is a list of items to be used when taking care of this type of battery:

1. A recording ledger listing each cell, the charge condition and date, electrolyte added, and the visual condition. Used as a maintenance history and to indicate changes in cell condition.
2. A cleaning brush, cleaning cloth, baking soda, and water. To remove corrosion on terminals and case.
3. White petroleum jelly to cover the terminals after they are cleaned and reconnected. Used to retard corrosion.
4. Charging equipment consisting of a battery charger, charge-rate meter, hydrometer, and an area separated from normally occupied areas so that a NO SMOKING rule may be observed.

Q57. What is the difference between a cell and a battery?

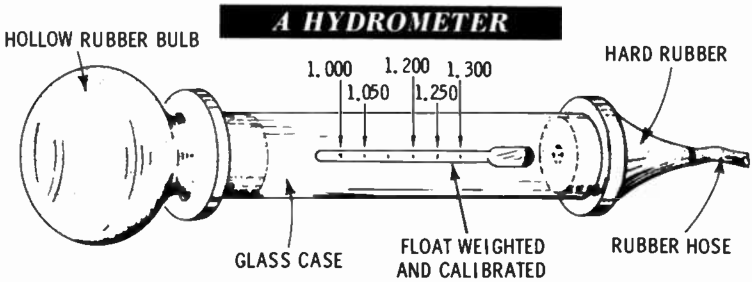
Your Answer Should Be:

A57. A battery is a combination of cells connected in series to form a voltage source.

The care of the lead-acid cell when it is in use or when it is being recharged requires special precautions.

1. Clean the battery or cell to remove corrosion. Coat the terminals with petroleum jelly to insure continued good connections.
2. Be careful when handling the battery to prevent spilling the electrolyte and to prevent internal damage to the plates. Remember that acid will cause serious burns and will develop a highly explosive atmosphere in a closed room.

A storage battery must be checked occasionally to see if it is charged properly, has sufficient electrolyte, is free of corrosion, and has clean tight connections. A **hydrometer** is a device commonly used to check the condition (specific gravity) of the electrolyte. In this way the condition of charge can be determined.

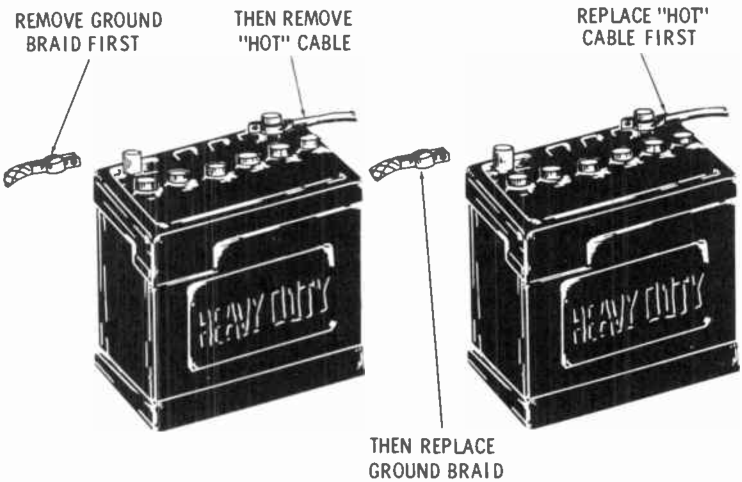


If the hydrometer reading is 1.210 to 1.220, the cell has a full charge. If the reading is 1.180 or less, the battery needs to be charged. If the reading is as low as 1.060, the battery is completely dead. A battery will rarely have the same reading for all cells. When using the hydrometer to check the battery, always keep the small tube or tip over the cell being checked so the electrolyte will drip back into the cell. After using the hydrometer, rinse it with water to remove any acid.

A dry cell should be purchased with a degree of caution. Even in storage, a dry cell will run down because of the chemical action of its components.

A quick method for checking an automobile battery is to try the horn. If the battery is weak, the sound of the horn will be weak. If a battery is being run down, recharged, run down, recharged again and again, its electrolyte level must be checked often. If a starter motor seems overly sluggish on cold mornings and the battery is known to be charged and in good condition, then all connections and cables should be checked. Many cars have been towed into a filling station or garage only to have a mechanic tighten a loose battery cable. When removing an auto battery, always remove the ground cable first. This will permit the use of metal tools. If the ground cable is removed first, the battery will be disconnected from the electrical circuit. Second, remove the "hot" side. This side will have no way of discharging to ground through a metal wrench if the ground post has had all connections removed first. When replacing the battery, attach the hot side first, then the ground cable. Making the ground connection last prevents arcing to the metal chassis of the auto during connection of the hot side.

REMOVING AND INSTALLING A CAR BATTERY



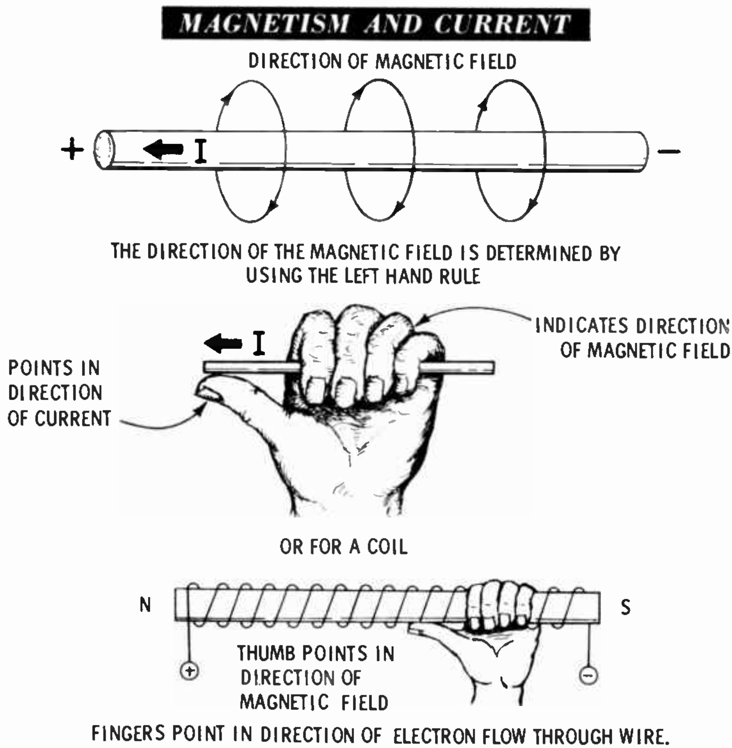
Q58. What action takes place that causes a dry cell to run down on the shelf?

Your Answer Should Be:

A58. **Chemical action** takes place within the cell even without a load.

MAGNETIC VOLTAGE SOURCES

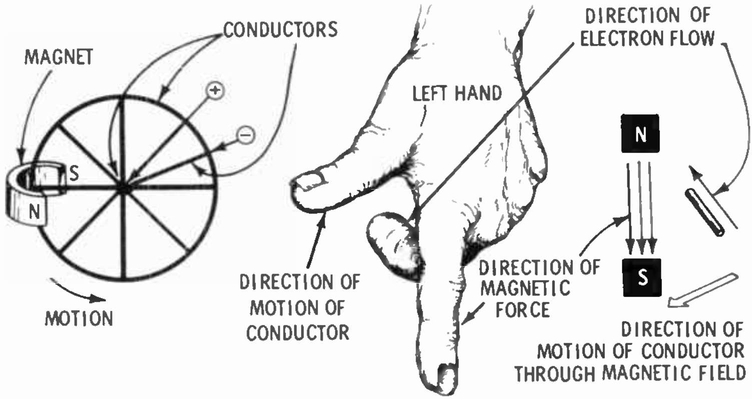
Electricity can also be generated by moving wires through a magnetic field. Also, electricity may be produced by moving the magnetic field through a number of wires.



To determine which way current will flow as a result of motion between a magnetic field and a wire, apply the **left-hand rule.** This rule will determine direction of current flow according to the electron theory. If the conventional current-flow theory is followed, use your right hand instead. Lines of force leave the north magnetic pole and enter the south pole.

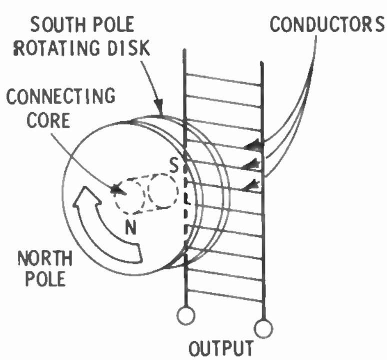
The amount of current which can be generated by using magnetism and mechanical motion depends on several factors. One factor is the number of magnetic lines of force being cut. The greater this number, the greater the current

DIRECTION OF CURRENT FLOW



will be. Another factor is the speed at which the lines of force are cut by the wires. The faster the relative motion between the two, the greater the force generating electron flow will be. Finally, the greater the number of wires cutting through the magnetic field, the greater will be the number of electrons that flow.

Q59. In which direction will the electrons flow in the following diagram?



Q60. Will an automobile generator produce more electricity when the car is traveling at 60 mph or at 20 mph?

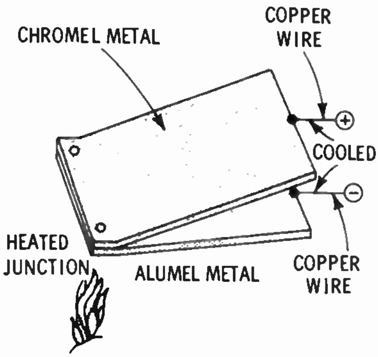
Your Answers Should Be:

A59. Left to right. (The effective direction of motion of the conductor is opposite to the direction of motion of the magnetic field.)

A60. The generator produces more electricity at **60 mph** than at 20 mph.

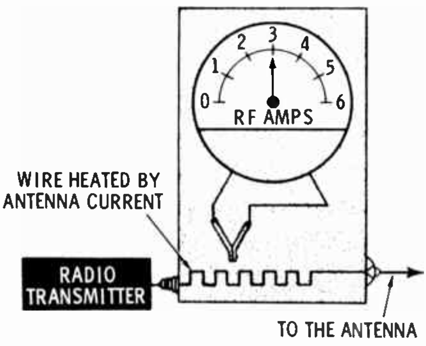
HEAT-GENERATED VOLTAGES

Heat can be used to produce electricity by joining two different metals, heating the junction, and taking the output at the cooler end. Such a device is called a **thermocouple generator.**



A THERMOCOUPLE

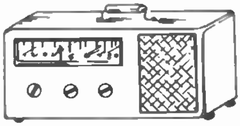
The thermocouple has many low-power applications. One such example is the radio-frequency current meter in the antenna circuit of a transmitter.



AN RF METER

A thermocouple produces an amount of voltage which is determined by the temperature difference between the two ends. The higher the difference, the greater the voltage.

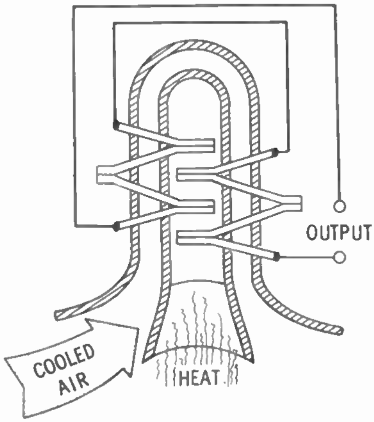
THERMOCOUPLE APPLICATIONS


TRANSISTOR RADIO


COAL MINER'S LAMP

Other applications for a thermocouple are in low-power devices such as small transistor radios and carbide lamps used by miners and hunters. A mixture of carbide and water produces a gas that will burn. The flame from a carbide burner heats the junctions of several thermocouples. The cooler ends are connected in series and produce a voltage which is then used to light an electric lamp.

A THERMOCOUPLE GENERATOR



How can you make a thermocouple? One way is to twist the ends of an iron and a copper wire together. Heat the twisted junction over a flame. If the free ends are connected to a milliameter, a small current reading may be observed.

Q61. Recalling the effect heat had on freeing the electrons in atoms, will the selection of thermocouple metals determine how much current will flow?

Q62. If electrons flow from one type of metal to the other in a thermocouple, is the current DC or AC?

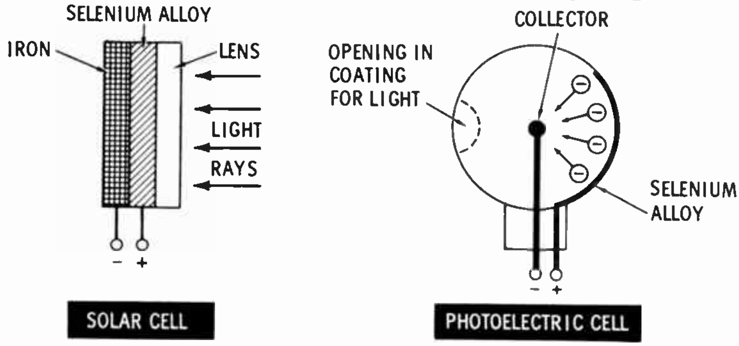
Your Answers Should Be:

A61. Yes. **A62. DC.**

LIGHT-GENERATED VOLTAGES

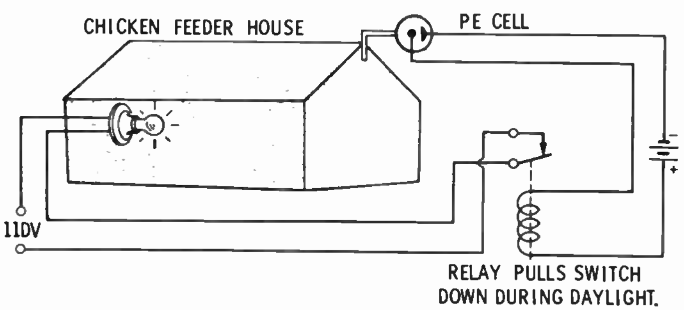
A **solar cell** uses light to produce electricity. This device produces only very small amounts of voltage and current. Light striking certain materials causes electrons to move and develops a voltage at the terminals of the material. A **photoelectric cell** develops a voltage in a similar manner.

PRODUCING ELECTRICITY WITH LIGHT



The photoelectric cell is often called a **PE cell.** A PE cell has many uses where a light beam can be broken, such as the automatic foul-line indicator on a bowling alley. Another application is an automatic lamp control. Here the PE cell is mounted so light from the sun will cause it to conduct and energize a relay. The energized relay turns the lamp off.

AUTOMATIC LAMP CONTROL



Selenium, used in solar and photoelectric cells, contains atoms that give up free electrons when struck by light. If iron is used as backing, the selenium will emit electrons into the iron. This will cause the iron to take on a negative charge, and the selenium to take on a positive charge. Wires connected to the two metals form the electrical source terminals.

In the solar cell, electrons travel from the selenium to the iron through their common bond. In the photoelectric cell, electrons move from the selenium through an evacuated area within the bulb to a center post.

Bonding, as used in a solar cell, is a common procedure employed in the electronics field. The bond is an electrical union similar to an electric weld. In fact, it is a bond created by a high current which causes the iron and the selenium to ionize and fuse together. When metals ionize they become very hot, just as in electric welding. Ionizing, as you recall, is the production of ions.

The vacuum bulb of the PE cell is the same type of evacuated bulb as that used for the electric light or the electron tube. The purpose of the vacuum is to allow electrons to travel from one location to another with a minimum of opposition from particles within the device. Air, for example, contains many millions of tiny particles which would hinder the flow of electrons.

The output of photoelectric and solar cells is very small. Therefore, the device which they control must require only a small amount of current. If they are to control larger objects, some form of electrical amplification must be used. The amount of voltage (or current) developed by these cells depends on the amount of light striking the selenium.

Q63. Electricity is generated in the PE cell through the electron-releasing action of ________.

Q64. When _____ strikes selenium, selenium gives off __________.

Q65. A(an) ______ allows electrons to travel with a minimum of opposition.

Q66. The output of a PE cell is very (small, large).

Q67. The voltage output of a solar cell is _______ with more light and ____ with less light.

Your Answers Should Be:

A63. Electricity is generated in the PE cell through the electron-releasing action of **selenium.**

A64. When **light** strikes selenium, selenium gives off **electrons.**

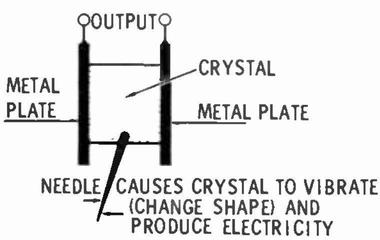
A65. A **vacuum** allows electrons to travel with a minimum of opposition.

A66. The output of a PE cell is very **small.**

A67. The voltage output of a solar cell is **greater** with more light and **less** with less light.

PRESSURE-GENERATED VOLTAGES

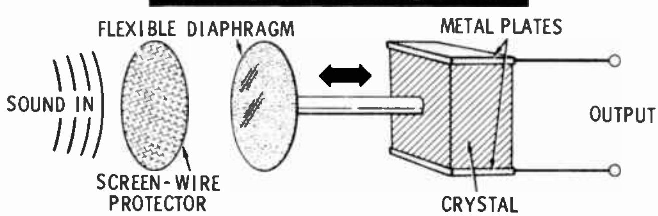
Crystals of certain kinds produce electricity when pressure is applied to them. A crystal phonograph pickup is of this nature. It consists of two metal plates separated by a crystal, and a needle which is vibrated by the wavy variations in the groove of the record. These vibrations cause the crystal to be alternately squeezed and released, developing a small voltage across the terminals.

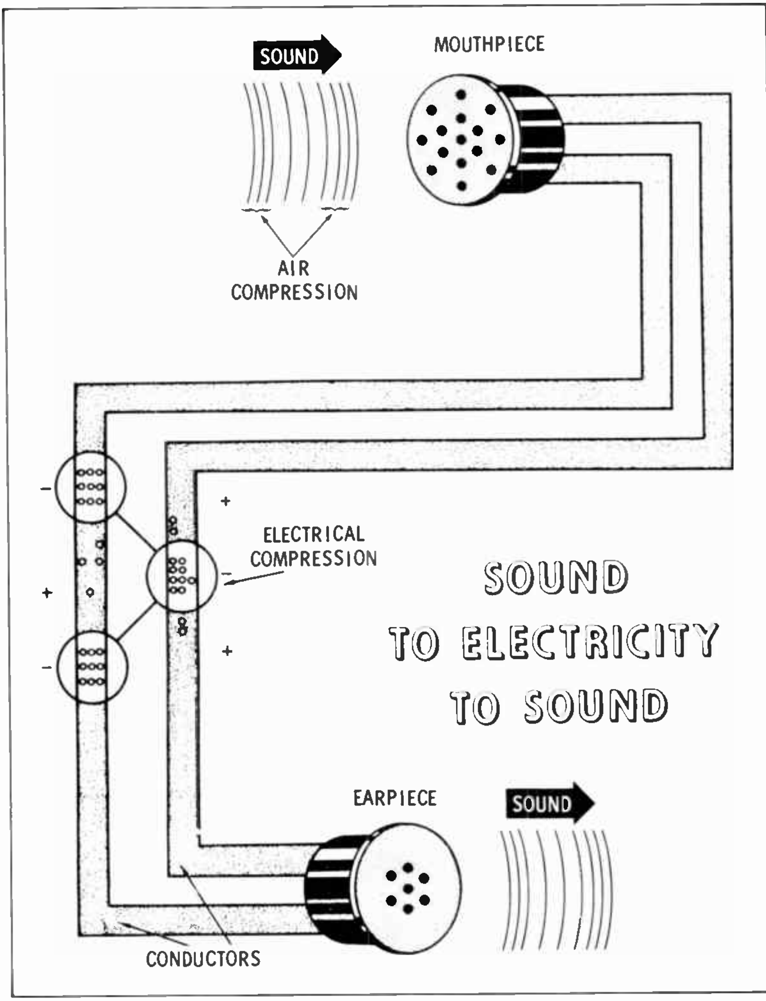


A Crystal Phonograph Pickup

The crystal most commonly employed for this form of electrical generator is Rochelle salt.

A Crystal Microphone





The ability of these crystals to produce a voltage when subjected to mechanical stress is called the **piezoelectric effect.** Conversely, when a voltage is applied to such crystals, a mechanical stress is produced.

Q68. How does the amount of electricity produced by a crystal compare with the amount of pressure applied?

Q69. How does sound produce electricity in a sound-powered phone system?

> **Your Answers Should Be:**
>
> A68. The **greater the pressure** is, the **greater the voltage.**
>
> A69. The pickup element (mouthpiece) transfers the sound-generated vibrations to a crystal. Thus, electricity is produced. The resulting current is carried by conductors to the earpiece. The earpiece changes the electricity back into sound.

RESISTANCE

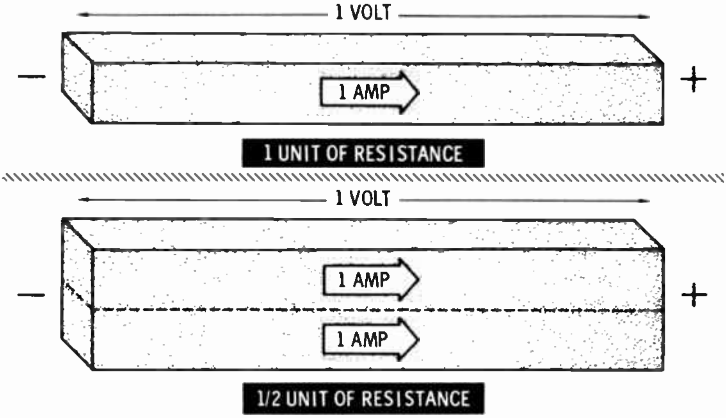
The amount of current flow in a circuit is determined by how much voltage is applied and how difficult it is for current to flow. **Resistance** is the term used to describe the opposition offered to the flow of current.

How easily current will flow in a conductor depends on the number of free electrons available in a given area of the material. The longer the wire, the more resistance it has.

Longer Conductor—More Resistance

At the same time, the larger the diameter, the less resistance a wire has.

More Area—Less Resistance



Computing Resistance of a Wire

The resistance of a wire can be determined as follows:

$$\text{Wire resistance is proportional to } \frac{\text{length}}{\text{area (cross-section)}}.$$

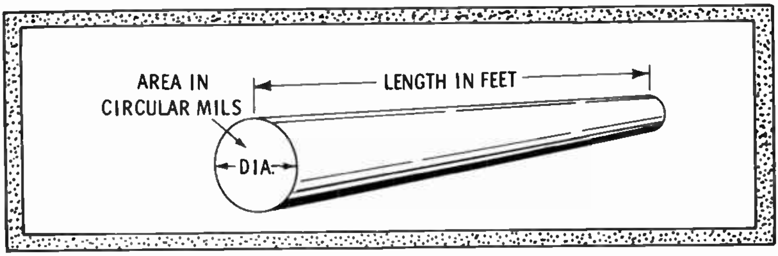
A wire 1,000 feet long will have twice the resistance of a 500-foot length having the same cross-sectional area. If both are the same length, a two-inch diameter wire will offer one-fourth as much resistance as a wire with a one-inch diameter.

Since the specific resistance of metals used as conductors can be determined, the preceding statement can be rewritten as a formula:

$$R = \rho \frac{L}{A}$$

where,

R is the resistance in ohms,
ρ (Greek letter rho) is the specific resistance of the material per circular mil-foot,
L is the length in feet,
A is the cross-sectional area in circular mils.



A **circular mil** is used as a unit instead of square inches to measure cross-sectional area of a wire. Circular mils can be determined by squaring the diameter (in mils) of a wire. A mil is 0.001 of an inch.

If the above wire had a diameter of 0.06 inch, the area (A) would be $(60 \text{ mils})^2$, or 3,600 circular mils. If the diameter was 0.6 inch, A would equal $(600 \text{ mils})^2$, or 360,000 circular mils. If the two wires were of equal length, the second wire would be able to conduct 100 times more current, or offer 100 times less resistance, than the first wire.

Specific Resistance

The value of rho (ρ), the specific resistance of a conducting material, is expressed in ohms per circular mil-foot. The table below provides the specific resistance for several conducting materials. The ohmic values are given at 68°F. Values will be slightly higher at higher temperatures.

SPECIFIC RESISTANCE (ρ)

Material	Ohms per circular mil-foot
Silver	9.796 ohms
Copper	10.370 ohms
Aluminum	16.060 ohms
Tungsten	33.220 ohms
Nichrome	660.000 ohms

Using this information, what is the resistance of 1,000 feet of copper wire having a diameter of 0.1 inch? This diameter is approximately the size of #10 electrical wire used for some applications in home wiring.

$$R = \rho \frac{L}{A}$$

ρ = 10.370 (from table)

L = 1,000 feet

A = 10,000 circular mils (100 mils squared)

$$R = 10.370 \times \frac{1,000}{10,000} = 10.370 \times \frac{1}{10} = 1.037 \text{ ohms}$$

Unless the diameter of a wire is extremely small, its length very long, or its specific resistance high, the resistance of a conductor in a circuit is usually not considered. Therefore, unless stated otherwise, conductors will not be considered as part of the circuit resistance in problems given in this text.

However, care should be exercised in selecting the size of a wire in circuits where current may be high. For example, #12 (electrical gauge size) copper wire normally used in the home has a safe current-carrying capacity of only 20 amps. Higher current will cause it to develop too much heat.

Valve Analogy

A valve used in the water system of a home is an example of resistance. When the valve is closed, water does not flow. If it is slightly open, a very small amount of water flows. The valve presents opposition (resistance) to the flow of the water. Even when the valve is completely open, less water will flow than if the valve were replaced with a pipe.

Will a large water pipe let more water flow than one of smaller diameter if the same amount of water pressure is applied? The answer is **yes.** By the same reasoning, a large wire will let more current flow than a small wire.

Will the length of the water pipe have any effect on the amount of water that flows out of the end? Yes. The longer the garden (lawn) hose you connect to the outside water valve, the less water pressure there will be at the end of the hose. Why is this? It is because the inside wall of the hose offers resistance to the flow of water.

As water travels through the hose, the water molecules rub against the side of the hose. The water molecules have motion but the hose does not, so the movement of the molecules is retarded. Slowing down the outer molecules also causes adjacent water molecules to decrease their speed. If the hose is of greater diameter, the center system of water molecules is less affected by the stationary outer wall.

Size of a wire has a similar effect on electron flow. A conductor of large diameter provides an easier (roomier) path for current than a conductor with a smaller diameter.

Factors Affecting Resistance

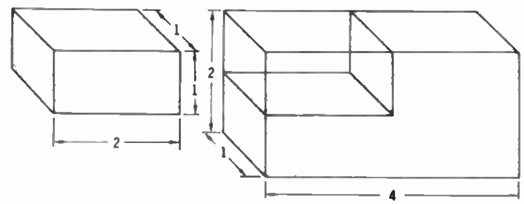
The length and the cross-sectional area of a conductor determine how much resistance is in the circuit. Other things, such as the kind of material, temperature, and kind of electricity (AC or DC), also determine the resistance.

Q70. Given a wire with a cross-sectional area of 2 circular mils and a length of 4 feet, and another wire with a cross-sectional area of 1 circular mil and a length of 2 feet, which wire will have the lesser opposition to current flow?

Q71. What is the difference between the resistance of a conductor and the resistance of an insulator?

Your Answers Should Be:

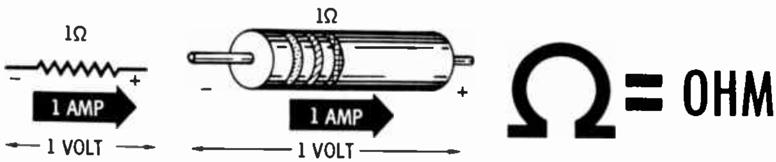
A70. They will have the **same** opposition to current.



A71. The **conductor has a very low resistance** to current flow, and the **insulator has a very high resistance** to current flow.

Resistance Units and Symbols

The standard unit of measurement for resistance is the **ohm.** One ohm of resistance in a circuit limits current to 1 ampere when 1 volt of electrical pressure is applied.



The symbol for the ohm is the Greek letter, **omega.** The uppercase omega (Ω) is used to represent ohm. The amount of resistance in a circuit is designated by a number of ohms.

The letter **R** is the letter symbol for resistance. It is used to identify resistance in electrical diagrams and as a mathematical symbol in electrical equations.

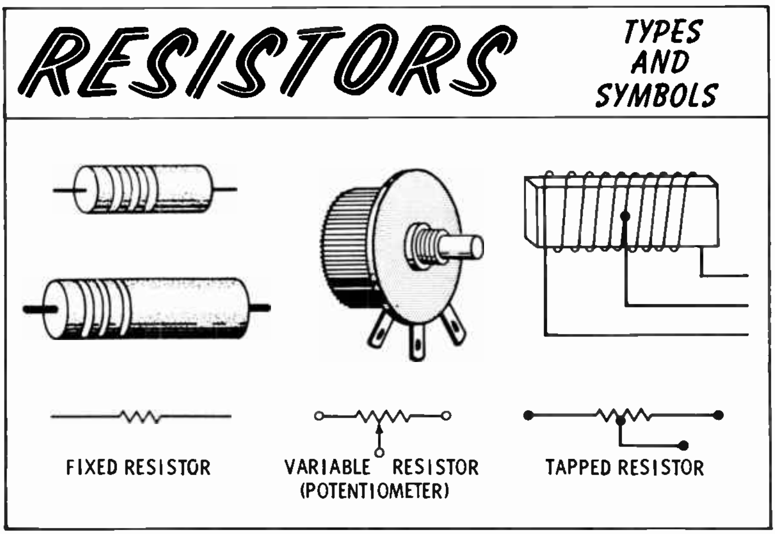
Resistance units have several values which are similar to those for voltage and current.

Resistance Designation	Meaning
1 ohm (Ω)	unit of resistance
1 kilohm	1 KΩ = 1,000 Ω
1 megohm	1 MΩ = 1,000,000 Ω
1 milliohm	1 mΩ = 0.001 Ω

Resistors and Resistive Components

Resistance is not limited to conductors alone. Electronic components, called **resistors**, are manufactured to have a specific amount of resistance. Many resistors of several values are used in radios and TV sets. Also, there are many applications for resistors in commercial and military equipments.

What is the purpose of resistors in these circuits? They are used to limit current flow and to develop voltages of lesser potential than the source. Resistors are manufactured in many different forms and many different values. They may also be of a fixed or variable value.



Q72. The unit of measurement for resistance is the ___.

Q73. The ___ is the symbol for resistance value.

Q74. What are resistors used for?

Q75. As an exercise, write the following resistance values in the shortest possible form.

(a) 37,500 Ω	**(b) 375,000 Ω**
(c) 1,030,000 Ω	**(d) 103 Ω**
(e) 99,000 Ω	**(f) 146,210 Ω**
(g) 4,900 Ω	**(h) 57,200 Ω**

Your Answers Should Be:

A72. The unit of measurement for resistance is the **ohm.**

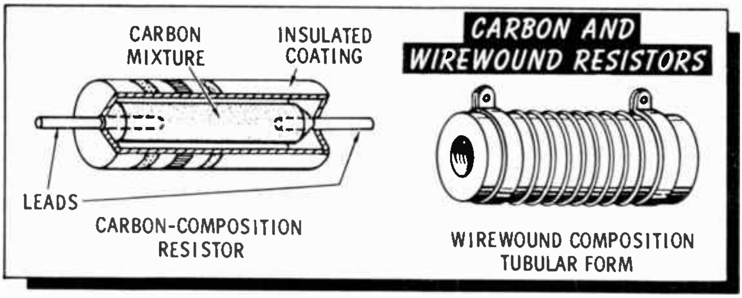
A73. The Ω is the symbol for resistance value.

A74. To **limit current flow** and to **develop voltages smaller than the source voltage.**

A75. (a) **37.5KΩ** (b) **375KΩ**
(c) **1.03MΩ** (d) **103Ω**
(e) **99KΩ** (f) **146.21KΩ**
(g) **4.9KΩ** (h) **57.2KΩ**

Resistor Values

The material from which resistors are made is of such a nature as to produce the desired values. Most resistors are manufactured from wire or from a mixture of materials.



Reading and Measuring Resistors

Resistors are color coded to permit determination of their resistance value. You will find three or four colored bands around the resistor. The bands will be nearer one end than the other. The first band is nearest the end of the resistor.

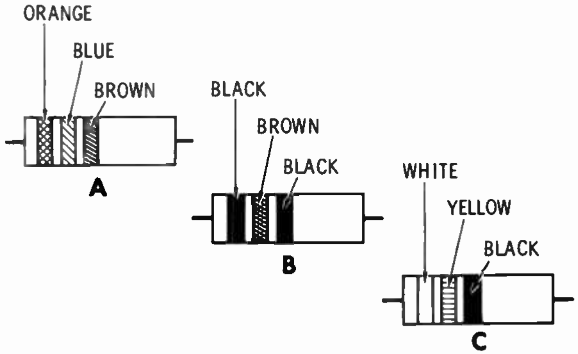
Ten colors are used to represent each of the digits in the decimal system. These colors are black, brown, red, orange, yellow, green, blue, violet, gray, and white. They represent the digits 0 through 9, in that order.

The first two colors on the resistor (the two nearest the end) represent the first two numbers of the resistance value. The third color band represents the number of zeros that follow the first two numbers. The fourth band (if there is one) determines how much the actual resistance can vary from the indicated value of the resistor. The difference between the indicated value (by color bands) and the actual value is called the resistor **tolerance.**

The fourth band will be either gold or silver. If it is gold, the tolerance of the resistor is plus or minus 5% ; if it is silver, the tolerance is plus or minus 10% . The absence of a fourth color band indicates the resistor tolerance is plus or minus 20% . For example, the actual value of a 68,000-ohm resistor having only three color bands is between 54,400 ohms and 81,600 ohms. (20% of 68,000 ohms is 13,600. The tolerance limits are therefore 68,000 + 13,600 = 81,600 ohms, and 68,000 — 13,600 = 54,400 ohms.)

Q76. What are the digits for the following colors? (a) Blue. (b) Gray. (c) Orange. (d) Black.

Q77. What are the values of the following resistors?



Q78. What is the resistance range of a 68,000-ohm resistor if its fourth band is gold?

Q79. What is the resistance range of a 68,000-ohm resistor if its fourth band is silver?

Your Answers Should Be:

A76. (a) Blue is 6. (b) Gray is 8. (c) Orange is 3. (d) Black is 0.

A77. (a) 360 ohms. (b) 1 ohm. (c) 94 ohms.

A78. 64,600 to 71,400 ohms (68,000 plus or minus 3,400 ohms).

A79. The resistor would read somewhere between 61,-200 ohms and 74,800 ohms.

WHAT YOU HAVE LEARNED

1. All matter is made up of molecules.
2. A molecule is the smallest possible particle that still retains the same physical and chemical characteristics of a substance.
3. Molecules are made up of atoms.
4. An atom is the smallest portion of an element which exhibits all the properties of that element.
5. An atom is made up of even smaller particles called protons, electrons, and neutrons.
6. Electrons have a negative charge and are the smallest of the three particles. Electrons revolve around the center cluster in orbit zones.
7. The center cluster of an atom is called the nucleus and consists of protons and neutrons bonded together.
8. A proton is the next largest particle and has a positive charge.
9. A neutron is the largest particle and has a positive and negative charge to make it neutral.
10. Different elements have different numbers of electrons and protons.
11. The electrons orbit around the nucleus in zones which may or may not be filled.
12. The first two orbit zones are filled when they have 2 and 8 electrons, respectively. Subsequent zones are filled with 8, 18, or 32 electrons.
13. If an atom has a different number of electrons than

protons, it has an electrical charge (either positive or negative).

14. A charged atom is called an ion. It is a negative ion if it has an excess of electrons. It is a positive ion if it has a deficiency of electrons.
15. An element whose atom does not have completely filled outer-orbit zones is called a free-electron type element.
16. A free-electron type element requires less energy from a voltage source to cause transfer of electrons from one atom to another than does an element whose orbit zones are filled.
17. To have electrical movement, energy must be applied to an atom.
18. To be of value, the energy must be applied so as to direct electrical movement.
19. Voltage (electrical pressure) is the most common form of control.
20. Voltage is a difference of electrical charge between two points.
21. The difference in electrical charge between two points establishes a force.
22. The amount of force is determined by the amount of charge at each point and the distance between them.
23. The production of electricity is the result of controlled movement of ions or electrons. This movement is called current.
24. Electricity, once produced, can be transferred from one location to another.
25. Electrically, materials may be classified as conductors or insulators.
26. Conductors can serve as a path for the transfer of electricity.
27. Insulators present a very difficult path for the transfer of electricity.
28. The human body is a conductor of electricity.

    NOTE: For this reason, any person near electricity should take every precaution possible in order not to become a part of the electric circuit!

29. Electricity may be produced by friction.
30. When electricity is produced as a result of one object rubbing against another, it is called static electricity.
31. Lightning is an example of static electricity.
32. The production of electricity is the result of a collection of more positive charges at one point than at another, or a collection of more negative charges at one point than at another.
33. An accumulation of an electrical charge (voltage) can be measured with a voltmeter.
34. The amount of current flowing through a circuit when voltage is applied can be measured with an ammeter.
35. The amount of force between two charged bodies can be calculated by using the expression:

$$F = \frac{Q_1 \times Q_2}{d^2}$$

36. Graphical representation of electric force and electrostatic fields is used to indicate the direction an electron will move when acted on by charged bodies.
37. Electric current is the flow of either ions or electrons.
38. There are two major current theories employed in the electrical and electronic fields.
39. One is electron-theory current flow and the other is conventional current flow.
40. Electron-theory current flows from the negative terminal of a voltage source through the circuit, and back to the positive terminal of the source.
41. Conventional current (ions) flows from the positive terminal, through the circuit, and back to the negative terminal of the source.
42. The standard unit for current is the ampere.
43. "a" is used to indicate ampere.
44. "I" is used to indicate the current flowing in a circuit.
45. Voltage is electrical pressure.
46. Voltage may be called potential difference, electromotive force (emf), or voltage potential.
47. The standard unit for voltage is the volt.

48. "V" is used to indicate volt.
49. "E" is used to represent voltage in a circuit.
50. Electricity can be produced by means of chemical action, heat, light, magnetism, pressure, or friction.
51. A battery is a device which uses chemical action to produce electricity.
52. A thermocouple employs heat to produce electricity.
53. An automobile generator uses magnetism to produce electricity.
54. A crystal pick-up of a record player converts pressure into electricity.
55. The amount of current flow in a circuit is determined by how much voltage is applied and the amount of resistance in the circuit.
56. The standard unit of measurement for resistance is the ohm.
57. The Greek letter omega (Ω) is used to represent ohm.
58. "R" is used to represent resistance in a circuit.
59. Colored bands around a resistor indicate the value of resistance in ohms.

2

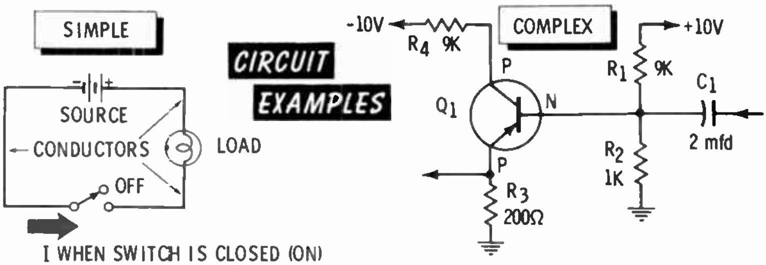
The Simple Electrical Circuit

What You Will Learn

You are now going to learn about basic circuits. You will be shown the application of Ohm's law and the electrical power relationships which exist between voltage, current, and resistance. From this information you will be able to identify basic circuits; visualize and describe voltage, current, and resistance relationships; determine power relationships; and construct a basic circuit.

BASIC CIRCUITS

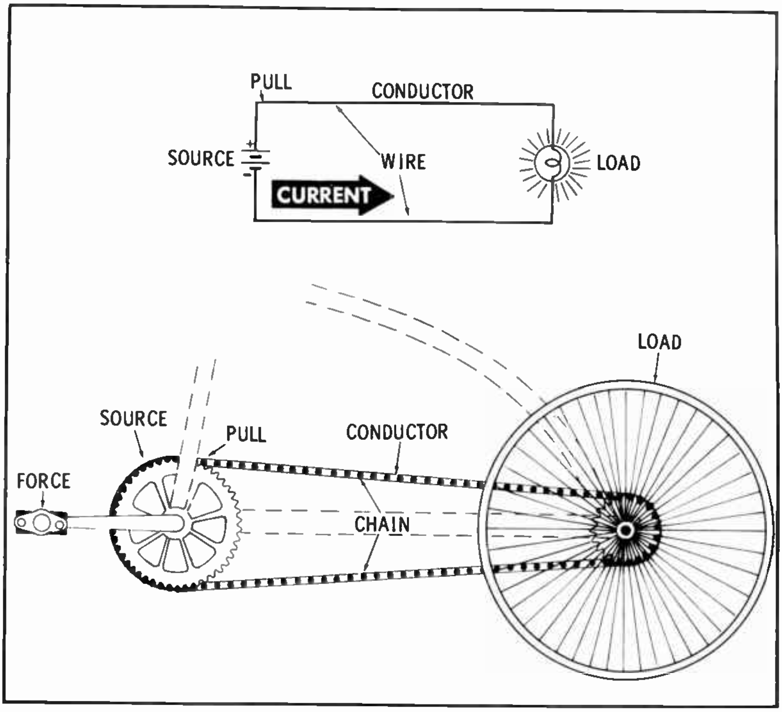
A circuit consists of a closed path through which an electric current flows. It is the route followed by current as it



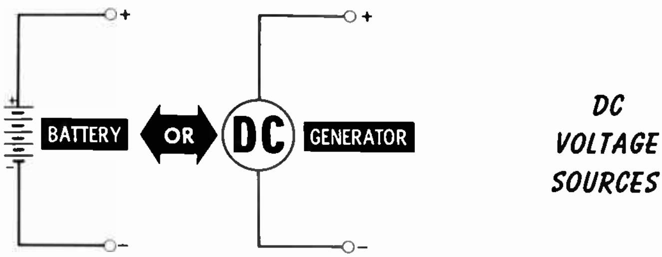
travels from the voltage source through the conductors and the load and returns to the source. This includes the path from terminal to terminal through the source.

Connecting a Source to a Load

A circuit must form a **complete** (unbroken) loop for current to flow. Current flows through a circuit in somewhat the same manner as a bicycle chain makes a complete loop between the driving gear (source) and the wheel (load).



An electrical/electronic circuit must form a complete loop from the voltage source to the load and back to the source.

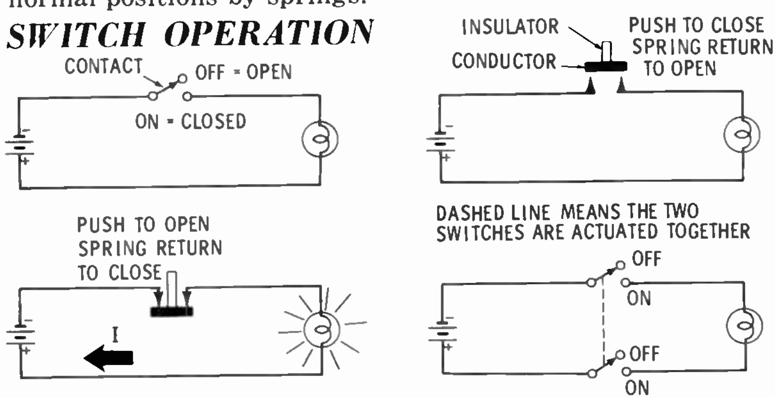


Symbols used for DC voltage sources in schematic diagrams are normally those of a battery or a DC generator.

The current-carrying paths between the terminals of a load and its voltage source are called **conductors.** A conductor can be a wire (usually copper), or the heavy metal that forms part of the equipment or device can serve as one of the paths between the load and voltage source.

SWITCHES

Switches have been developed so that a circuit may be opened and closed with little effort or danger to the operator. Some switches are normally closed. When these switches are actuated, they **open,** or break, the circuit. Other types of switches are normally open. When actuated, they **close** (make) a circuit. Such switches are maintained in their normal positions by springs.



Q1. If a lamp is mounted on an insulator in an automobile, how many wires must be connected to the lamp socket?

Q2. There are no wires in a flashlight. How is the circuit completed?

Q3. A tail lamp on an automobile is mounted on a very rusty body. If the lamp lights only part of the time, what is the possible cause of the trouble?

Q4. A completed circuit containing a voltage source will always have _______ _______ through it.

Q5. A circuit is open if current (does, does not) flow.

Q6. A lamp circuit is ______ if the lamp lights.

Q7. ________ are used to open and close circuits.

Your Answers Should Be:

A1. There must be **two** wires connected to the lamp socket. One is connected to a "hot" terminal and the other to the chassis.

A2. The flashlight shell (case) forms one conductor from the lamp to the batteries. A battery terminal in direct contact with the lamp forms the other conductor.

A3. The probable cause is a **poor** or **open conductor** (the rusty body).

A4. A complete circuit containing a voltage source will always have **current flowing** through it.

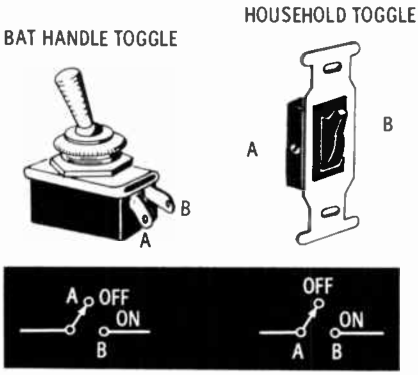
A5. A circuit is open if current **does not** flow.

A6. A lamp circuit is **closed** if the lamp lights.

A7. **Switches** are used to open and close circuits.

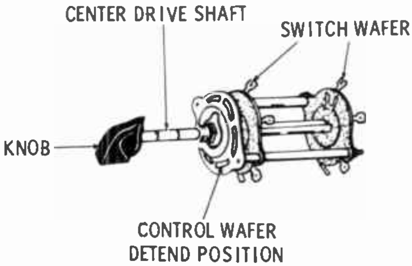
The **knife switch** was probably the first switch used to any great extent. A basic requirement for the knife switch is the alignment of the two ends. This is required to permit a movable blade to make positive connection with stationary contacts. The switch is usually mounted on insulators or on an insulated board.

THE COMMON TOGGLE SWITCH



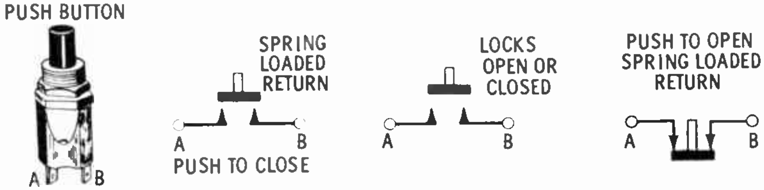
A **toggle switch** is an improved knife switch. It uses a spring-loaded mechanism to open and close the contacts.

THE WAFER SWITCH



A **wafer switch** is a rather recent development resulting from the many advances in electronic and electromechanical devices. Electromechanical devices include equipment that converts electrical energy to mechanical energy or mechanical energy to electrical energy. One advantage of the wafer switch is its ability to be rotated from one position to another, providing a multiple switching action. Wafer switches are made to rotate either a full 360°, or part of a turn. Another advantage is that more than one wafer may be actuated with a single shaft.

THE PUSH-BUTTON SWITCH



A **push-button switch** uses a button which must be pushed to form a closed (or open) condition. One type remains closed (or open) until the next push. Another kind is the **momentary** push button. It stays closed (or open) as long as the button is depressed.

Regardless of the style, a switch is used to fulfill only one purpose—to open or close a circuit.

Q8. What is the purpose of a switch in an electrical circuit?

Q9. What unique feature does the wafer switch have over other switches discussed in this chapter?

Your Answers Should Be:

A8. A switch is used to **open and close circuits.**

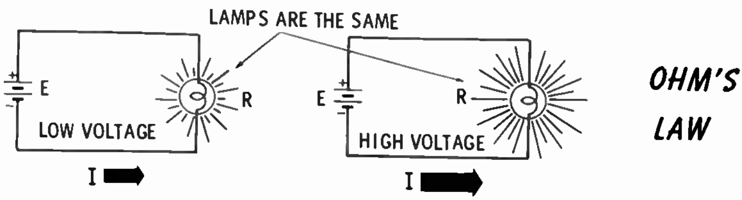
A9. A wafer switch is the only one that employs **rotary motion** for positioning.

OHM'S LAW

Ohm's law expresses the precise relationship that exists between voltage, current, and resistance. Relationships concerning this law for DC circuits will be used for evaluation of all other electrical circuits. You should therefore study the next few pages carefully.

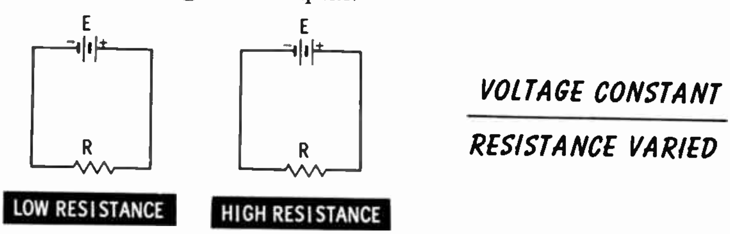
Basic Relationships

Which circuit below will have the greater current flow?



The circuit with the lower voltage will not have as much current flow as the other. The current will therefore be greater in the circuit on the right.

In which of the following circuits will current be greater? The two voltages are equal.



Current cannot flow as easily through a high resistance as it can through a low resistance. Thus, the circuit on the left will have the greater current flow. The circuit with the higher resistance will require a higher voltage source to cause an equal amount of current to flow.

Explanation of Ohm's Law

Current will decrease if voltage is decreased or resistance is increased. The reverse is also true. Current will increase if voltage is raised or resistance is reduced. Therefore, Ohm's law can be stated as an equation, with current (I) being made equal to a ratio between voltage (E) and resistance (R).

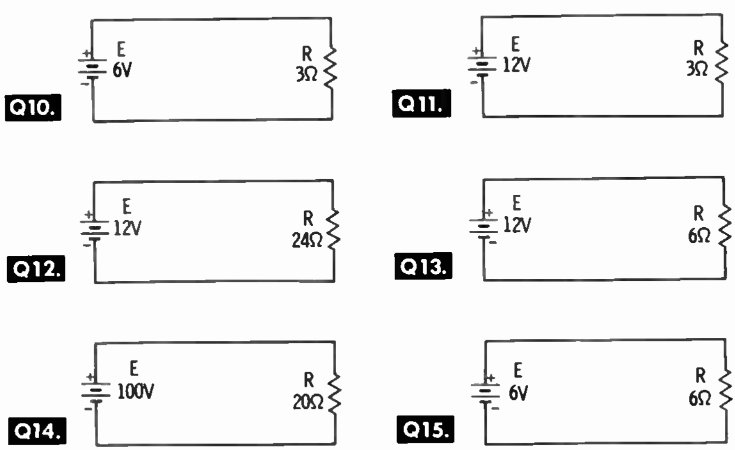
$$I = \frac{E}{R}, \text{ or amperes} = \frac{\text{volts}}{\text{ohms}}$$

This statement (equation) is true for the current-voltage-resistance relationship in any DC circuit. If R (in ohms) remains the same, and E (in volts) is increased by a factor of two, five, ten, or any other number, then I (amperes) will be increased by the same factor. A decrease in the number of volts will result in a proportional decrease in amperes. In other words, to determine I, E is divided by R.

$$I = \frac{E\ (10\text{ volts})}{R\ (2\text{ ohms})} = \frac{10}{2} = 5\text{ amps}$$

The same reasoning holds true for changes in resistance. For a given voltage, current will be twice as large if resistance is decreased to one-half its former value. If the resistance is increased four times, current will become one fourth as large.

Q10-15. Find I in each of the six circuits below.



Your Answers Should Be:

A10. 2 amps.

$$I = \frac{E}{R} = \frac{6 \text{ volts}}{3 \text{ ohms}} = 2 \text{ amps}$$

A11. 4 amps. Note the amount of increase in current when the voltage was doubled.

A12. 0.5 amp

A13. 2 amps. Note how much current increased when the resistance was reduced by one fourth.

A14. 5 amps

A15. 1 amp

Application of Ohm's Law

Ohm's law can be used to find either current, voltage, or resistance in a circuit if the other two factors are known.

Solving for Current—You have already seen how current in a circuit can be determined by dividing the circuit voltage by the load resistance. I is equal to E divided by R.

Solving for Voltage—In the chapters which follow, you will see the need for determining voltage when current and resistance are known. For example, how much voltage is required to force a current of 2 amperes through a load resistance of 50 ohms? The Ohm's-law equation would be:

$$I = \frac{E}{R}, \text{ or } 2 \text{ amps} = \frac{? \text{ volts}}{50 \text{ volts}}; E = 100 \text{ volts}$$

Arithmetic reasoning tells you that voltage units must be twice the number of resistance units to permit 2 amperes to flow. Or, you multiply the number of ohms by the number of amperes to obtain the number of volts. E is equal to I multiplied by R. By using a mathematical rule, you multiply both sides of the basic equation by R to obtain the same equation for voltage.

$$(R) \times I = \frac{E \times (R)}{R}, \text{ or } IR = E$$

The R's on the right side of the equation cancel, leaving E equal to IR (I multiplied by R). If 0.5 amp is flowing through 20 ohms, E applied (IR) is 10 volts.

Solving for Resistance—If the voltage and current in a circuit are known, its resistance can be determined by similar reasoning. What is the resistance of a coil that permits 2 amperes of current to flow when connected to a 6-volt battery?

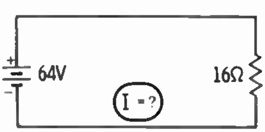
$$I = \frac{E}{R}, \text{ or } 2 \text{ amps} = \frac{6 \text{ volts}}{? \text{ ohms}}; \ R = 3 \text{ ohms}$$

To obtain 2 amperes, 6 volts must be divided by 3 ohms. In other words, resistance can be determined by dividing voltage by current. Mathematically, the equation for resistance is obtained in the following manner:

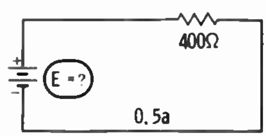
$$I = \frac{E}{R} \text{ (transpose I and R)} : R = \frac{E}{I}$$

Q16-23. Solve for the quantity indicated in the circuits below.

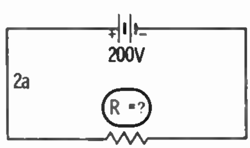
Q16.



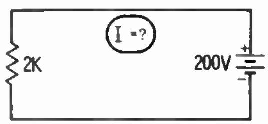
Q17.



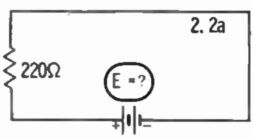
Q18.



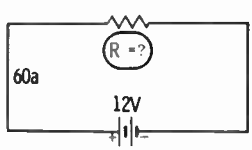
Q19.



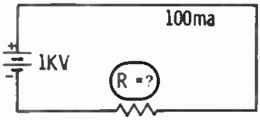
Q20.



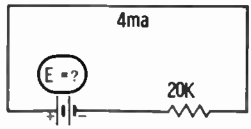
Q21.



Q22.



Q23.



Your Answers Should Be:

A16. $I = \frac{E}{R} = \frac{64}{16} = 4$ **amps**

A17. $E = IR = (0.5)(400) = 200$ **volts**

A18. $R = \frac{E}{I} = \frac{200}{2} = 100$ **ohms**

A19. $I = \frac{E}{R} = \frac{200}{2{,}000} = 0.1$ **amp**

A20. $E = IR = (220)(2.2) = 484$ **volts**

A21. $R = \frac{E}{I} = \frac{12}{60} = \frac{1}{5}$, **or 0.2 ohm**

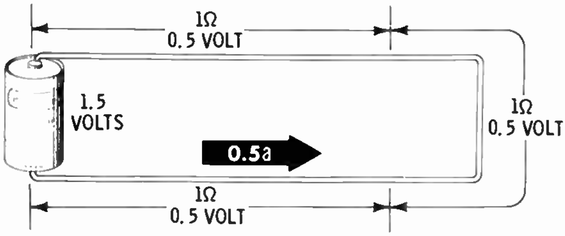
A22. $R = \frac{E}{I} = \frac{1{,}000}{0.1} = 10{,}000$, **or 10K ohms**

A23. $E = IR = (0.004)(20{,}000) = 80$ **volts**

VOLTAGE DROP

Voltage drop is a term which can be misleading. The word "drop" may lead you to believe that an amount of voltage is lost. This is not true, however; voltage never disappears. Voltage drop merely refers to the manner in which the source voltage is distributed (dropped) throughout the circuit.

VOLTAGE DROP IN A CIRCUIT

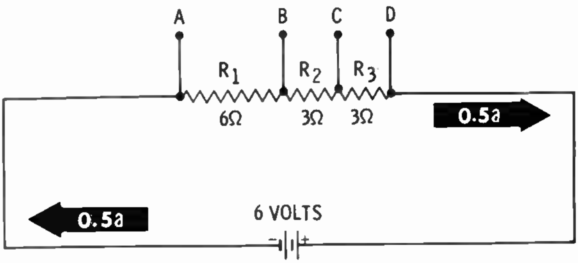


All of the source voltage is distributed proportionally across the resistance in a circuit. The voltage drop between any two points in a circuit can be determined by the ratio of the individual resistance to the total resistance of the circuit. The diagram, for example, shows a 3-yard length of wire connected to the terminals of a 1.5-volt cell. The resistance of the wire is one ohm per yard, or a total of three ohms for the circuit. Current for the circuit (E/R) will be 0.5 amp.

The total 1.5 volts will be dropped across the total length of the wire. Since E = IR, the voltage distribution is often called the **IR drop.** This version of Ohm's law can be used to determine the voltage drop across any portion of a circuit.

Since one yard of wire presents one ohm of resistance to the current flowing through it, its IR drop (share of the circuit voltage) is 0.5 amp × 1 ohm, or 0.5 volt. A yard of wire represents one third of the total resistance and would have one third (0.5 volt) of the total voltage across it. A sensitive voltmeter would record this drop.

VOLTAGE DROP IN A LOAD



Normally, the relatively small voltage drop of conductors is disregarded since the wire resistance is usually a very small fraction of the total load resistance. The tapped resistance in the diagram above has a total of 12 ohms with a total of 6 volts (from the source) applied across it. A current of 0.5 amp flows through each portion. The voltage (IR) drop between terminals A and B will be 3 volts in accordance with Ohm's law, resistance ratio, or a voltmeter measurement.

Q24. What is the voltage drop across R3?

Q25. What is the IR drop between terminals A and C?

Q26. How much voltage will be measured between terminals B and D?

Q27. The sum of the total voltage drops in a circuit is (equal to, less than, more than) source E.

Q28. R5 is 0.2 of the total circuit resistance. The circuit voltage is 9 volts. What is the IR drop across R5?

Your Answers Should Be:

A24. The voltage drop across R3 is **1.5 volts.**

A25. **4.5 volts** (0.5 amp × 9 ohms) is distributed between terminals A and C.

A26. **Three volts** between B and D.

A27. The sum of the total voltage drops in a circuit is **equal to** source E.

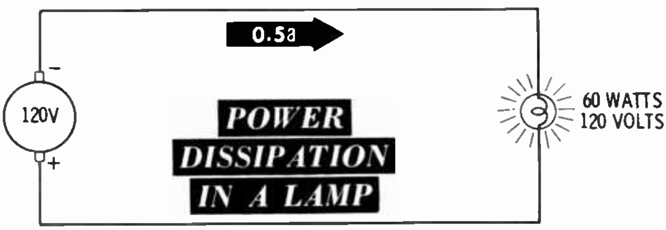
A28. **1.8 volts** (two tenths of nine volts.)

ELECTRIC POWER

When voltage forces current through a resistance, heat is generated. **Electrical energy** is converted to **heat energy.** The rate at which this conversion takes place is called **power,** and its unit of measurement is the **watt.** Power is determined by the product of current flowing through the device and the voltage dropped across the device.

$$P \text{ (power in watts)} = E \text{ (volts)} \times I \text{ (amps)} = EI$$

Since P = EI, the wattage rating of a device reveals its voltage or current if one of these values is known. For example, an electric light bulb has its wattage and voltage stamped on its surface. Why do you think this is done?



Connected to 120 volts, the 60-watt lamp will draw 0.5 amp. If P = IE, I is equal to P divided by E. If the filament has been properly constructed, the lamp will burn for many hours with ½ ampere flowing through it. What will happen if the lamp is connected across 240 volts? Since the voltage is doubled, current will also double. The power (IE) that the lamp must now dissipate is 1 ampere multiplied by 240 volts, which is equal to 240 watts. The filament, constructed for 60 watts, will be rapidly consumed by the increased heat. For this reason electrical devices should be connected to proper voltages only.

Power can be determined by knowing only E and R, or only I and R. The power equations can be developed by substituting the appropriate Ohm's law equations in $P = IE$.

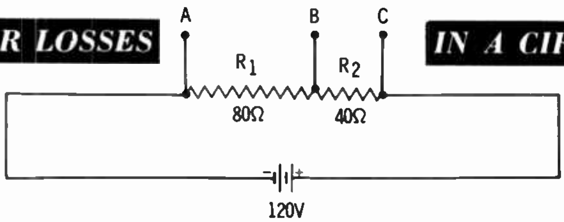
If $P = IE$, and $E = IR$, then (by substitution):
$P = (I)(IR) = I^2R$.

Since $I = \frac{E}{R}$, $P = \left(\frac{E}{R}\right)(E) = \frac{E^2}{R}$

By use of the appropriate expression, power can be determined if the voltage and current, the current and resistance, or the voltage and resistance are known.

Since electrical energy is dissipated in the form of heat in a resistance, the power developed in a resistance is considered to be a loss. If 1 ampere of current causes a voltage drop of 120 volts, the power (IE) loss is 120 watts. If 2 amps flow through 10 ohms, the power loss (also called an I^2R loss) is 40 watts. A voltage drop of 10 volts across 20 ohms of resistance will dissipate 5 watts of power (E^2/R).

POWER LOSSES IN A CIRCUIT



Q29. What is the total circuit current in the above circuit?

Q30. How much current is flowing through R_1?

Q31. What is the voltage drop between terminals A and C?

Q32. How many volts will be measured across R_1?

Q33. What is the IR drop across R_2?

Q34. What is the power loss in R_1?

Q35. How much power is dissipated in the total load?

Q36. If the source voltage is decreased to 60 volts, how many watts will be dissipated by R_2?

Your Answers Should Be:

A29. **1 ampere.** (Source voltage of 120 volts divided by the total resistance of 120 ohms.)

A30. **1 ampere.** (The same current flows through all parts of this circuit.)

A31. **120 volts.** ($E = 1 \text{ amp} \times 120 \text{ ohms}$)

A32. **80 volts.** ($E = IR$)

A33. **40 volts.**

A34. **80 watts.**

A35. **120 watts.**

A36. **10 watts.** This can be determined by several methods based on the current now being 0.5 amp (E/R) and the new voltage drop of 20 volts across R_2:

(a) $P = IE = (0.5)(20) = 10$ watts

(b) $P = \frac{E^2}{R} = \frac{(20)^2}{40} = \frac{400}{40} = 10$ watts

(c) $P = I^2R = (0.5)^2 \times (40)$
$= (0.25)(40) = 10$ watts

(Note that decreasing the voltage to one half the original value halved the amount of current flowing and decreased the power consumption of the circuit to one fourth.)

As in the Ohm's law equations, all factors in the power equations must be in equivalent units. E must be in volts; I in amperes; R in ohms.

WHAT YOU HAVE LEARNED

1. Current will flow only in a complete circuit.
2. A circuit consists of a source connected to a load.
3. A basic circuit consists of a source, conductors, and a load.
4. Switches are used to open and close the current path.
5. A toggle switch is the most common switch.
6. A knife switch was probably the first form of switch.

7. Wafer switches rotate and may have more than one set of terminals.
8. A push-button switch is designed to be either normally open or normally closed. Depressing the switch button opens a closed circuit or closes an open circuit.
9. Current will not flow through an open circuit but will flow in a closed circuit.
10. Because of the Ohm's law relationship between I (current), E (voltage), and R (resistance), the value of one of these factors can be determined if the other two are known.
11. The voltage applied across a resistance is equal to the current flowing through the resistor times its resistance. $E = I \times R$.
12. Current through a resistor is equal to the voltage applied divided by the resistance:

$$I = \frac{E}{R}$$

The greater the resistance, the smaller the current will be for a given voltage.
13. Resistance is equal to the amount of voltage applied divided by the amount of current the resistor permits to flow:

$$R = \frac{E}{I}$$

14. The power dissipated in an electrical circuit generates heat. The amount of heat depends on how much current is flowing and the amount of voltage forcing it to flow.
15. $P = IE$, where the power is measured in watts (w).
16. Power is equal to I^2R, where IR is substituted for E in the $P = IE$ expression.
17. Power is equal to E^2/R, where E/R is substituted for I in the $P = IE$ expression.
18. Ohm's law expressions:

$$E = IR,\ I = \frac{E}{R},\ R = \frac{E}{I}.$$

19. Power expressions:

$$P = IE,\ P = I^2R,\ P = \frac{E^2}{R}.$$

3

DC Series Circuits

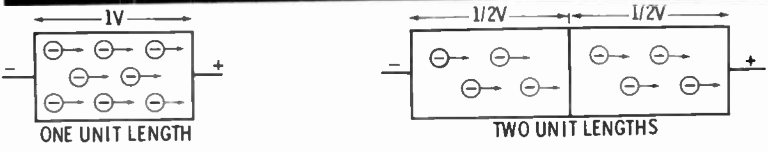
What You Will Learn

This chapter contains a thorough description of the series circuit and its basic connections. It also explains how total resistance, total current, and voltage drops are determined in such a circuit. You will learn how to reduce a voltage to a desired level by the use of a dropping resistor, identify series connections in complex electronic circuits, and determine total resistance and total current in a series circuit.

WHAT IS A SERIES CIRCUIT?

A **series circuit** is an electrical circuit in which all the components are connected end to end.

VOLTAGE AND CURRENT

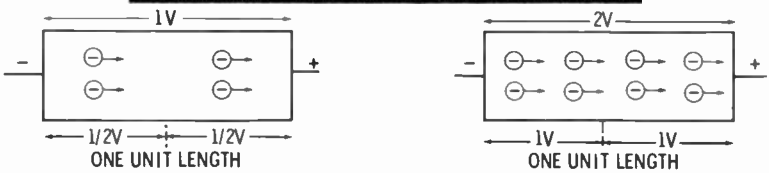


Do you recall the voltage distribution which occurs across a resistance? If one volt is applied across one unit length of wire, for example, what will happen to the voltage distribution across the same size wire that is twice as long? One-half volt will appear across each unit length. One-half the total voltage will be dropped across each of the two units. Since the resistance is doubled, the current will be one-half as much.

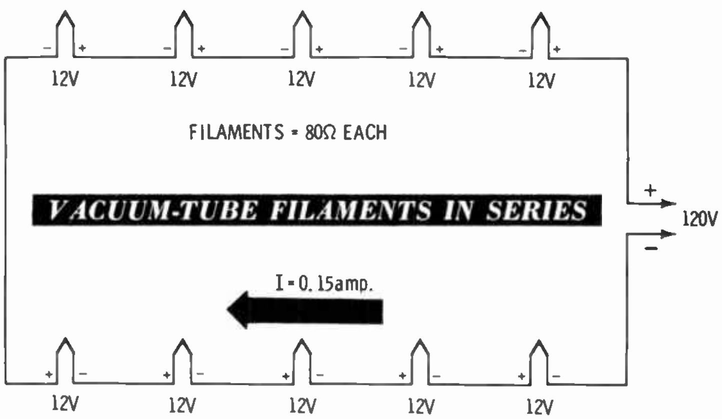
VOLTAGE DISTRIBUTION

Voltage will be distributed across the unit length of resistance in the manner shown in the diagram. Doubling the voltage will cause twice the current to flow through the resistance. One volt is distributed (dropped) across each half of the resistance, increasing the current that flows through its section.

CURRENT DEPENDS ON VOLTAGE



An example of a series circuit is the manner in which the vacuum-tube filaments of some radio and television sets are connected. As you can see in the diagram below, each filament requires 12 volts and a current of 0.15 ampere. This identifies another characteristic of a series circuit—all components in a series circuit have the same current flowing through them.



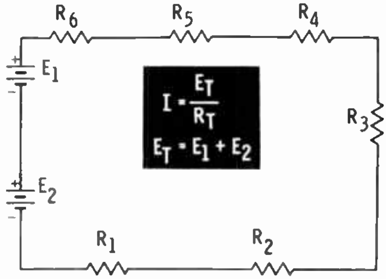
VACUUM-TUBE FILAMENTS IN SERIES

Another application of the series circuit is the economical series-string Christmas-tree lamps. The number of lamps needed in a string or the amount of voltage to apply can be determined by Ohm's law. If the voltage drop required by each lamp is 15 volts and the string is to be connected to a 120-volt outlet, then eight lamps are required in series.

Symbol Designations

Care must be used when referring to voltage in a series circuit. A voltage drop across one resistance among many may be a different value from the IR drop across the others. A voltage across R_1, for example, should be identified as that voltage. The source voltage should be designated as E_T (for E total). Total resistance becomes R_T. Since current is the same in all parts of a series circuit, it remains as I.

IDENTIFY ALL PARTS OF A CIRCUIT

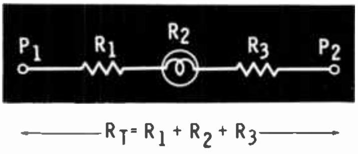


Total Resistance in the Series Circuit

Current in a series circuit is determined by the values of **total resistance** and **total voltage.** The total source voltage is distributed proportionally across each of the series resistances, depending on their ratios to the total resistance.

Total resistance in a series circuit is the sum of the resistances between the terminals of the source. That is, R_T will equal $R_1 + R_2 + R_3$ + etc.

TOTAL RESISTANCE



The lamp shown above does have a resistance, even though it is not a resistor. Therefore it is marked as R_2 for calculation purposes.

Q1. Can the circuit on the opposite page be called a series circuit?

Q2. The symbol for total voltage is ____ .

Q3. If R_1 is 4.5 ohms, R_2 is 6 ohms, and R_3 is 6 ohms in the diagram above, what is R_T?

Your Answers Should Be:

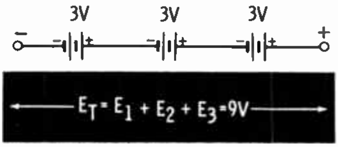
A1. **Yes.** All elements are connected end to end.

A2. The symbol for total voltage is $\mathbf{E_T}$.

A3. $\mathbf{R_T = 16.5}$ **ohms.** (The total resistance in a series circuit is the sum of all the resistance values across the source.)

Total Voltage in a Series Circuit

In addition to determining the total resistance of a series circuit, the total voltage must be calculated if there are two or more voltage sources in series. Total voltage is found in the same manner as the total resistance; that is, the sum of the individual voltages equals the total voltage.

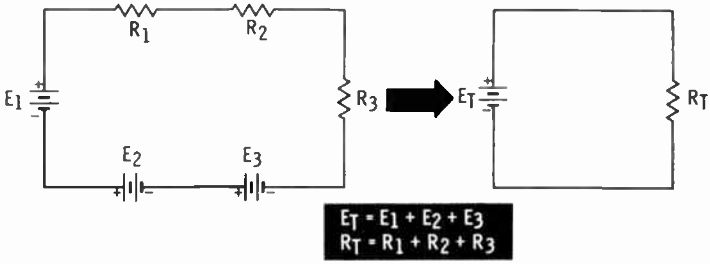


TOTAL VOLTAGE

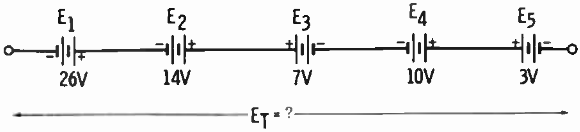
There is a separate problem in the calculation of total voltage, however. Some of the voltage sources may be in opposition to others, in which case the total voltage will not be the simple numerical sum of all the voltages. If the polarities of all the voltage sources are in the same direction, the voltage values are added together. If the polarities are in opposite directions, the values are subtracted, and the polarity of E_T is that of the larger voltage source.

A series circuit with more than one source and more than one load can be redrawn to show a circuit with only one source and one load.

SIMPLIFYING A SERIES CIRCUIT



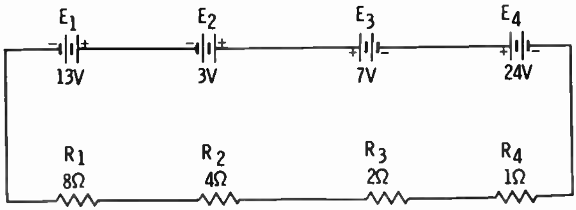
Q4. How must you treat the following series circuit to find the total source voltage?



Q5. What is E_T for the circuit below?

Q6. What is R_T for the circuit below?

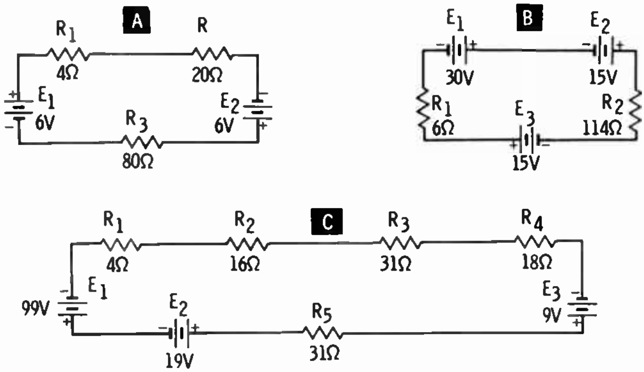
Q7. What is I_T for the circuit below?



Q8. In which direction will current flow in the circuit above?

Q9. Could the total resistance be represented by a single resistor?

Q10. What is the total resistance in each circuit (a, b, and c) below?

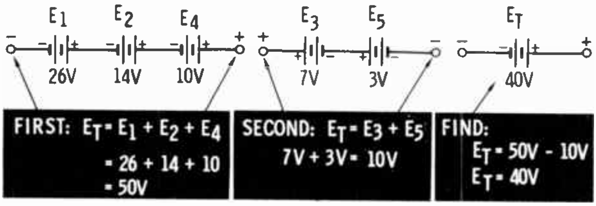


Q11. What is the total voltage in each circuit?

Q12. Draw an equivalent circuit, containing only one source and one load, for each of the circuits. Label the value and polarity of the source and the value of the resistance.

Your Answers Should Be:

A4. You must first add all the voltages having a polarity in one direction (negative to plus). Then add all the other voltages having a polarity in the other direction. Subtract the smaller from the larger. This will determine the amount of the overall voltage (E_T) and its polarity.



A5. $E_T = 24 + 7 - 13 - 3$. That is, $31 - 16 = 15$. Therefore, $E_T = 15$ volts, negative to positive left to right.

A6. $R_T = R_1 + R_2 + R_3 + R_4$. $R_T = 15$ **ohms.**

A7. $I_T = E_T/R_T$. $I_T = 15/15$, or **1 amp.**

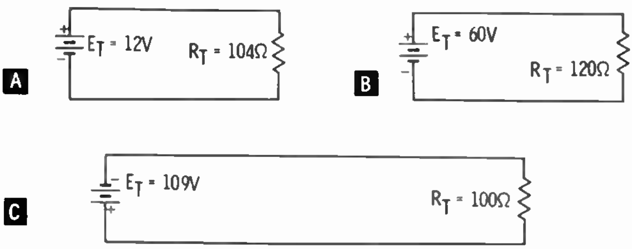
A8. The current will flow away **from the negative terminal and into the positive terminal of E_T.**

A9. **Yes.** Once the total resistance has been found, it may be represented by a single resistor.

A10. (a) **104 ohms**
(b) **120 ohms**
(c) **100 ohms**

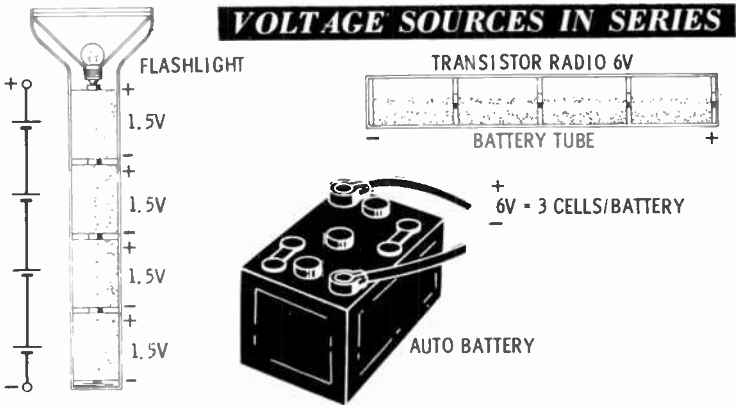
A11. (a) **12 volts**
(b) **60 volts**
(c) **109 volts**

A12.



Examples of devices having several voltage sources in series are flashlights, transistor radios, and automobile batteries.

VOLTAGE SOURCES IN SERIES



Current in a Series Circuit

If a series circuit has an R_T of 170 ohms and an E_T of 34 volts, what is the current in the circuit? The current will be equal to E_T/R_T or 0.2 ampere (34/170). If a series circuit has three sources (all aiding one another) and two resistances, current can be determined by:

$$I_T = \frac{E_1 + E_2 + E_3}{R_1 + R_2}$$

Voltage Drop in a Series Circuit

The voltage drop across each resistance in a series circuit is found in the same manner as the voltage across a resistor if the resistance value and the current flowing through the resistor are known. The Ohm's law expression is $E = IR$. Voltage across a resistance is determined by multiplying current by resistance.

The current is the same through each resistance in a series circuit. After finding the current, the value of I is used to determine the voltage drop across each resistance in the circuit.

Q13. What is the total voltage of a source having eight 1.5-volt flashlight cells connected in series?

Q14. What is the total voltage of a source having fifty-five 2-volt lead-acid cells connected in series?

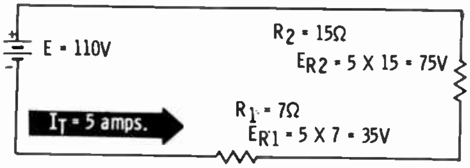
Your Answers Should Be:

A13. Eight 1.5-volt dry cells connected in series will develop 12 volts.

A14. Fifty-five 2-volt lead-acid cells connected in series will provide 110 volts.

Determining Voltage Drops

The sum of the voltage drops in a series circuit is always equal to the total applied voltage.

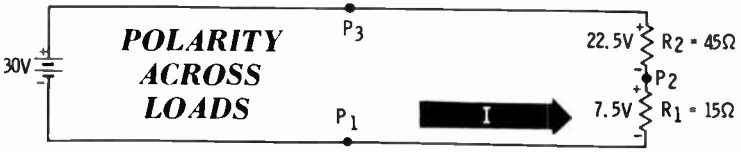


VOLTAGE DROPS EQUAL APPLIED VOLTAGE

In the above circuit, 5 amps will cause a 35-volt drop across the 7-ohm resistor and a 75-volt drop across the 15-ohm resistor. $E_{R1} + E_{R2} = E_T$.

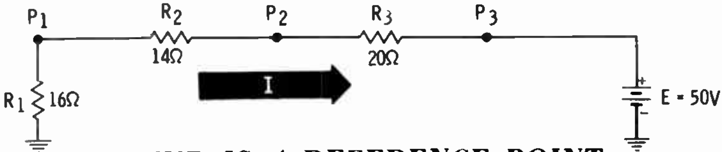
Polarity Across the Loads

Current leaves the negative terminal of a voltage source, flows through the circuit, and returns to the positive terminal. This direction of current flow occurs because of the voltage polarity. One of the terminals of the source is negative (repels electrons) with respect to the other. The opposite terminal is positive (attracts electrons). In the diagram, for example, P_1 is 30 volts negative with respect to P_3.



Voltage in a circuit exists only between two points—never at one point only. Therefore, voltage is expressed as being across two points in a circuit, or in terms of one point with respect or in reference to another point. The point at which current enters a resistance is negative with respect to the point at which it leaves.

A **common ground** is used as the reference point for expressing voltages unless otherwise specified. If a ground symbol is shown (see the diagram below), it becomes the common reference point for all voltage points in the circuit.

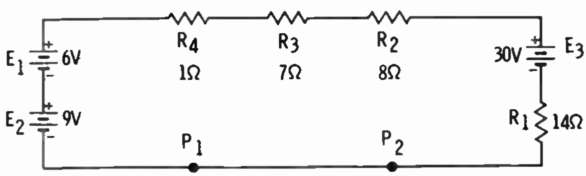


GROUND IS A REFERENCE POINT

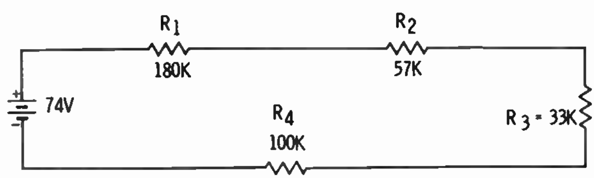
Current will flow from P_1 to P_2 to P_3 through the source to ground and from ground to P_1. In this case, I is equal to 1 amp. This means P_1 is +16 volts with respect to ground. P_2 is +14 volts with respect to P_1 (thus 30 volts positive to ground). P_3 to ground (in either direction) is +50 volts (the source voltage or the drop across the three resistors).

Q15. What is the value of E_T in the circuit below?

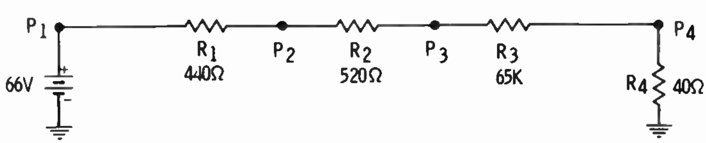
Q16. What is I_T in the following circuit? Which way will current flow with respect to P_1 and P_2?



Q17. What is the total resistance of the following circuit?



Q18. What is the voltage, with reference to ground, for all the points (P) on the following diagram?



Your Answers Should Be:

A15. 15 volts.

A16. $I_T = E_T/R_T$. $E_T = E_3 - (E_1 + E_2) = 15V$

$R_T = R_1 + R_2 + R_3 + R_4 = 30$ ohms

$I_T = 15V/30 =$ **0.5 amp**

Since the 30-volt source is larger than the combined 15 volts of the other two, the **current will flow from P_2 toward P_1.**

A17. $R_T = 370K$.

That is, $R_T = R_1 + R_2 + R_3 + R_4 = 370K$

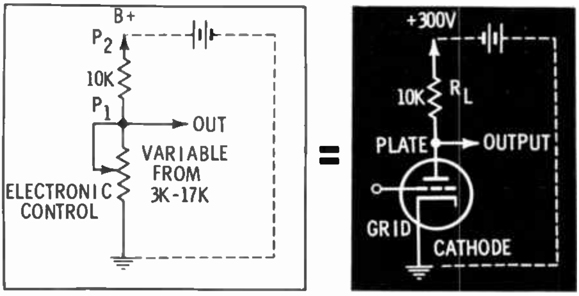
A18. $I_T = \frac{E_T}{R_T} = \frac{66V}{66K} = 0.001$ amp, or 1 ma

$P_1 = +66V$, $P_2 = +65.56V$,
$P_3 = +65.04V$, $P_4 = +0.04V$

Voltage Division in a Series Circuit

Voltage reference is one of the most important concepts to be learned in electricity or electronics. An understanding of how much voltage exists between two points in a circuit often reveals the purpose of the circuit and how it works.

As an example, a schematic of a vacuum-tube circuit is shown below. The figure on the right shows a vacuum tube in series with a load resistance, R_L. The figure on the left shows how the tube can be considered as a variable resistance. The output of this circuit is taken at a point between the tube and the load resistance.

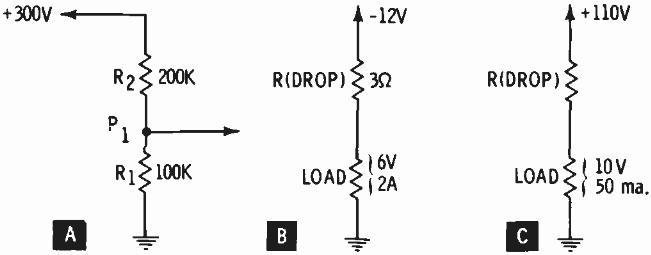


In effect, the grid varies the resistance of the vacuum tube. P_2 is always +300V (to ground). P_1 is a positive voltage (to ground); its value depends on tube resistance at any particular instant. The tube resistance changes from 3,000 to 17,000 ohms. Since 300 volts is always across the tube and load resistance, the output voltage at P_1 (with respect to ground) is large when tube resistance is high and small when tube resistance is low.

VOLTAGE DIVIDER

Current is the same through all elements in a series circuit. In the circuit on the opposite page the 300 volts can also be used for other purposes and in other circuits. Yet, 300 volts is often too much voltage for some circuits. A voltage divider is used to reduce the 300 volts to a level acceptable for use in a lower-voltage circuit. To select the correct resistors for use in a voltage divider, you must know how much voltage is required by the lower-voltage circuit. A voltage divider, therefore, is a series of resistances whose values are such that the desired output voltages are obtained at the various points with respect to the voltage reference point. In some cases, a voltage dropping resistor is connected in series with a load to obtain the desired voltage.

VOLTAGE DIVIDERS



Q19. What is I in the voltage divider of part A above?

Q20. How much voltage is available at P_1 in part A?

Q21. R (drop) in part B above is a(an) ________________ resistor.

Q22. Load voltage (part B) is ______ to ground.

Q23. ___ ampere(s) flow through R (drop) in part B.

Q24. R (drop), part C, is ______ ohms.

Q25. The load in part C dissipates ______ watt(s).

Your Answers Should Be:

A19. 0.001 amp, or **1** ma.

A20. 100 volts. $E = I \times R_1$. 0.001 amp multiplied by 100,000 ohms.

A21. R (drop) in part B is a **voltage dropping** resistor.

A22. Load voltage (part B) is **—6V** to ground.

A23. Two amps flow through R (drop) in part B. (Current is the same throughout a series circuit.)

A24. R (drop), part C, is **2,000** (or 2K) ohms. If the voltage across the load is 10 volts, R (drop) must have 100 volts across it. 100 volts divided by 0.05 amp (circuit current) is 2,000 ohms.

A25. The load in part C dissipates **0.5** watt. $P = IE$. (Current through the load multiplied by the voltage across the load.)

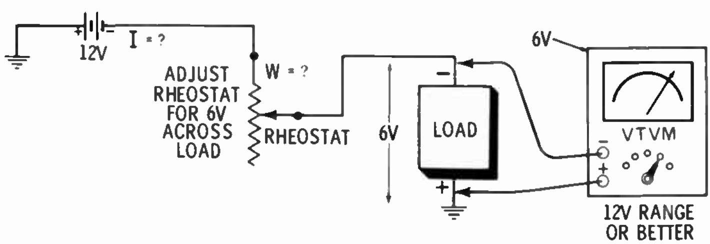
PRACTICAL APPLICATION OF THE SERIES CIRCUIT

In addition to what you have learned, there are many other applications for a series circuit. They exist in almost every electrical device used.

Reducing Output Voltage of a Battery

A voltage-dropping resistance can be used to lower the output of a 12-volt car battery to operate a 6-volt device (radio, meter, lamp, etc.). The dropping resistor (when in series with the load) must have a value in ohms which will

REDUCING VOLTAGE WITH A RHEOSTAT



permit the desired amount of current to flow through the device. It must also have the proper wattage rating as determined by its current and voltage drop. A rheostat (variable resistor) is quite often used as a dropping resistor in this application.

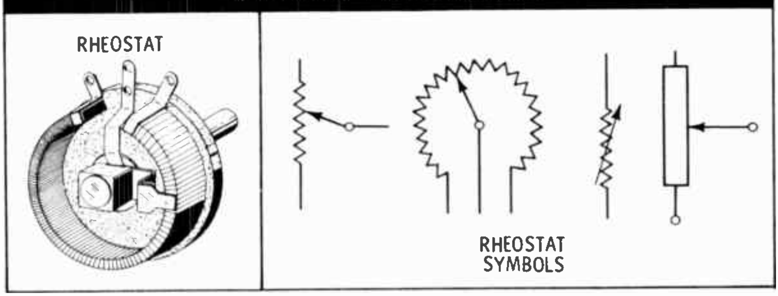
The circuit on the opposite page requires many careful adjustments and a common-sense application of Ohm's law and power equations. Solutions to the voltage-current-resistance problems are no more difficult than those you have already solved.

Steps in the Adjustments of the Rheostat

1. Determine the approximate current the load will draw. The device should be marked with its voltage and current requirements. The information can also be found in the service manual for this particular component.
2. Be sure the multimeter is set on a voltage scale which will read the source voltage (12 volts in this case).
3. Adjust the rheostat for 6 volts across the load.

   NOTE: The rheostat must be of high enough wattage to carry the load current.
4. Be sure the device can be switched on and off.
5. Put a fuse in the device. The fuse should be capable of carrying the current requirements of the load, while protecting it from an accidental overload.

RHEOSTAT AND SYMBOLS



Q26. If you do not know the current through the load and the rheostat, and you do not have an ammeter which will measure the current, how do you find the power required for the rheostat?

Q27. How do you determine the size of the fuse?

Q28. Why should the multimeter be set to the range which can read the voltage of the source?

Your Answers Should Be:

A26. You know the voltage drop across the rheostat, and you can measure the resistance of the rheostat from the end of the wiper contact.

$$\text{Power} = \frac{E^2}{R}$$

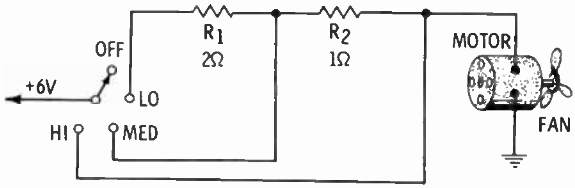
A27. The fuse must be able to carry the calculated current and should be able to carry normal surges. Normal surges are determined by the characteristics of the device (load).

A28. The voltage range of the multimeter must always be set to the scale that you know will not be exceeded. Voltage greater than the range of the meter can cause excess current through the meter and, therefore, cause possible damage.

Speed Control for an Electric Motor

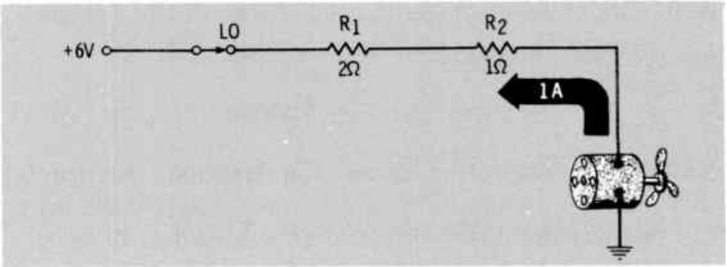
Motors, such as the one used in an automobile for the defroster fan, are sometimes connected to a switch having four positions (OFF-LO-MED-HI). The low and medium positions are separated from the high position by fixed resistors. Assume the motor turns at three speeds which require 3V at 1 amp (LO), 4.5V at 1.5 amps (MED), and 6V at 2 amps (HI). This circuit is shown below.

SPEED CONTROL CIRCUIT

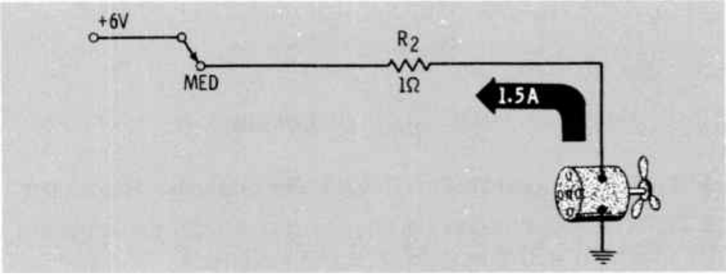


In the LO position the series resistance equals 3 ohms, which permits 1 ampere of current to flow. The 3 ohms is not the only resistance in the circuit. The motor adds its resistance in series with the circuit. In the MED position of the switch, the series resistance is 1 ohm. Again, the motor resistance is in series with it.

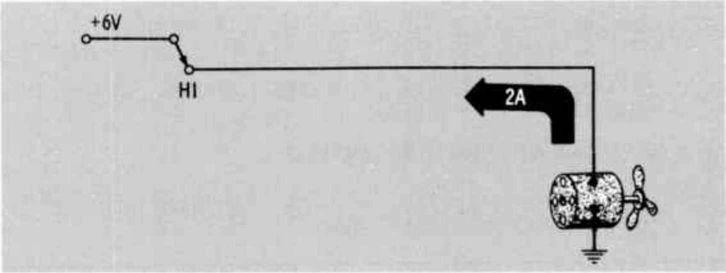
Q29. What is the resistance of the motor when the switch is in the LO position?



Q30. What is the resistance of the motor when the switch is in the MED position?



Q31. What is the resistance of the motor when the switch is in the HI position?



Q32. What is the power requirement for each of the two resistors, R_1 and R_2?

Q33. What type of switch would be the one most likely used?

Your Answers Should Be:

A29. The voltage applied to the motor in the LO position is 3V. The current is 1 amp. Therefore:

$$R = \frac{E}{I} = \frac{3}{1} = \textbf{3 ohms}$$

A30. The voltage drop across the dropping resistor is equal to 1 ohm times 1.5 amps. This 1.5V drop across the 1-ohm resistor is subtracted from the source (E_T).

$$E_{motor} = E_T - E_{R2} = 4.5V$$

$$R_{motor} = \frac{E_{motor}}{I_T}$$

$$R = \frac{4.5V}{1.5A} = \textbf{3 ohms}$$

A31. **3 ohms again.** The full 6 volts is across the motor.

A32. It is determined by the largest amount of current which will flow through the resistors.

$P_{R2} = I_{R2} \times E_{R2} = 1.5 \times 1.5 = 2.25$ watts

$P_T = (E_{R1} + E_{R2}) \times I_T$. $E_{R1} = R_1 \times I_T$, and $E_{R2} = R_2 \times I_T$.

$E_{R1} = 2 \times 1 = 2V$, $E_{R2} = 1 \times 1 = 1V$.
$P_{R1} = 1 \text{ amp} \times 2V = 2$ watts, $P_{R2} = 1$ watt.

Therefore, R_1 must have a power rating no smaller than 2 watts. The rating of R_2 must be no smaller than **2.25 watts.**

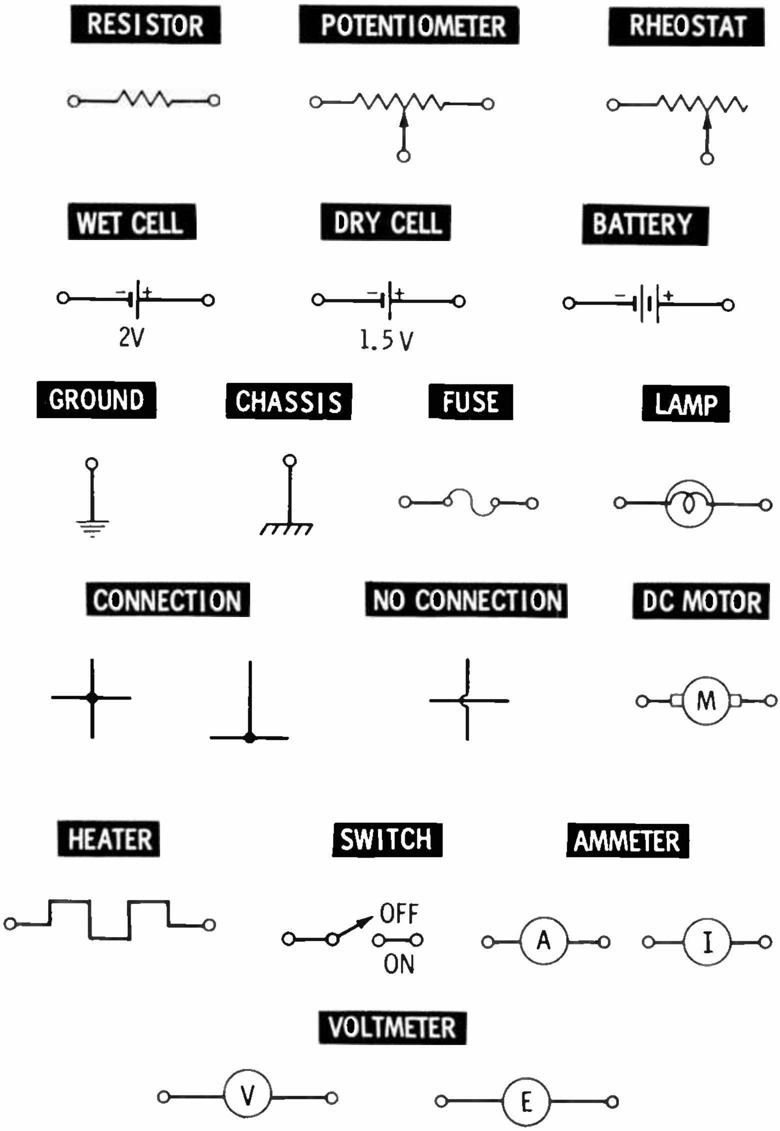
A33. The most probable selection for the switch would be a **rotary or wafer type.**

WHAT YOU HAVE LEARNED

1. The basic electrical circuit is a series circuit.
2. A series circuit may have more than one source and load.
3. Current in a series circuit is the same through all components.

4. Total resistance in a series circuit is computed by finding the sum of all the resistances. That is, $R_T = R_1 + R_2 + R_3$ plus whatever additional resistors may be in series.
5. Total source voltage in a series circuit is the sum of the individual sources if their polarity direction is the same, or is the difference of the sums of the opposing potentials. The larger will become E_T and will control the direction of current.
6. A series circuit may be represented with an equivalent circuit.
7. Total voltage drop in a series circuit is equal to the source voltage, or E_T.
8. To describe a voltage at any given point you must identify its polarity with respect to a reference point.
9. A voltage divider is a series circuit which employs a dropping resistor to provide a desired voltage output.
10. When a dropping resistor is used to form a voltage divider, it must have a safe power rating.
11. In all practical applications of a dropping resistor or voltage divider, voltage, current, and power requirements must be calculated to determine the proper value and rating of the required resistor.
12. Symbols are used to represent components in schematic diagrams.

COMPONENT SYMBOLS



4

DC Parallel Circuits

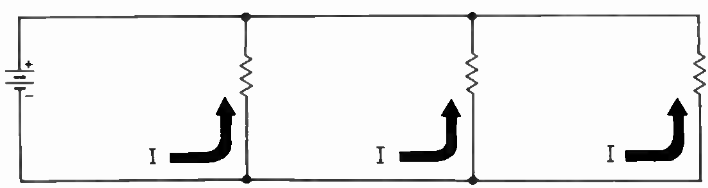
What You Will Learn

Contained here is a thorough description of a DC parallel circuit. Included are the basic parallel connections, determination of total current and total resistance, the series equivalent circuit, current and voltage relationships, and typical applications of parallel circuits. You will learn how to identify parallel circuit networks, determine total current and total resistance, and develop series equivalent circuits.

WHAT IS A PARALLEL CIRCUIT?

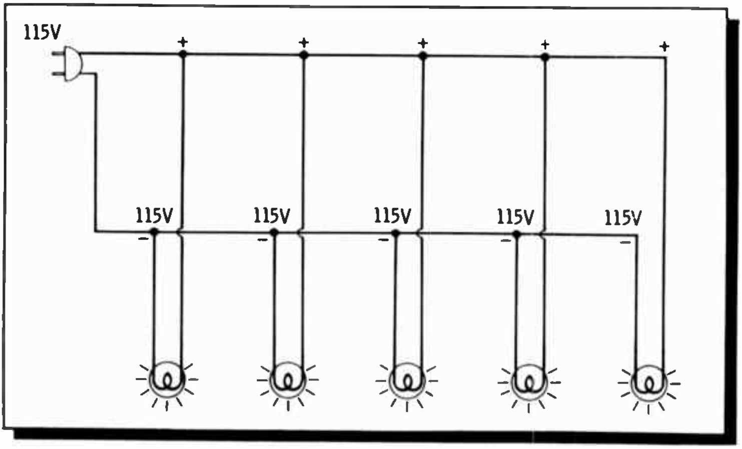
A parallel circuit contains two or more basic circuits, each of which is connected to common terminal points. Two or more resistances, for example, may be connected together across the same voltage source.

A PARALLEL CIRCUIT



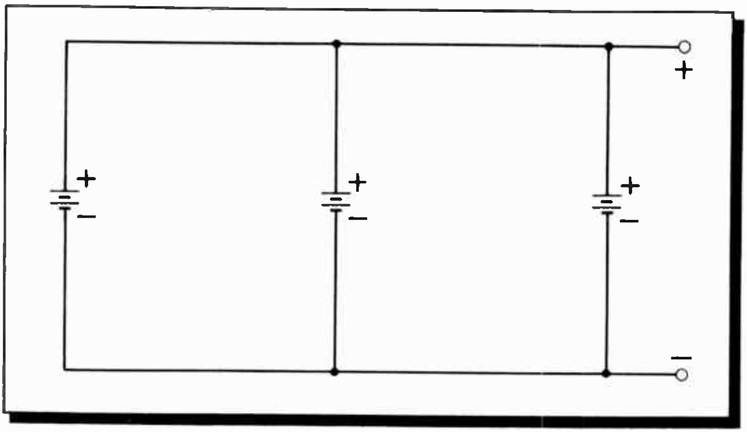
A string of Christmas-tree lamps which will permit one or more lamps in the circuit to be opened and still allow the others to operate properly is one example of a parallel circuit. Each lamp has the same voltage applied.

LAMPS IN PARALLEL



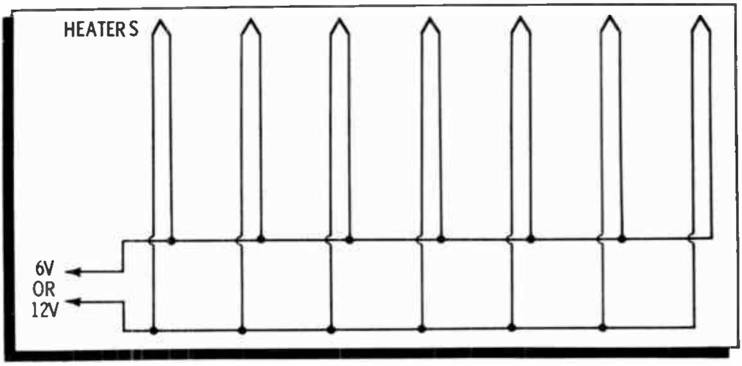
Another form of parallel circuit uses more than one voltage source in parallel to increase the availability of current. The greater the amount of stored energy available, the longer the source can produce a current at a given voltage.

MORE BATTERIES—MORE AVAILABLE CURRENT



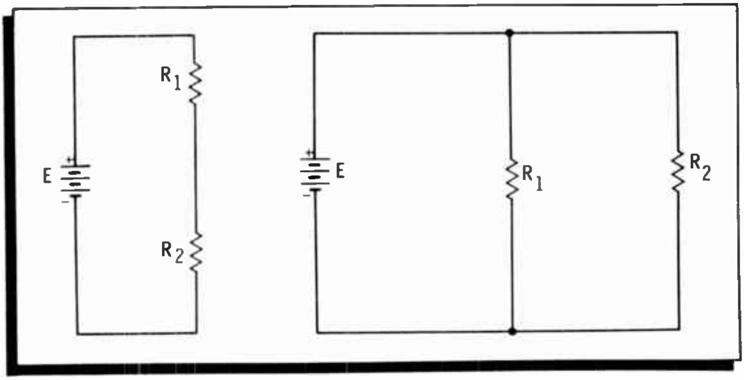
Still another example of a parallel circuit is the filament circuit for the vacuum tubes used in automobile radios. The filaments are all connected in parallel, and either 6 or 12 volts is applied to each. The tubes have either 6- or 12-volt filaments, depending on the type of battery in the automobile.

VACUUM-TUBE FILAMENTS IN PARALLEL



In each case, you can see that all sources or all loads are connected across the same two points. This produces a circuit which has one common voltage applied to all loads.

You have previously learned that in a series circuit all loads and sources are connected end to end. The same current flows through all components, and the source voltage is divided among the separate loads. In a parallel circuit, all loads and sources are connected across the same points. Therefore, each load has the same voltage applied.



Q1. In a parallel circuit, each resistance can have the same (voltage, current) but different (voltage, current).

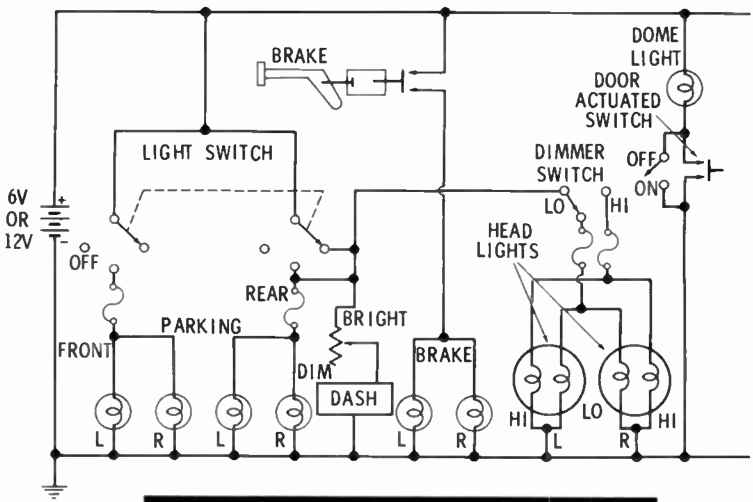
Q2. In a series circuit, each resistance can have the same (voltage, current) but different (voltage, current).

Your Answers Should Be:

A1. In a parallel circuit, each resistance can have the same **voltage** but different **current.** With the same voltage across each load, current will equal the voltage divided by the resistance.

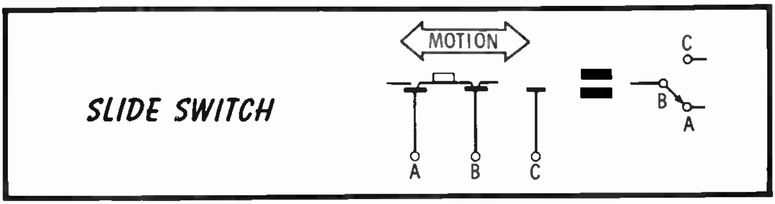
A2. In a series circuit each resistance can have the same **current** but different **voltage.**

AUTOMOBILE CIRCUITS



AUTOMOBILE LIGHT CIRCUIT

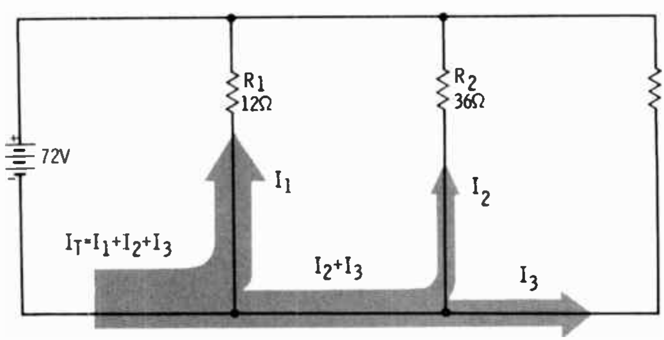
The diagram above is an example of a schematic for a lighting circuit in an automobile, and is also an example of a parallel circuit. Notice that fuses are used in the separate branches. This permits one circuit to short and blow its fuse while the other circuits remain energized. Notice that different switches are used for different jobs. The main light switch might be a rotary type (wafer). The stop-light switch is usually actuated by the same hydraulic fluid pressure that applies the brakes. That is, the switch is a push-button type that is spring-loaded to form a normally open circuit. When the brakes are applied, pressure builds up in the master brake cylinder, causing the stop-light switch to close. The head-light dimmer switch is located on the floor of most cars. It is a push-button switch which remains in one position until pressed again. The dome light is switched on and off by either of two switches in parallel. One is a push-button type that is spring-loaded to stay normally closed, and is actuated by opening and closing the car door. When the door opens, the switch returns to its normally closed position; when the door is closed, it pushes the switch open. In parallel with this switch is a slide switch, sometimes a part of the dome-light fixture.



CURRENT FLOW IN A PARALLEL CIRCUIT

Current in each branch of a parallel circuit must originate from the same source. This means that each branch will have a different current if the resistance of each branch is different. The source must supply current for each branch, so the total current is the sum of all the branch currents.

Total Current Is the Sum of the Branch Currents



Q3. What is common to all light circuits in a car?

Q4. What sort of a load does a car battery have?

Q5. The total current in a parallel circuit is the ___ of all the branch currents.

Your Answers Should Be:

A3. The voltage source.

A4. Since more than one circuit can be switched into use, the battery can have many different loads. The total load is the sum of the individual loads.

A5. The total current in a parallel circuit is the **sum** of all the branch currents.

Calculating Current in a Parallel Circuit

To find the current in each branch of a parallel circuit you must apply Ohm's law; that is, E/R equals I for each branch. In the diagram on the preceding page, I_1 (branch 1) will equal 72/12, I_2 (branch 2) will equal 72/36, and I_3 (branch 3) will equal 72/9. The current in branch 1, therefore, is 6 amps; in branch 2 there is 2 amps; and in branch 3 there is 8 amps. Total current supplied by the source is 16 amps.

CALCULATING TOTAL RESISTANCE

Since I_T in a parallel circuit is equal to the sum of all the branch currents, R_T is equal to E/I_T. Also, I_T equals the source voltage divided by R_T, and I (any branch) equals the source voltage divided by the resistance of that branch.

$$I_1 = \frac{E}{R_1},\ I_2 = \frac{E}{R_2},\ \text{and } I_3 = \frac{E}{R_3}$$

Substituting for I_T, I_1 (branch 1), etc.

$$(1)\quad I_T = I_1 + I_2 + I_3$$

$$(2)\quad \frac{E}{R_T} = \frac{E}{R_1} + \frac{E}{R_2} + \frac{E}{R_3}$$

E can be any value you choose for the solution of R_T. This leads to two possible methods of solving for R_T.

First Process—R_T can be found by assuming any value for E that is easy to work with. Then, divide each resistance into E to find I for each branch.

In the figure on the opposite page, select a value for E hat permits an easy solution for all branches. In this case, 00 volts would be a likely selection. Therefore, $E/R_1 = I_1$, $/R_2 = I_2$, and $E/R_3 = I_3$. $I_1 = 100/100 = 1$ amp, $I_2 =$ 00/200 $= 0.5$ amp, and $I_3 = 100/200 = 0.5$ amp. Now, find he sum of the branch currents to determine I_T.

$$I_T = I_1 + I_2 + I_3 = 1a + 0.5a + 0.5a = 2a$$

You now know I_T for a selected E. All that remains in rder to find R_T is to divide the assumed voltage by the mount of total current the parallel resistances allow to ow.

$$R_T = \frac{E}{I} = \frac{100}{2} = 50 \text{ ohms}$$

The shorthand statement that describes all of the operaions used in finding the total resistance (50 ohms) is:

$$R_T = \frac{E}{I}$$

ince,

$$I_T = \frac{E}{R_1} + \frac{E}{R_2} + \frac{E}{R_3}$$

nd,

$$E = 100 \text{ volts}$$

hen,

$$R_T = \frac{100}{1+0.5+0.5} = \frac{100}{2} = 50 \text{ ohms}$$

Second Process—Looking at the expression $I_T = I_1 + I_2$ $+ I_3$ and using its equivalent expression, $E/R_T = E/R_1 +$ $/R_2 + E/R_3$, you can arrive at the same expression for R_T s before.

$$\frac{E}{R_T} = \frac{E}{R_1} + \frac{E}{R_2} + \frac{E}{R_3}$$

ow, follow these steps closely.

. $\left(\frac{E}{R_T}\right)R_T = \left(\frac{E}{R_1} + \frac{E}{R_2} + \frac{E}{R_3}\right)R_T$ (Multiplying both sides by R_T.)

2. $E\left(\frac{R_T}{R_T}\right) = \left(\frac{E}{R_1} + \frac{E}{R_2} + \frac{E}{R_3}\right)R_T$ (R_T's on left cancel.)

(Divide both sides by I_T and cancel the like quantities on right.)

$$3.\quad \frac{E}{\frac{E}{R_1}+\frac{E}{R_2}+\frac{E}{R_3}} = \frac{\left(\frac{E}{R_1}+\frac{E}{R_2}+\frac{E}{R_3}\right)}{\frac{E}{R_1}+\frac{E}{R_2}+\frac{E}{R_3}} R_T$$

$$4.\quad \frac{E}{\frac{E}{R_1}+\frac{E}{R_2}+\frac{E}{R_3}} = R_T$$

$R_1 = 100\ \Omega$, $R_2 = 200\ \Omega$, $R_3 = 200\ \Omega$, and 100 volts was previously selected for E. Now, substitute and perform the arithmetic to solve for R_T.

$$R_T = \frac{100V}{\frac{100V}{100\Omega}+\frac{100V}{200\Omega}+\frac{100V}{200\Omega}}$$

$$= \frac{100V}{1 \text{ amp} + 0.5 \text{ amp} + 0.5 \text{ amp}}$$

$$= \frac{100V}{2 \text{ amp}} = 50 \text{ ohms}$$

The two processes have led you to the common expression used in the field for the total resistance of a parallel circuit. ("1" is used as the common value for E.)

$$R_T = \frac{1}{\frac{1}{R_1}+\frac{1}{R_2}+\frac{1}{R_3}+\cdots+\frac{1}{R_n}}$$

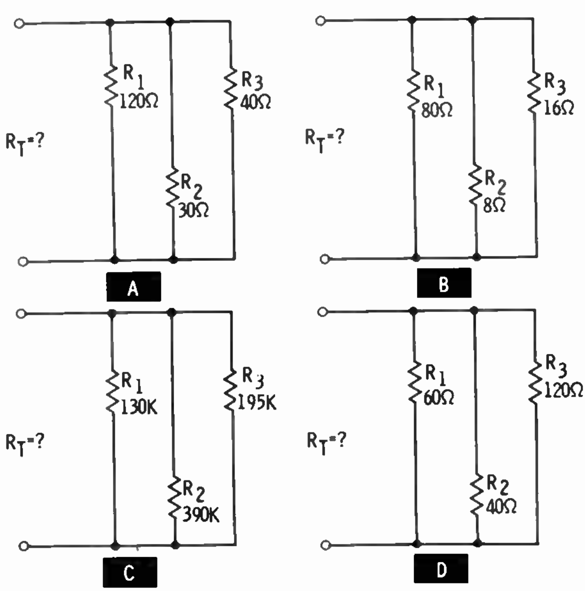
This is called a **reciprocal** expression because there are operations in which a value is divided into one. You will find this true for many different mathematical operations. To improve your ability to apply them, examine such expressions to determine the several arithmetic operations each contains. The development of mathematical processes is not often explained in technical literature. Difficult expressions, such as the reciprocal formula above, contain simple arithmetic steps that make the "shorthand" expression reasonable and meaningful. Find and analyze these steps. Acceptance or memorization is of little value unless you understand the reasoning behind each expression.

You should now review the entire process (the solution of R_T) until all steps are clear and appear reasonable to you. Evaluate each new step with questions, such as, "Why perform this operation?" or "What arithmetic operations are the symbols representing?" Remember that any operation you will ever follow is nothing more than arithmetic applied with logical rules and sequences.

Many times you will be faced with a "new" mathematical expression (at least it will be strange to you). If you determine the answer to the two questions above, you will find there is a simple hidden reason or step.

The question below asks you to find the solution for R_T, using either process. If you do not use the reciprocal form, E can have any value you choose to select. Your selection should be one that permits simple number operations with arithmetic. A hint for the selection of E—always select a value for E equal to or larger than the largest resistance. Another hint—try to select a value for E which results in a whole number when divided by any value of R. Don't forget the Ohm's law relationship where $R_T = E/I_T$.

Q6. What is the total resistance of the following circuits?



Your Answers Should Be:

A6. (a) Select E of 120V

$$R_T = \frac{E}{I_T} = \frac{120V}{\frac{120V}{120\Omega} + \frac{120V}{30\Omega} + \frac{120V}{40\Omega}}$$

$$R_T = \frac{120V}{1a + 4a + 3a} = \frac{120V}{8a} = \textbf{15 ohms}$$

(b) Select E of 80V

$$R_T = \frac{E}{I_T} = \frac{80V}{\frac{80V}{80} + \frac{80V}{8} + \frac{80V}{16}}$$

$$R_T = \frac{80V}{1a + 10a + 5a} = \frac{80V}{16a} = \textbf{5 ohms}$$

(c) Select an E of 390V

$$R_T = \frac{E}{I_T} = \frac{390V}{\frac{390V}{130K} + \frac{390V}{390K} + \frac{390V}{195K}}$$

$$R_T = \frac{390V}{3ma + 1ma + 2ma} = \frac{390V}{6ma} = \textbf{65K}$$

(d) Select an E of 120V

$$R_T = \frac{E}{I_T} = \frac{120V}{\frac{120V}{60} + \frac{120V}{40} + \frac{120V}{120}}$$

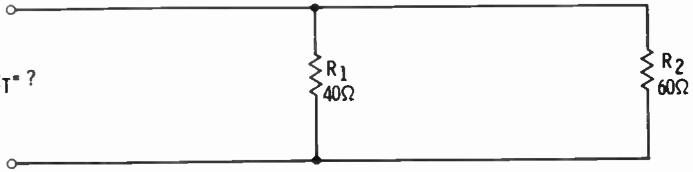
$$R_T = \frac{120V}{2a + 3a + 1a} = \frac{120V}{6a} = \textbf{20 ohms}$$

Total R in a Two-Branch Circuit

Another method for finding the total resistance of a two-branch parallel circuit is the **product-over-the-sum** process. Given the values of two resistors in parallel, multiply one times the other and divide by the sum of the two.

$$R_T = \frac{R_1 \times R_2}{R_1 + R_2}$$

The total resistance of the parallel circuit below is 24 ·hms. This can be determined by using the product-over-he-sum process.



$$R_T = \frac{40 \times 60}{40 + 60} = \frac{2{,}400}{100} = 24 \text{ ohms}$$

$$R_T = \frac{E}{\frac{E}{R_1} + \frac{E}{R_2}} = \frac{E}{\frac{E_{R2} + E_{R1}}{R_1 \times R_2}} = \frac{E(R_1 \times R_2)}{E(R_2 + R_1)}$$

To find the total resistance of a parallel circuit containing ·esistors of equal value in parallel, all that needs to be done s to divide the value of one of the resistors by the number ›f resistors in parallel.

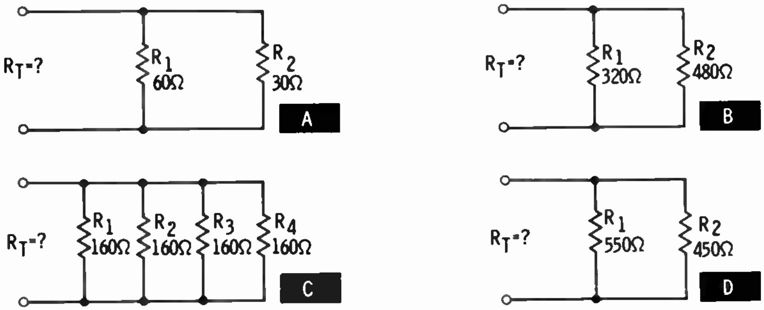
If a parallel circuit, for example, contains three 90-ohm ·esistors, R_T can be determined by dividing 90 by 3.

$$R_T = \frac{90}{\frac{90}{90} + \frac{90}{90} + \frac{90}{90}} \quad \text{(selecting an E of 90)}$$

$$= \frac{90}{1 + 1 + 1}$$

$$= \frac{90}{3} = 30 \text{ ohms}$$

Q7. What is the total resistance of these circuits?



Your Answers Should Be:

A7. (a) $R_T = \frac{R_1 \times R_2}{R_1 + R_2} = \frac{60 \times 30}{60 + 30} = \frac{1{,}800}{90} = 20$ **ohms**

(b) $R_T = \frac{320 \times 480}{320 + 480} = \frac{153{,}600}{800} = 192$ **ohms**

(c) $R_T = \frac{160}{4} = 40$ **ohms**

(d) $R_T = \frac{550 \times 450}{550 + 450} = \frac{247{,}500}{1{,}000} = 247.5$ **ohms**

Equivalent Resistance

Just as in the series circuit, the resistances in a parallel circuit can be represented by an equivalent. The equivalent indicates the load (R_T) which the source must work into. Since I_T is the easiest unknown to find (it is the sum of all the currents), it becomes a simple task to divide I_T into the source voltage to find R_T.

By the same reasoning, it is easy to find the power that the source must supply.

$$P = IE$$

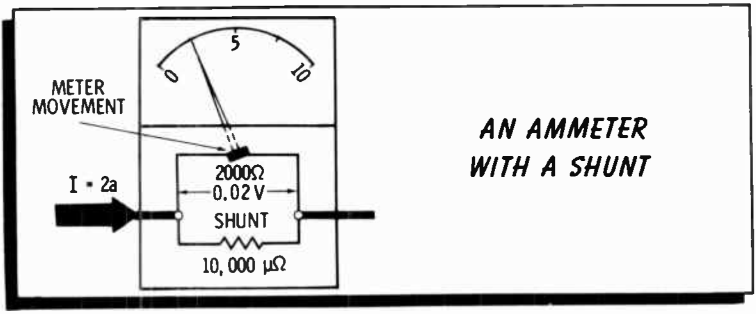
In this case:

$$P_T = (I_1 \times E) + (I_2 \times E) + (I_3 \times E) = I_T E$$

TYPICAL APPLICATIONS

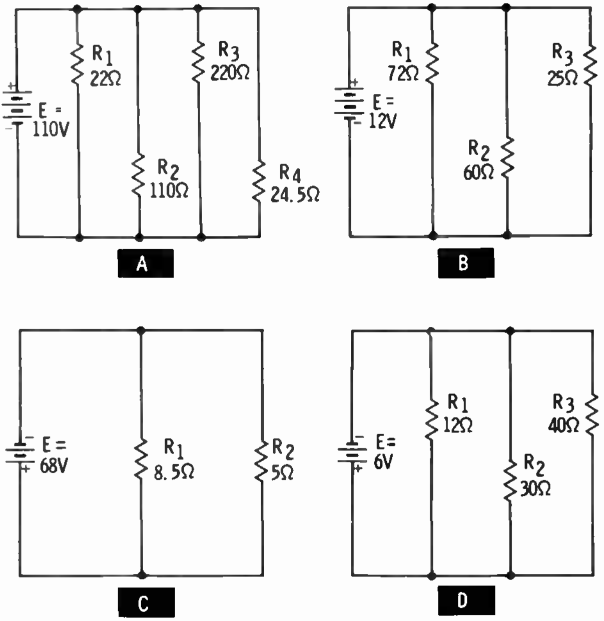
A parallel circuit is used where current is to be divided. This is similar to the action of the series circuit, except that voltage was divided.

Current Meter—An ammeter is used to indicate the amount of current flowing in a circuit. Very often the meter used will be one that has a full-scale deflection, indicating an amount of current much less than the circuit current to be measured. There is a method of bypassing the meter with the excess current. This is called **shunting** the meter. With a shunt, the meter reads a percentage of the total current. This means normal current flows through the entire parallel network (consisting of the meter and shunt), with only a small portion flowing through the meter.



This meter has a movement with 2,000 ohms of resistance and is shunted by a 10,000 micro-ohm (0.01 ohm) resistor. This permits 10 μa of current to flow through the movement and 2 amps (minus the 10 μa) of current to flow through the shunt. These may not be the exact values for a particular multimeter, but all multimeters employ similar ratios.

Q8. What is the total current in the following circuits?



Q9. What is the power dissipated by each resistor and the total power for each circuit above?

Your Answers Should Be:

A8. (a) $I_T = I_1 + I_2 + I_3 + I_4 = 110/22 + 110/110 + 110/220 + 110/24.5 = 5$ amps $+ 1$ amp $+ 0.5$ amp $+ 4.489$ amps $=$ **10.989 amps**

(b) $I_T = 12/72 + 12/60 + 12/25 = 0.167$ amp $+ 0.2$ amp $+ 0.48$ amp $=$ **0.847 amp**

(c) $I_T = 68/8.5 + 68/5 = 8$ amps $+ 13.6$ amps $=$ **21.6 amps**

(d) $I_T = 6/12 + 6/30 + 6/40 =$ **0.85 amp**

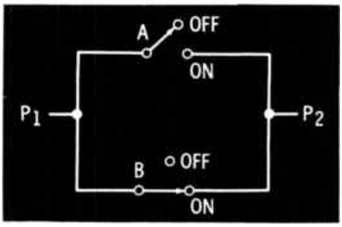
A9. (a) $P_1 = 5 \times 110 =$ **550 watts**; $P_2 = 1 \times 110 =$ **110 watts**; $P_3 = 0.5 \times 110 =$ **55 watts**; $P_4 = 4.489 \times 110 =$ **493.79 watts**; $P_T = 10.989 \times 110 =$ **1,208.79 watts**

(b) $P_1 = 0.167 \times 12 =$ **2.004 watts**; $P_2 = 0.2 \times 12 =$ **2.4 watts**; $P_3 = 0.48 \times 12 =$ **5.76 watts**; $P_T = 0.847 \times 12 =$ **10.164 watts**

(c) $P_1 = 8 \times 68 =$ **544 watts**; $P_2 = 13.6 \times 68 =$ **924.8 watts**; $P_T = 216 \times 68 =$ **1,468.8 watts**

(d) $P_1 = 0.5 \times 6 =$ **3 watts**; $P_2 = 0.2 \times 6 =$ **1.2 watts**; $P_3 = 0.15 \times 6 =$ **0.9 watt**; $P_T = 0.085 \times 6 =$ **5.1 watts.**

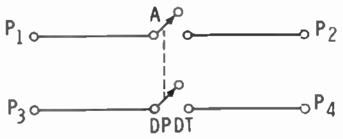
Switches in Parallel—Switches are connected in series in some cases and in parallel in others.



SEPARATELY ACTUATED SWITCHES IN PARALLEL

As can be seen in the figure above, the switches can form a closed-circuit condition from P_1 to P_2 if either one or the other or both are closed. To obtain an open circuit from P_1 to P_2, both switches must be open. Another form of the parallel switch is the type which has two or more poles actuated by the same mechanical element.

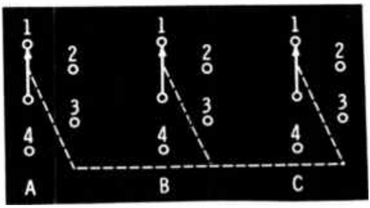
GROUP ACTUATED SWITCHES IN PARALLEL



The dashed line indicates that the two poles of the switch are actuated at the same time.

The rotary action available in the application of the wafer switch permits many parallel operations. In the illustration

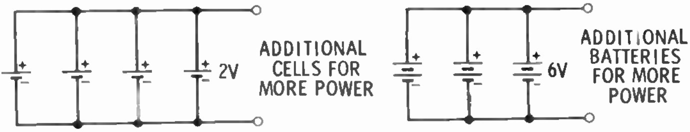
WAFER SWITCH PARALLEL OPERATION



above, the switch has three wafers (A, B, and C). Again, the dashed line represents mechanical connection whereby all wafers are actuated at the same time. In this case the switch is said to be a **three-** (triple) **pole, quadruple-throw** (four position), or **TPQT** (triple-pole, quadruple-throw).

Batteries in Parallel—For heavy-duty operation, batteries of equal voltage are constructed with plates in parallel or connected with many cells in parallel. This means they require more charging current to become fully charged. Yet, in another sense, more current must be drawn to cause the batteries to be discharged.

BATTERIES IN PARALLEL



Q10. What precautions must you take before connecting batteries in parallel?

Q11. Could you use a lamp bulb for a shunt, or parallel, resistance in a circuit? How would you determine the resistance of the lamp?

Your Answers Should Be:

A10. You must make sure all batteries to be connected in parallel have **the same voltage.**

A11. **Yes,** you could use a lamp for a shunt in a circuit. The wattage and voltage ratings permit you to calculate the resistance. That is , $I = \frac{P}{E}$ and then $R = \frac{E}{I}$.

WHAT YOU HAVE LEARNED

1. A parallel circuit is a combination of two or more basic circuits connected to a common voltage source.
2. Batteries may be connected in parallel to produce power for a longer time.
3. Switches may be connected in parallel to form parallel turn-on operations; yet they all have to be turned off to open the circuit.
4. Filaments in vacuum tubes may be connected across a common voltage source.
5. Each branch of a parallel circuit may have a different current flowing through it. All branches will have the same voltage applied.
6. To find the total current in a parallel circuit, you determine the sum of all the branch currents.

$$I_T = I_1 + I_2 + I_3 + \ldots$$

7 To find the total resistance of a parallel circuit, divide the applied voltage by the total current in the circuit.

$$R_T = \frac{E}{I_T}$$

8. If the resistance is the only factor known, you may use any value for E that permits simple arithmetic operations for determining the current in each branch. After the total current has been computed, the same value for E must be used to determine total resistance.

5

Combined Series and Parallel Circuits

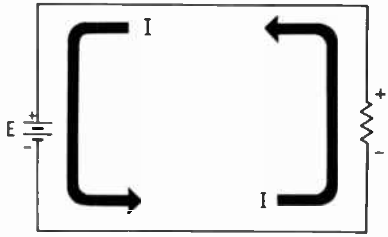
What You Will Learn

This chapter contains applications of the series and parallel fundamentals you learned in preceding chapters. You will now learn how to determine the direction of current flow in series-parallel circuits. When you complete this chapter, you will be able to reduce combinations of series and parallel circuits to a series equivalent. Also you will be able to determine and compute currents and voltages in each part of the circuit, and to apply Kirchhoff's law properly when needed. A good understanding of the material in this chapter prepares you for complex electrical and electronic circuit examination, using a simple step-by-step logical process.

IDENTIFYING INDIVIDUAL CIRCUITS

A basic electrical circuit consists of a source, a load, and conductors that connect the source to the load. The basic circuit was discussed in preceding chapters as if it were a loop. An applied voltage will cause a current to flow through a resistive element in a complete round-trip path. There are two ways to explain the direction of current flow—conventional and electron. If you employ the conventional theory for current flow, you describe all electrical flow in terms of positive ions in motion. Electron flow (the concept used in this text) states that current is the movement of electrons.

According to this theory, electrons leave the negative terminal of a source, move through the circuit, and return to the positive terminal.



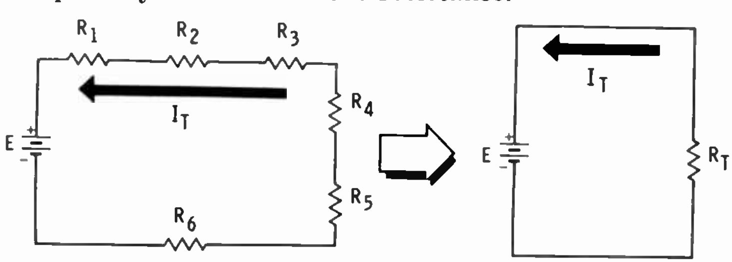
ELECTRON CURRENT FLOW

SERIES CIRCUITS

A series circuit is a basic circuit with all electrical components connected end to end. The key for determining the total voltage when there are two or more sources having different voltages and polarities is to find the potential difference between them. Next, assign the polarity of the larger voltage to the output terminals.

In a series circuit the total resistance is calculated by finding the sum of the individual resistances. Current in a series circuit is found by dividing the source voltage by the total resistance.

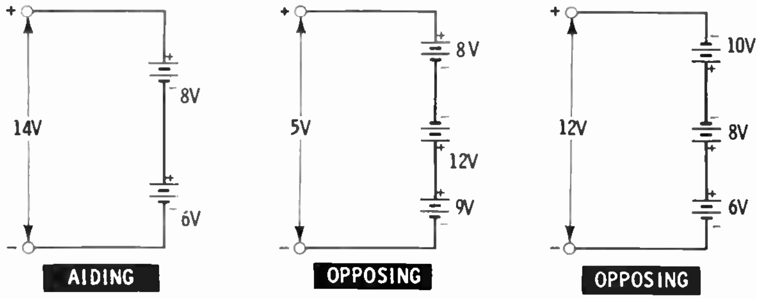
Since the total current (I_T) is flowing through all resistances, the voltage drop across a series resistance can be found by multiplying the current by the individual value of resistance. In other words, $E = IR$. The voltage drop across any resistance is equal to the current through the resistance multiplied by the value of the resistance.



$$R_T = R_1 + R_2 + R_3 + R_4 + R_5 + R_6$$

$$I_T = \frac{E}{R_T}$$

A series circuit can have more than one source connected in such a manner as to aid or to oppose one another.

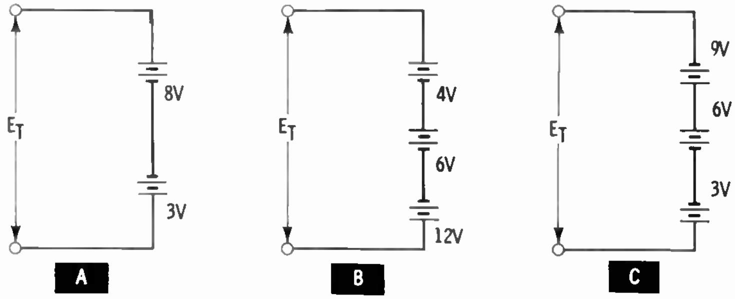


Q1. In which direction does current flow inside the source when the conventional current-flow theory is being employed?

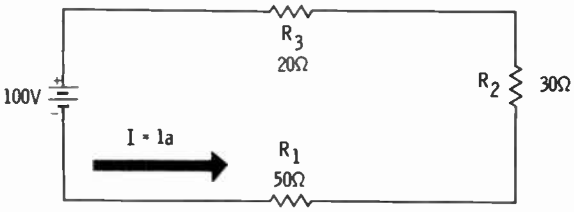
Q2. Draw a basic circuit and indicate the direction of current flow. (Use the electron theory.)

Q3. Can a basic circuit be considered a series circuit?

Q4. What is the total voltage at the terminals of the following sources?



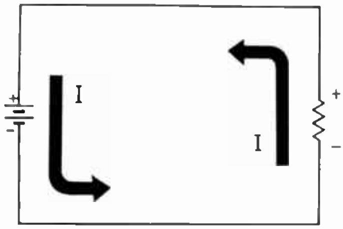
Q5. How does I_T compare with the value of current through any one of the resistances in the following circuit?



Your Answers Should Be:

A1. When conventional current theory is being employed, current will flow **from the negative terminal to the positive terminal** within the source.

A2.



A3. A basic circuit is a fundamental series circuit.

A4. A. Negative to positive, bottom to top, **5 volts.**

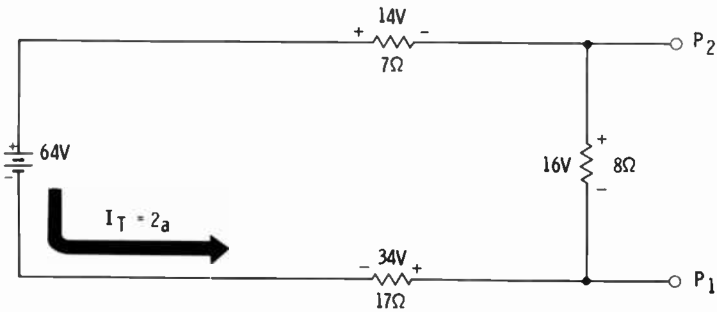
B. Negative to positive, top to bottom, **2 volts.**

C. Negative to positive, top to bottom, **6 volts.**

A5. I_T has **the same value** as the current through any of the resistances.

Voltage Division

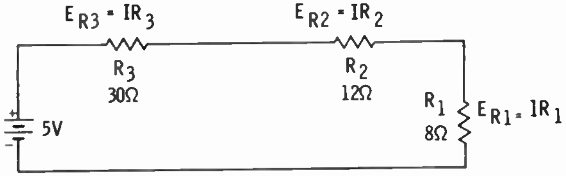
When current flows through a resistance, a voltage can be measured across it. The voltage across each resistor in a series circuit is equal to the total current times the value



of its resistance. That is, the 17-ohm resistor in the above circuit will have 34V (2 amps times 17 Ω) developed across it. The other voltages are determined similarly. Thus the voltage between P_1 and P_2 is 16V.

IR Drop

What is another way of expressing voltage drop across a resistor? Since voltage equals IR, it may be called **IR drop.** This is the same as saying the voltage developed across R_1, R_2, etc. The resistor voltage drops would be IR_1, IR_2, etc.

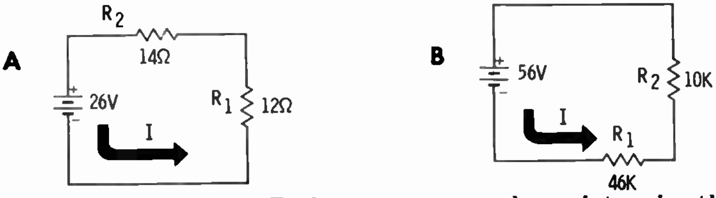


$$I_T = \frac{E}{R_1 + R_2 + R_3} = \frac{5}{50} = 0.1 \text{ amp}$$

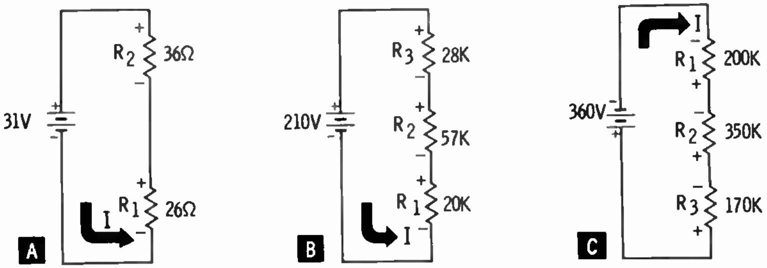
The voltage across R_1 equals IR_1, or $0.1 \times 8 = 0.8V$. The voltage across R_2 equals $IR_2 = 0.1 \times 12 = 1.2V$. The voltage across R_3 equals $IR_3 = 0.1 \times 30 = 3V$. The total IR drop is equal to the source voltage.

$$0.8V + 1.2V + 3.0V = 5V$$

Q6. What is the voltage drop across the R_1 resistors in the following circuits?



Q7. What is the IR drop across each resistor in the following circuits?



Q8. How does the voltage drop across the 36-ohm resistor affect the amount of voltage drop across the 26-ohm resistor in (a) above?

Your Answers Should Be:

A6. (a) **12 volts** = 1 amp times 12 Ω.

(b) **46 volts** = 1 ma times 46K.

A7. (a) IR_1 = **13V**, and IR_2 = **18V** (I_T = 0.5 amp)

(b) IR_1 = **40V**, IR_2 = **114V**, and IR_3 = **56V** (I_T = 2 ma)

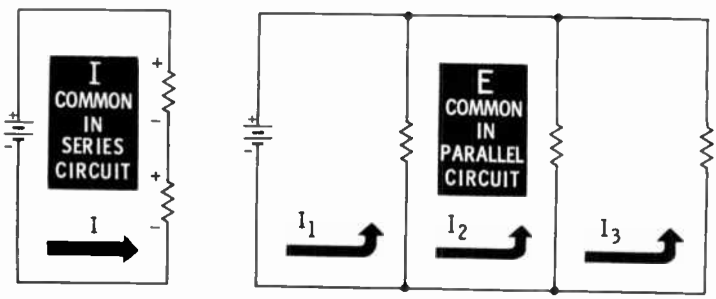
(c) IR_1 = **100V**, IR_2 = **175V**, and IR_3 = **85V** (I_T = 0.5 ma)

A8. The voltage across the 26-ohm resistor will be **decreased** from the source voltage by an amount equal to the voltage drop across the 36-ohm resistor.

PARALLEL CIRCUITS

A parallel circuit has two or more loads (resistances) connected across a source. The current flow through each resistance depends on the amount of that resistance. The total load (R_T) can be determined by dividing the source voltage by the total current. The total current equals the sum of the separate branch currents. $I_T = I_1$ (branch 1) $+ I_2$ (branch 2) + etc.

How does this compare to the series circuit? In a series circuit, the same current flows through all resistances, and thus a portion of the source voltage is dropped (proportional to the value of resistance) across each resistance.



A parallel circuit has a common supply voltage, and thus a possible different current through each resistance (branch), depending on the value of the resistance.

These two factors must be remembered in all operations concerned with calculations in both series and parallel circuits—to work problems in series circuits, employ the common current as the working component of Ohm's law along with the different resistances; to work problems in parallel circuits, employ the common voltage as the working component of Ohm's law. Let a parallel circuit with two resistors serve as an example.

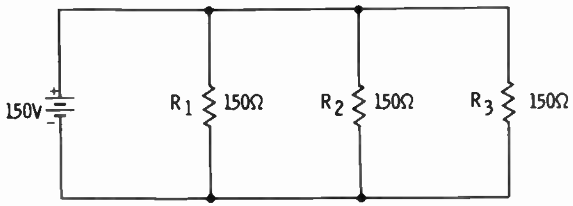
$$(1)\quad R_T = \frac{E}{\frac{E}{R_1} + \frac{E}{R_2}} = \frac{E}{I_T}$$

This can also be stated as:

$$(2)\quad R_T = \frac{R_1 \times R_2}{R_1 + R_2}$$

If all resistors are equal:

$$(3)\quad R_T = \frac{\text{R (value of one resistor)}}{\text{the number of resistors in parallel}}$$



Using (1):

$$R_T = \frac{150V}{\frac{150V}{150} + \frac{150V}{150} + \frac{150V}{150}} = \frac{150V}{1a + 1a + 1a}$$

$$R_T = \frac{150V}{3a} = 50 \text{ ohms}$$

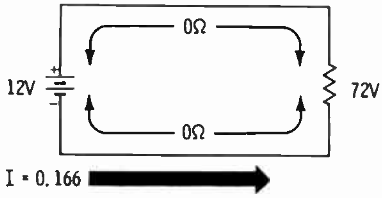
However, using (3):

$$R_T = \frac{150}{3} = 50 \text{ ohms}$$

Q9. When working problems from a schematic, what value of resistance do the conductors have?

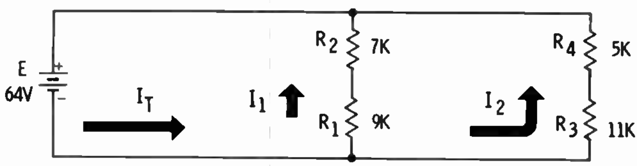
Your Answer Should Be:

A9. The conductors are considered to have a **zero resistance,** unless otherwise stated, when working problems from a schematic.



SERIES AND PARALLEL COMBINATIONS

From the basic series and parallel circuits there are many combinations possible which will contain both series and parallel characteristics. The diagram below demonstrates the two in combination.

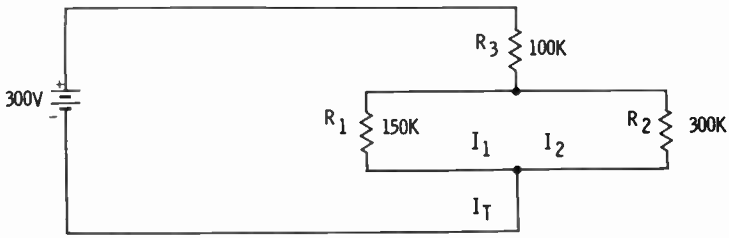


The first parallel branch consists of two resistors in series (R_1 and R_2). The second parallel branch contains two more resistors in series (R_3 and R_4). Many solutions can be derived from the problems which may stem from such arrangements. For instance, the first branch resistance is determined by finding R_T for the series circuit. The second branch resistance is determined by the same process. The total resistance can be determined by employing the $R_T = E/I_T$ expression. In this case, I_T would be the result of the sum of I_1 in branch 1 plus I_2 in branch 2. This is the parallel circuit process.

The possible routes of solution for the circuit above may be evaluated using many processes. The best approach is always the direct application of Ohm's law expressions. In this case, $R_T = E/I_T$. E is known but I_T must be determined. $I_T = I_1 + I_2$. $I_1 = E/R_T$ for branch 1, and $I_2 = E/R_T$ for branch 2. Since they are series branches, R_T is the sum of the resistances. That is, $R_{T1} = R_1 + R_2$ for branch 1, and $R_{T2} = R_3 + R_4$ for branch 2.

The total resistance of each branch can be used to find the branch currents, the branch currents to find the total circuit current, and the total circuit current to find the total circuit resistance (R_T). Other combination circuits may take on almost any form. The forms are limited only by the designer's need to construct a circuit which will perform a specific function.

Another example of a combination circuit is shown below:



To find the effective load for the 300V source, R_T must be calculated. One approach for finding R_T is to first find the total resistance for the parallel branch (R_1 and R_2); then the sum of the total parallel resistance plus R_3 should be found. After the total resistance has been determined, the total current can be calculated.

The total resistance for the parallel combination of R_1 and R_2 may be found by employing the product-over-the-sum process. That is:

$$R_{T1} = \frac{R_1 \times R_2}{R_1 + R_2} = \frac{150K \times 300K}{150K + 300K} = 100K$$

for the parallel branch. The final series-circuit resistance becomes $R_T = 100K + 100K = 200K$. The total current for the entire combination is 300V/200K, or 1.5 ma.

Q10. What is the total resistance in the circuit on the opposite page?

Q11. What is the total current in the circuit on the opposite page?

Q12. What is the voltage drop across R_4?

Q13. Draw the equivalent circuit.

Your Answers Should Be:

A10. $R_{T1} = R_1$ plus R_2 for branch 1. $R_{T2} = R_3$ plus R_4 for branch 2.

$R_{T1} = 9K + 7K = 16K$ for branch 1.

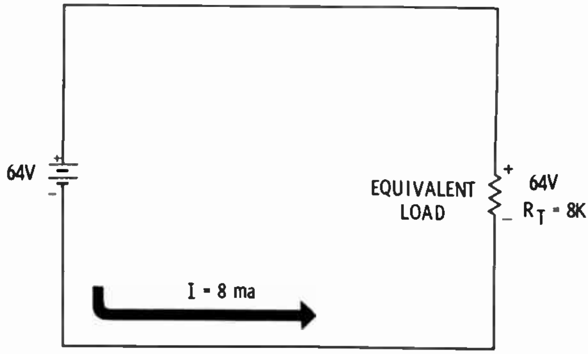
$R_{T2} = 11K + 5K = 16K$ for branch 2.

Total resistance equals 16K/2 = 8K.

A11. $I_T = E/R_T = 64V/8K = 8$ **ma.**

A12. The voltage drop across R_4 equals $IR_4 = 4$ ma $\times$ 5K = 20V.

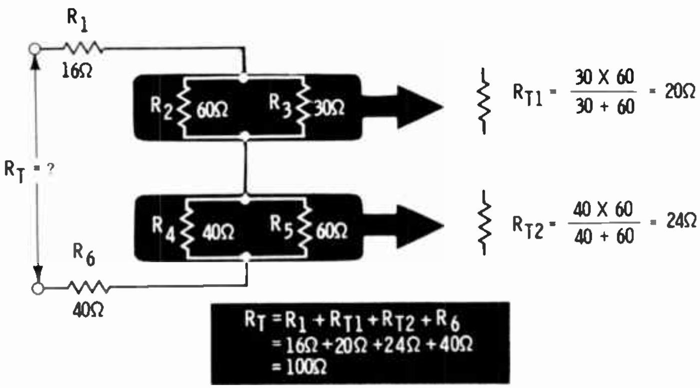
A13.



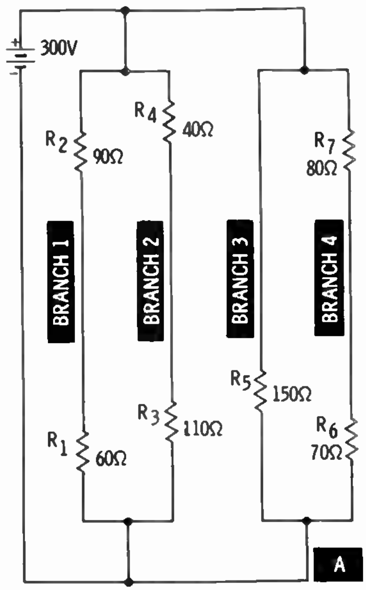
The voltage drop across R_3 (diagram on preceding page) is equal to IR_3. $IR_3 = 1.5$ ma $\times$ 100K = 150 volts. The voltage common to both R_1 and R_2 is the source voltage minus the voltage drop across R_3. This results in a voltage of 150 volts across the two resistors in parallel. R_1 will have 1 ma of current flowing through it. R_2 will have 0.5 ma of current flowing through it. The total current of the branches (and the circuit) will equal 1.5 ma. The equivalent circuit would consist of a 300-volt source connected to a 200-ohm load.

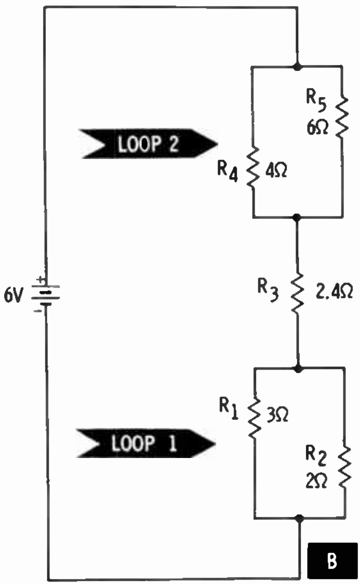
The illustration on the next page, under Question 14, shows another example of a combination series-parallel circuit. Included in this illustration is a method recommended for converting this type of circuit to an equivalent series circuit. This conversion simplifies the calculations.

Q14. If a 100-volt source is applied to the circuit below, what will be the voltage drop across R_4? What will be the current flow through R_4?



Q15. What is the voltage drop across each resistor in the following circuits?





Your Answers Should Be:

A14. The total current will be **1 ampere.** The current through R_4 will be **0.6 amp.** So, $E_{R4} = 24V$.

A15. (a) To find the voltage drop across each resistor, you must find the current through each branch. In this case, total current is of no concern.

BRANCH 1: $I_{loop\ 1} = \frac{300V}{R_1 + R_2} = \frac{300V}{150\Omega}$

$= 2$ amps

$IR_1 = 2a \times 60\Omega = \mathbf{120V}$

$IR_2 = 2a \times 90\Omega = \mathbf{180V}$

BRANCH 2: $I_{loop\ 2} = \frac{300V}{R_3 + R_4} = \frac{300V}{150\Omega}$

$= 2$ amps

$IR_3 = 2a \times 100\Omega = \mathbf{200V}$

$IR_4 = 2a \times 40\Omega = \mathbf{80V}$

BRANCH 3:

IR_5 will equal the **supply voltage (300V).**

BRANCH 4: $I_{loop\ 2} = \frac{300V}{R_6 + R_7} = \frac{300V}{150\Omega}$

$= 2$ amps

$IR_6 = 2a \times 70\Omega = \mathbf{140V}$

$IR_7 = 2a \times 80\Omega = \mathbf{160V}$

(b) To find the voltage drop across each resistor, proceed as follows:

$$R_{T(loop\ 1)} = \frac{R_1 \times R_2}{R_1 + R_2} = \frac{3 \times 2}{3 + 2} = 1.2\Omega$$

$$R_{T(loop\ 2)} = \frac{R_4 \times R_5}{R_4 + R_5} = \frac{4 \times 6}{4 + 6} = 2.4\Omega$$

$$R_T = R_{T(loop\ 1)} + R_3 + R_{T(loop\ 2)}$$

$$R_T = 1.2\Omega + 2.4\Omega + 2.4\Omega = 6\Omega$$

$$I_T = \frac{E}{R_T} = \frac{6V}{6\Omega} = 1 \text{ amp}$$

$IR_{(loop\ 1)} = 1a \times 1.2\Omega = \mathbf{1.2V}$

$IR_{(loop\ 2)} = 1a \times 2.4\Omega = \mathbf{2.4V}$

$IR_3 = 1a \times 2.4\Omega = \mathbf{2.4V}$

$IR_T = 1.2V + 2.4V + 2.4V = \mathbf{6V}$

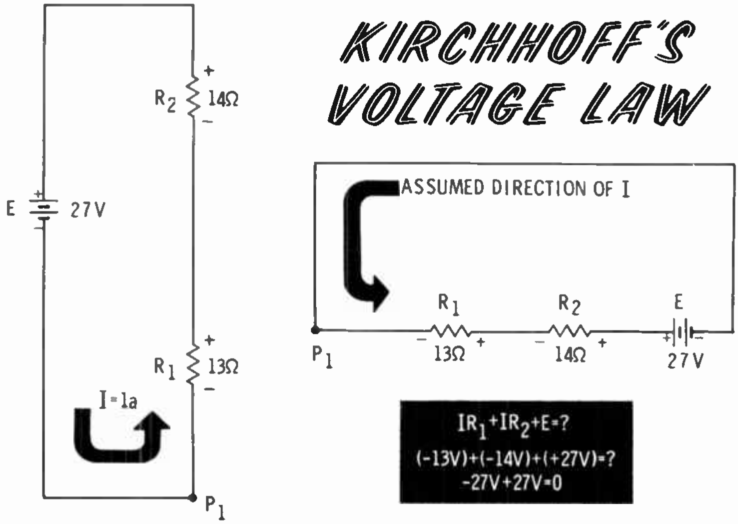
KIRCHHOFF'S LAW

Kirchhoff's law defines the distribution of currents and voltages within an electrical circuit. This law is used as a method of checking to see if you have assigned the proper direction for current flow and to see if your arithmetic is correct. It consists of two parts—one for voltages and one for currents. You will find this law a very useful tool when the direction of current is in question and/or when the total voltage or current is to be determined.

Primarily, Kirchhoff's law is a complete circuit application of Ohm's law. It makes use of Ohm's law many times in some circuits. Because of this application and the unique methods employed in handling points in the circuit—one with respect to another—you should master every process.

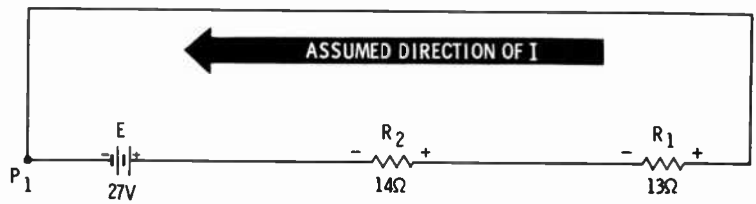
Voltage Applications

Upon determining voltage and polarity for each source and across each resistance, choose a point in the circuit and assign a direction of current flow. Find the algebraic sum of all the IR drops plus the source, from the chosen point, around the entire circuit and return. It should be zero.



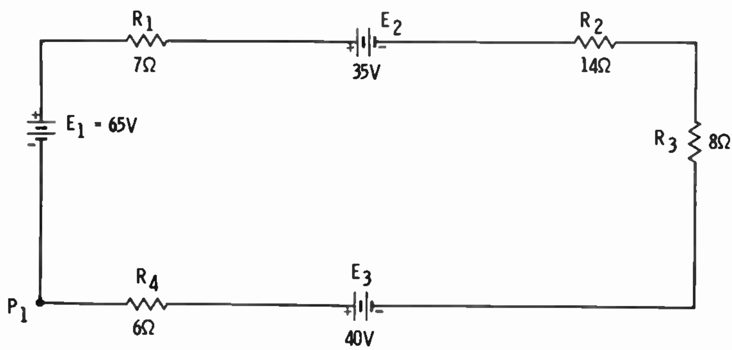
The sum of voltages in the loop from point 1 back to point 1 is zero. The current was assumed to be in the correct direction, and I_T and the IR drops were calculated properly.

Another look at the same circuit, with an opposite direction of current assignment, is as follows.



$$E+IR_2+IR_1=?$$
$$(-27V)+(-14V)+(-13V)=-54V$$

The sum of the voltages in the loop from point 1 back to point 1 equals —54V. Therefore the current was assumed to be going in the wrong direction.



(1) $E_T = +E_3 - E_2 + E_1 = (+40V)+(-35V)+(+65V)=+70V$

(2) $R_T = 6\Omega + 8\Omega + 14\Omega + 7\Omega = 35\Omega$

(3) $I = \frac{E_T}{R_T} = \frac{70V}{35\Omega} = 2a$

(4) $(-IR_4)+(+E_3)+(-IR_3)+(-IR_2)+(-E_2)+(-IR_1)+(+E_1)=?$

Calculating the IR drop across each resistor: $IR_4 = 12V$, $IR_3 = 16V$, $IR_2 = 28V$, and $IR_1 = 14V$. Kirchhoff's application (4) above: —12V + 40V — 16V — 28V — 35V — 14V + 65V = ? 105V — 105V = 0V.

Current Application

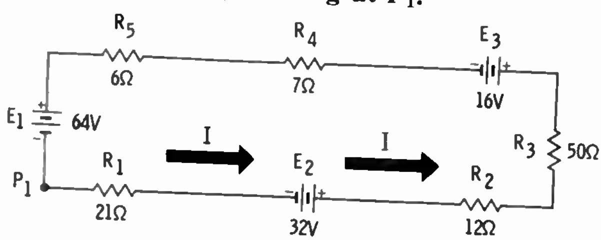
Finding the sum of the voltages around the circuit for the series network is one basic application of Kirchhoff's law. Finding the sum of the currents is another application and is the process employed in a parallel circuit. Kirchhoff's current law states that **the current flow away from a given point in a circuit must equal the current flow to that point.**

Q16. What is the E_T for the following circuit?

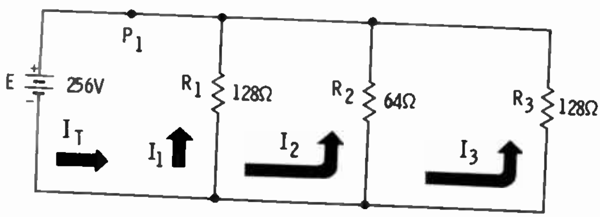
Q17. What is the R_T for the following circuit?

Q18. What is the I for the following circuit?

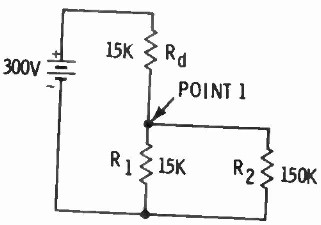
Q19. Write the complete Kirchhoff expression for the following circuit, starting at P_1.

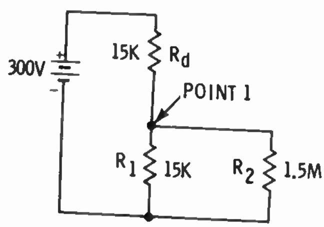


Q20. Write Kirchhoff's current expression for the following circuit.



Q21. What is the voltage at point 1 and the current through R (dropping resistance) for the following circuits?





Your Answers Should Be:

A16. $E_T = 64V - 32V + 16V = 48V$

A17. $R_T = R_1 + R_2 + R_3 + R_4 + R_5 = 21\Omega + 12\Omega + 50\Omega + 7\Omega + 6\Omega = \mathbf{96\Omega}$

A18. $I = E_T/R_T = 48V/96\Omega = \mathbf{0.5\ amp}$

A19. $-IR_1 - E_2 - IR_2 - IR_3 + E_3 - IR_4 - IR_5 + E_1 = -10.5V - 32V - 6V - 25V + 16V - 3.5V - 3V + 64V = 0V$

A20. $I_T = I_1 + I_2 + I_3$

$E/R_T = E/R_1 + E/R_2 + E/R_3$

$256V/32\Omega = 256V/128\Omega + 256V/64\Omega + 256V/128\Omega$

8 amps = 2 amps + 4 amps + 2 amps

A21. $I_T = 300V/R_T$

$$R_T = \frac{R_1 \times R_2}{R_1 + R_2} + R_d$$

$R_T = 28.6K$ for (A); $R_T = 29.8K$ for (B)

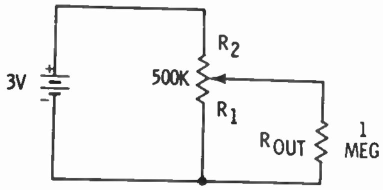
$I_T = 10.49$ ma for (A); $I_T = 10.06$ ma for (B)

Voltage at $P_1 = 300 - (15K \times 10.49\ ma) = 300 - 157.35 = $ **142.65 volts for (A)**

Voltage at $P_1 = 300 - (15K \times 10.06\ ma) = 300 - 150.9 = $ **149.1 volts for (B)**

APPLICATION

Some circuits have their components connected in series, others have a parallel-circuit form. Still others are different combinations of series and parallel circuits. Combination-type circuits are the most widely used arrangements. These arrangements often are a result of switching action or of variable resistance. When such applications need to be constructed or examined, you need a good command of Ohm's and Kirchhoff's laws. One example is shown below.



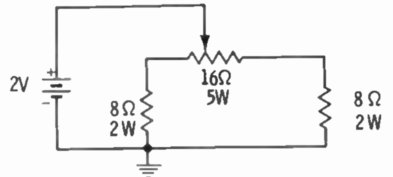
THE POTENTIOMETER

The output voltage (across R_{out}) equals $3V - I_T R_2$, $I_T = 3V/R_T$, and $R_T = \frac{R_1 \times R_{out}}{R_1 + R_{out}} + R_2$. Another method or approach would be to find IR_{out}. This would require calculating I.

$$I = I_T - I_{R1}$$

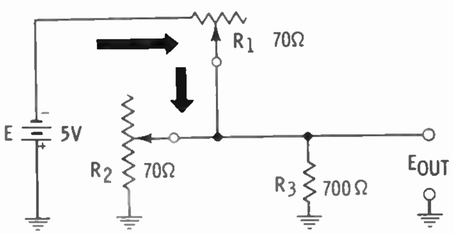
The following diagram is an example of resistor voltage division. The goal in this case is to control the current through the two paths.

VOLTAGE DIVIDER



If the wiper of the potentiometer is centered, the resistance from either side to ground will be equal.

The following circuit is another example of a variable voltage output, presenting to the source a constant or near-constant resistance. With the wiper centered on both rheostats, the output voltage is approximately 2.5 volts.



$$R_T = 35\Omega + \frac{35\Omega \times 700\Omega}{35\Omega + 700\Omega}$$
$$= 35\Omega + 33.3\Omega = 68.3\Omega$$
$$I_T = \frac{5V}{68.3\Omega} = 0.073 \text{amp} = 73 \text{ ma}$$

The voltage across R_1 will equal 73 ma times 35 ohms, or 2.555 volts. This leaves 2.445 volts for the output. Dividing 2.445 volts by R_3 equals approximately 3.49 ma.

Q22. Solve for the current through the output resistor in the potentiometer circuit on the opposite page, with the wiper arm first at the top of the 500K potentiometer and then in the center (as shown).

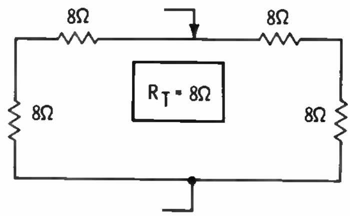
Q23. What would be the total current in the potentiometer circuit at the top of this page? (Assume the wiper is in the center of the potentiometer.)

Q24. What will be the total resistance in the same circuit if the wiper is all the way to the left?

Your Answers Should Be:

A22. If the wiper is all the way to the top, the output voltage will be 3 volts. Therefore the current will be equal to the 3 volts divided by 1 megohm of resistance. This results in **3 μa** of current flow. The total resistance across the source at this time will be 333K. If the wiper were in the center position, the total resistance would be 450K. This results in **6.66 μa** of current flow. The current flow through R_2 (250K) causes 1.68 volts to be dropped across R_2. The resulting output will be 3V — 1.68V, or 1.32V.

A23. The total current for the circuit would be 2 volts divided by the total resistance. $I_T = 2V/R_T$ (R_T = 8 ohms plus 8 ohms divided by 2).



The total current will equal: $2V/8\Omega$ = **0.25 amp**

A24. If the arm is all the way to the left, the total resistance will equal: $\frac{8 \times (16 + 8)}{8 + (16 + 8)} = 6\Omega$. I_T for this setting is $2V/6\Omega$ = 0.33 amps.

WHAT YOU HAVE LEARNED

1. The basic circuit is a series circuit.
2. The series circuit has the same current through all components.
3. The parallel circuit has the same voltage across all branches.
4. IR drop is determined by multiplying the value of a resistance (in ohms) by the value of the current (in amps) flowing through it.

5. In a series circuit the total IR drop across the resistances is equal to the effective total source voltage.
6. The sum of the branch currents in a parallel circuit is equal to the total current of the circuit.
7. Both series and parallel solutions may be employed when solving for current, voltage, or resistance in combination circuits.
8. Kirchhoff's law is an application of Ohm's law.
9. Kirchhoff's law for series circuits states that the sum of all voltages around a circuit, from one point through the circuit and back to the point, will be equal to zero. In addition, the sum of all the voltage drops will equal the effective voltage of the source.
10. Kirchhoff's law for parallel circuits states that the amount of current leaving a junction must be equal to the amount of current entering the junction.
11. The total voltage of the source will be the product of R_T times I_T.
12. In a series circuit, the Kirchhoff's law application results in zero if the direction of current is assumed correctly.
13. If the current is assumed to be going in the wrong direction, the result is equal to twice the effective voltage of the source.

6

Electromagnetism

What You Will Learn

This chapter explains the principles of magnetism for DC applications. It includes a description of magnetism, natural magnets, electromagnets, magnetic properties and relationships, magnetic measurements and associated terms, and DC applications of electromagnetic principles. The DC applications include the effects of magnetic fields on current flow and electrical reactions associated with relays, motors, etc.

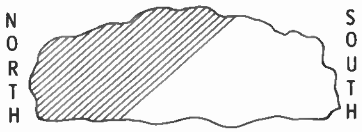
The fundamental characteristics and typical applications of DC electromagnetism are employed in electrical machinery, radio equipment, laboratory and test equipment, automotive devices, television, radar equipment, computer systems, and many others.

When you complete this chapter you will be able to visualize and describe magnetic principles for both permanent magnets and electromagnets, perform experiments and describe the actions and reactions observed, and relate the operating principles of relays, motors, solenoids, and meters to electromagnet fundamentals.

HISTORY OF MAGNETISM

During the ancient period in the world's history, in a district in Asia Minor known as Magnesia, the Greeks noticed that a lead-colored stone had an attraction for small particles of iron ore.

In later years the Chinese made use of this stone in their desert travels. They suspended the stone or floated it on water and called it **loadstone,** meaning "leading stone." Loadstone (also spelled **lodestone**) is a natural magnet, because it possesses magnetic properties when found in its natural state. At the present time the most common method of producing electricity is through the use of the magnetic properties of certain materials.



A LOADSTONE

WHAT IS MAGNETISM?

The dictionary defines magnetism as "a peculiar property possessed by certain materials by which they can naturally repel or attract one another according to determined laws."

In order to provide a better understanding of magnetism it will be necessary to look further into this definition and study the properties, circumstances, and laws referred to.

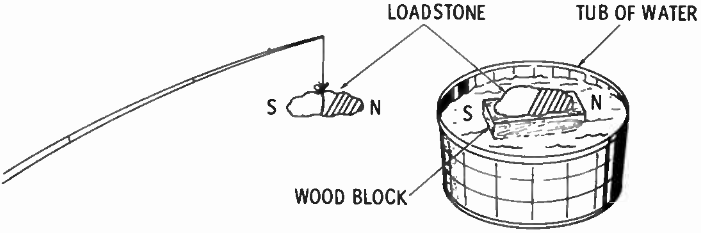
Magnetism is actually a force which cannot be seen, although you can witness the effects of magnetism on other materials.

THE MAGNET

We have already discussed one magnet, the loadstone, as being a natural magnet found in the earth. Magnets manufactured today are much stronger than the loadstone.

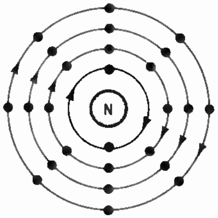
Iron, cobalt, and nickel are used in the manufacture of artificial magnets. Iron is easy to magnetize, but loses its magnetic properties almost immediately after the magnetizing force is removed. Steel is harder to magnetize, but it holds its magnetism over a greater period of time after the magnetizing force is removed.

The Chinese learned that when the loadstone was suspended or it was floated on a liquid, one end of the stone always pointed in a given direction. Today we know that any magnetic or magnetized material, when suspended or floated, aligns itself with the earth's magnetic field. The end of the magnet or magnetized material that points toward the north pole of the earth is called the "north-seeking" pole or "north pole"; the opposite end is called the "south-seeking" pole or "south pole."



Since magnetism is more pronounced in iron and its alloys than in most other materials, we will take a close look at an atom of iron.

AN ATOM OF IRON



Notice that the majority of electrons in orbit around the nucleus appear to be traveling in the same direction. This is the first clue as to why certain materials are easy to magnetize while other materials are almost impossible to magnetize. If you could take a close look at the atoms in a material that cannot be magnetized, you would see that the electrons in orbit appear to be traveling in different directions; they will cancel out each other's magnetic effects, thus preventing any external magnetic field.

You have learned that any magnet or magnetized material has a north-seeking and a south-seeking pole. One important characteristic possessed by magnets is that if the north poles of two magnets are brought near each other, they repel one another. This also occurs if two south poles are brought near each other.

Q1. Write the definition of a molecule.

Q2. How do like charges affect each other?

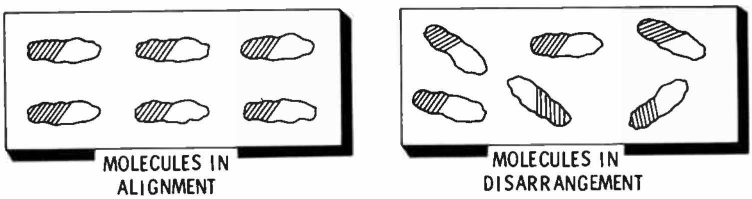
Your Answers Should Be:

A1. A molecule is the **smallest particle of any substance that still retains the physical characteristics of that substance.**

A2. Like charges are **repelled** by each other.

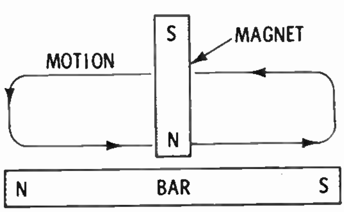
Magnetic Molecular Alignment

If you were able to view the molecules inside a block of unmagnetized iron, you would see the total disarrangement of the molecules.



Each molecule within a bar of iron has its own north-seeking and south-seeking poles. Although the magnetic strength of a single molecule is very weak, there are many millions of molecules in a very small piece of metal. When magnetically aligned in the same direction, they can develop a strong magnetic field. This is known as the **molecular theory of magnetism.**

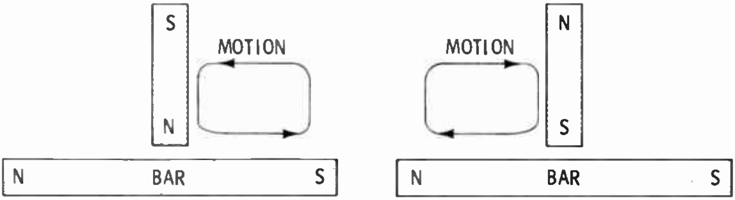
To magnetize a bar of iron, stroke the bar with a material known to be a magnet. Let us assume you choose to apply the north pole of the magnet to the iron. In the illustration below, stroke the iron bar from left to right.



MAGNETIZING AN IRON BAR

Note that in stroking the iron bar, the same pole of the magnet is always applied to the iron bar and the stroking action is always in the same direction. Make sure the magnet is lifted free of the bar at the end of each stroke.

An alternate method of magnetizing an iron bar is to apply the magnet at the center of the bar and stroke in one direction. After half of the bar is magnetized, reverse the magnet and, again starting at the center, stroke the iron bar in the opposite direction.

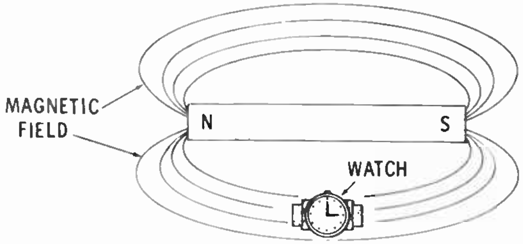


A steel bar can be magnetized in exactly the same way. Steel requires a greater force to align its molecules and therefore takes longer to magnetize. However, steel retains its magnetic properties for a much longer time than iron.

Because steel retains its magnetic properties, it is considered to have a high **retentivity** (the property of any material to remain magnetized).

Other Methods of Magnetizing Metal

Whenever a piece of iron or steel is placed in a magnetic field, it assumes the properties of the magnetic field.



You probably know the danger to your watch if you wear it when working near magnets. Many watches made today are said to be nonmagnetic. This doesn't mean that you can lay your watch on a strong magnet with safety, but it does mean that the watch is shielded from ordinary magnetic fields (lines of force surrounding a magnet).

Q3. What is the retentivity of iron as compared with steel?

Q4. What is meant by a magnetic field?

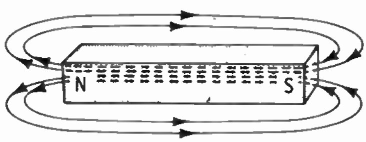
Your Answers Should Be:

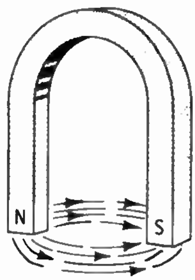
A3. **The retentivity of iron is very low.**

A4. A magnetic field is **the pattern of lines of force that surround** a **magnet.**

Magnetic Lines of Force

All magnets have invisible force lines surrounding them. These lines leave the north pole of a magnet, form a loop, and enter the south pole of the magnet, completing the loop inside. These loops run parallel to each other inside the magnet and never cross or unite.





ARROWS ILLUSTRATE THE PATHS OF MAGNETIC LINES OF FORCE

The lines formed by the magnetic loops are called **magnetic lines of force.** The area occupied by these lines is called the **magnetic field.** The magnetic field is the induced energy surrounding the magnet or the space through which the influence of these magnetic lines of force can be measured. The strength of the magnetic field is measured by determining the number of magnetic lines of force per unit area surrounding the magnet.

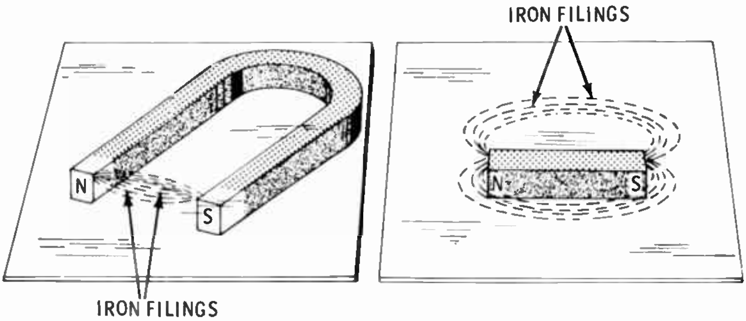
These lines are invisible; therefore, you may wonder how their total number can be determined or what pattern they form. A simple experiment that you may wish to perform will answer these questions and enable you to see these lines for yourself.

Magnetic Field Pattern Demonstration

You will need:

1. A bar or horseshoe magnet.
2. A piece of glass or clear plastic about 12 inches square.
3. A small can of iron filings.

Place the glass or plastic sheet over the magnet and sprinkle a small amount of iron filings (about a thimble full) over the magnet area on the surface of the sheet. Tap the sheet and notice how the iron filings form a definite pattern similar to that shown in the figure below.



It was stated previously the lines of force were invisible but that you could see their effects. Notice the heavy concentration of iron filings near the poles of the magnet.

It is possible to magnetize an iron or steel bar by stroking it with a magnet. A steel bar or rod can also be magnetized by placing it parallel to the earth's magnetic field and striking it several sharp blows with a hammer. The force from these blows causes the molecules in the bar or rod to change positions and to align themselves with the earth's magnetic field. If a screwdriver becomes magnetized, strike it on a hard surface a few times. Providing its original magnetic properties were rather weak, this striking will rearrange the molecules and demagnetize the screwdriver. Be sure the screwdriver isn't held parallel to the earth's magnetic field as it strikes the hard surface.

Heating, as well as jarring, reduces the magnetism of any material. When iron is heated above 770°C, it can no longer be magnetized or hold any magnetism. Heating a material accelerates the movement of the molecules, and this action causes the molecules to rearrange their alignment.

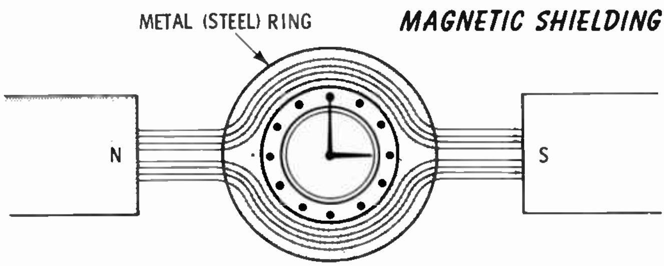
Q5. How is the strength of the magnetic field around a magnet determined?

Q6. What part of a magnet has the greatest magnetic attraction for a steel bar?

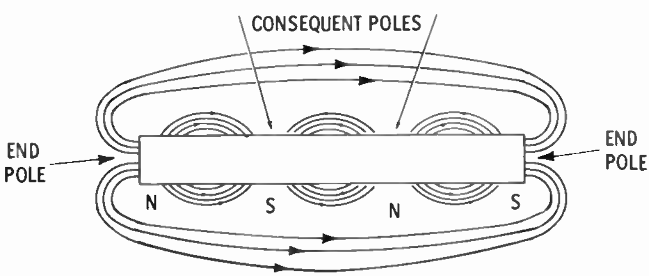
> **Your Answers Should Be:**
>
> **A5. The number of lines of force per unit area** around a magnet indicates its magnetic field strength.
>
> **A6. The area around either pole** has the greatest influence on a steel bar.

Magnetic Poles

The path of magnetic lines of force can be controlled. The lines of force concentrated at the poles of the magnet are much closer together than those surrounding the magnet. This is true because magnetic lines of force always take the path of least opposition. Iron or steel offers less opposition to these lines of force than air or other nonmagnetic material. This principle can be used to advantage. If an iron or steel ring is placed around a watch, the magnetic lines will follow a path through the ring and will not pass through the watch. This method of diverting magnetic lines of force is called **magnetic shielding.**



The minimum number of poles a magnet can have is two—a north-seeking pole and a south-seeking pole. It is possible, however, for a magnet to possess more than two poles.



The poles between the ends of a magnet are called **consequent poles**. Notice there are magnetic fields existing between the consequent poles and the end poles. These fields are the same as the field that exists between the end poles. The magnetic lines of force leave a north-seeking pole and enter a south-seeking pole.

TYPES OF MAGNETS

Basically, there are two types of magnets—permanent and temporary. As their names imply, one magnet retains its magnetism for a long period of time (years in some cases), and the other loses its magnetism almost as soon as the magnetizing force is removed. Manufactured magnets are called artificial magnets since the only natural magnet is the loadstone. Incidentally, a loadstone is very weak compared to a manufactured magnet; therefore, a loadstone has very few applications.

Applications

The types of magnets which have been discussed are widely used in speakers, meter movements, and magnetic compasses. You may wonder about the third use since a magnet deflects the needle of a compass. A compass installed on most boats, cars, or airplanes is usually surrounded by metal. This metal is affected by the earth's magnetic field. Small bar magnets, called compensating magnets, are placed around the compass to counteract the effects of the earth's magnetic field on the surrounding metal. This makes it possible to use the compass in such places.

Q7. Magnetic lines of force always take the path of ----- opposition.

Q8. Diverting magnetic lines of force is one method of magnetic ----------.

Q9. What is the minimum number of poles a magnet can have?

Q10. The poles between the ends of a magnet are called ----------- poles.

Q11. Magnetic lines of force leave the ----- pole and enter the ----- pole.

Your Answers Should Be:

A7. Magnetic lines of force always take the path of **least** opposition.

A8. Diverting magnetic lines of force is one method of magnetic **shielding.**

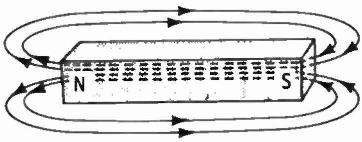
A9. **Two.**

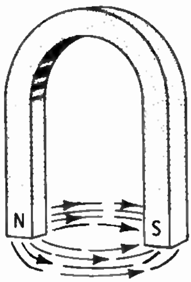
A10. The poles between the ends of a magnet are called **consequent** poles.

A11. Magnetic lines of force leave the **north** pole and enter the **south** pole.

Horseshoe Magnets

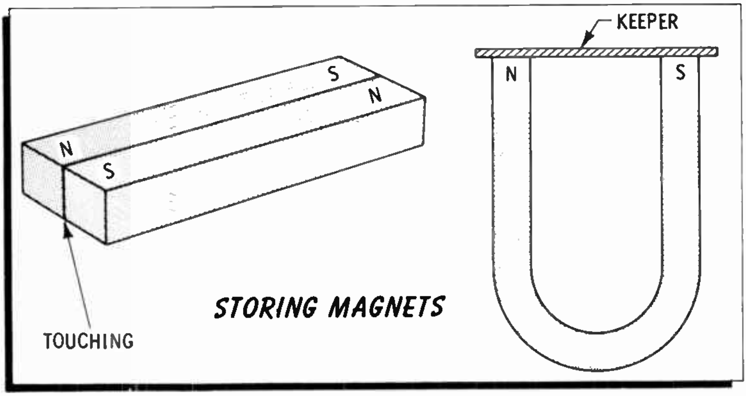
The magnets used in meters are shaped like a horseshoe. By bringing the two poles close together, the lines of force are concentrated and thus provide a much stronger magnetic field.





Care of Magnets

Magnets that are not properly cared for lose their magnetic properties over a period of time. How much magnetism is lost depends on many variables—how the magnet was originally magnetized, how it is used, where it is used, etc. When a horseshoe magnet is not in use, a soft iron bar should be placed across the poles. This bar will provide a path for the magnetic lines of force, and the magnet will retain its magnetic properties for a much longer period. The iron bar used for this purpose is called a **keeper.** Bar magnets should be stored parallel to each other with unlike poles together.



In some cases, it is important for the magnet to maintain a specific magnetic force over a long period of time. When this function is necessary, magnets are put through a process of **aging** during their manufacture. This is done by placing the magnet in an oven and subjecting it to controlled temperature changes and to vibrations. This process causes the strength of the magnet to remain nearly constant for a long period of time.

Reluctance

Some materials offer less opposition to magnetic lines of force than do others. In magnetic circuits this opposition is called **reluctance.**

In the study of electrical circuits, you learned that electromotive force causes current to flow in a circuit and the flow of that current is limited by resistance. There is also a magnetic circuit in which the magnetic lines of force form closed loops, called **flux loops.** The force that produces these flux loops is called the **magnetomotive force (mmf).** The opposition to the flux loops is called **reluctance.** Notice the similarity to the electrical circuit. In a magnetic circuit the magnetic lines of force always take the path of least reluctance. This is why the magnetic lines followed the steel ring around the watch discussed previously. The steel ring offered less reluctance than the air and the nonmagnetic metal of the watch in the center of the ring.

Q12. The opposition that some materials offer to magnetic lines of force is called ___________.

Your Answer Should Be:

A12. The opposition that some materials offer to magnetic lines of force is called **reluctance.**

Magnetic Flux

An expression for determining the amount of flux present in a magnetic circuit is:

$$\text{flux} = \frac{\text{magnetomotive force}}{\text{reluctance}}$$

Flux varies directly with the magnetomotive force and inversely with the reluctance. This is the Ohm's law expression for magnetic circuits. Compare the two formulas.

$$\text{Current} = \frac{\text{electromotive force}}{\text{resistance}}$$

Magnetic flux is the total number of magnetic lines existing in a magnetic circuit or extending through a specific region. The symbol for magnetic flux is the Greek letter ϕ (phi). One magnetic line of force is equal to **1 maxwell.**

The concentration of these magnetic lines determines the **flux density.** The symbol for flux density is **B,** and the unit of measurement is the **gauss.** One gauss is a flux density of one line of force per square centimeter.

The degree of flux density between the poles of a horseshoe magnet is directly proportional to the area of the air gap between the poles. The force of attraction or repulsion between the poles varies directly with the strength of the poles and inversely with the square of the distance separating them. This force can be determined as follows.

$$F = \frac{P_1 \times P_2}{\mu d^2}$$

where,

F is the force between poles in dynes (unit of force),
P_1 and P_2 are the strengths of the two poles,
d is the distance in centimeters between the poles,
μ is a constant that depends on the medium between the poles. It is 1 for air and greater than 1 for other mediums.

To find the total number of flux lines, multiply the flux density (in gausses) by the area (in square centimeters).

Certain materials have more opposition (reluctance) to magnetic lines of force than others. It is therefore true that some materials allow magnetic lines of force to pass more easily than others. The ease with which magnetic lines of force pass through a material is known as **permeance**, the reciprocal of reluctance (permeance $= \frac{1}{\text{reluctance}}$). Any substance that allows the magnetic flux to pass with little or no opposition is said to have a high **permeability**. Iron, for example, has a high permeability. High-permeability materials can be easily magnetized, but they will not retain their magnetism. Permeability varies with the intensity of the magnetic field in which the material is located.

It is also possible to determine the flux in any material by multiplying the magnetomotive force by the permeance.

$$\text{flux} = \text{mmf} \times \text{permeance}$$

Not all materials can be magnetized. Actually, materials can be broken down into three classifications—diamagnetic, paramagnetic, and ferromagnetic. **Diamagnetic** materials are those that normally cannot be magnetized. **Paramagnetic** materials are those that are difficult to magnetize. **Ferromagnetic** materials are those that are relatively easy to magnetize. Some ferromagnetic materials are iron, cobalt, nickel, silicon steel, and cast steel.

A diamagnetic material is extremely difficult to magnetize and has a permeability of less than 1. A paramagnetic material is also difficult to magnetize, but has a permeability of slightly greater than 1. A ferromagnetic material is easily magnetized, and its permeability is quite high.

Q13. If there are 3,000 magnetic lines of force passing through a magnet, what is the magnetic flux?

Q14. If there are 2,700 maxwells in a cross-sectional area of 9 square centimeters and the lines are evenly spaced, how many maxwells are there in 1 square centimeter?

Q15. In an area of 5 square centimeters the flux density is 6,000 gausses. How many flux lines pass through the area?

Your Answers Should Be:

A13. The magnetic flux is **3,000 maxwells.**

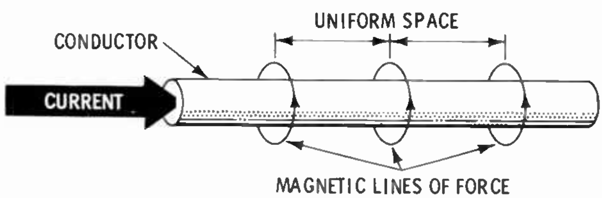
A14. There are **300 maxwells** in 1 sq. cm.

A15. **30,000** flux lines pass through the area.

ELECTROMAGNETS

There is another type of magnet that has a wide range of applications in electricity. This is the **electromagnet.** The dictionary defines an electromagnet as "a bar of soft iron that will become a temporary magnet if an electrical current is caused to pass through a wire coiled around it."

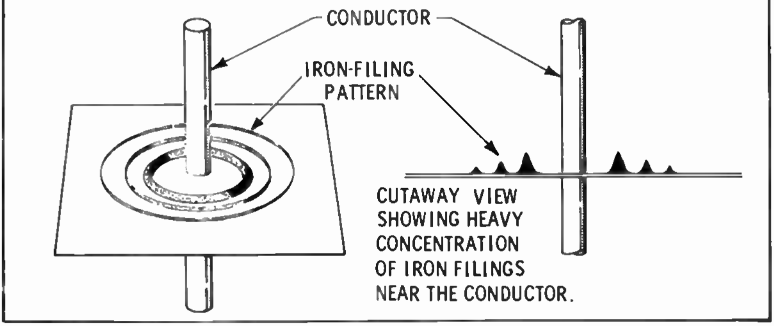
Electromagnetism was first discovered by Hans C. Oersted, a Danish scientist, in 1820. Oersted found that a needle placed near a wire would deflect when current passed through the wire. Further experiments led to the discovery that current flowing through a conductor creates a magnetic field about the conductor. This magnetic field is composed of lines of flux (magnetic lines) that encircle the conductor at right angles to the flow of current. The flux lines are uniformly spaced along the length of the conductor.



This is another method of creating a magnet. The magnetic field around a straight conductor is not very strong, but it exhibits the same properties as the bar or horseshoe magnet discussed previously. If a compass is placed near the conductor, the compass needle is deflected at right angles to the current-carrying conductor. The compass also indicates that the magnetic field around the current-carrying conductor is polarized. If the current is reversed through the coil, the position of the compass needle also reverses.

The magnetic field around a conductor diminishes with an increase in distance from the conductor.

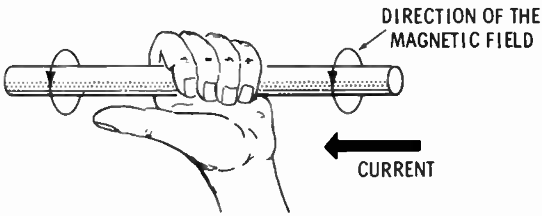
FIELD IS STRONGEST NEAR THE CONDUCTOR



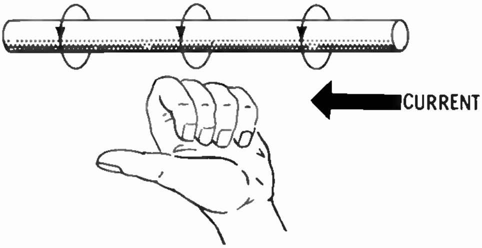
Left-Hand Rule

To determine the direction of the magnetic field around a current-carrying conductor, grasp the conductor in your left hand, with your thumb pointing in the direction of current flow. The direction that your fingers curl around the wire indicates the direction of the magnetic field.

LEFT-HAND RULE



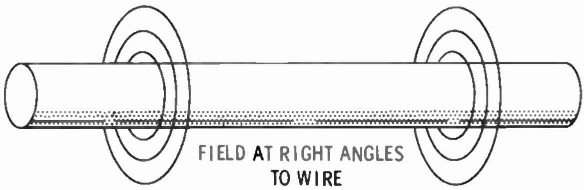
Do not attempt such an experiment on a bare wire. Instead, place your left hand in a position away from the wire with your thumb pointing in the direction of current flow. Your curled fingers will indicate the direction of the magnetic field. It isn't necessary to grasp the conductor.



A16. In what plane do the magnetic lines around a current-carrying conductor lie?

Your Answer Should Be:

A16. The magnetic lines around a current-carrying conductor lie in a plane at **right angles to the conductor.**



Magnetic Field Strength

Magnetomotive force is the force that tends to drive the flux through a magnetic circuit. The unit of magnetomotive force is the **gilbert.**

The unit of measurement used to express field intensity is the **oersted.** The strength of the magnetic field can be found by using the following expression:

$$H = \frac{I}{5d}$$

where,

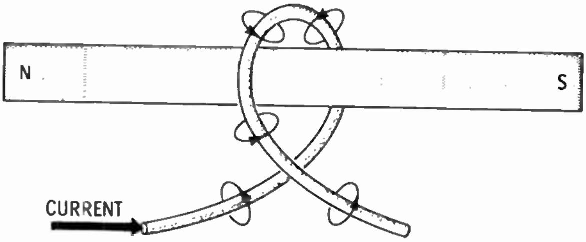
H is the field intensity at a point nearest the wire in oersteds,
I is the current through the wire in amperes,
d is the distance of this point from the axis of the wire in centimeters (1 inch = 2.54 centimeters).

Constructing an Electromagnet

The magnetic field developed around a straight wire or conductor is seldom strong enough to be useful. However, if the wire is formed into a coil, the magnetic field becomes quite strong.

The figure on the next page shows the action that takes place when current flows through a coil. All of the magnetic lines of force enter the coil at one end and emerge at the opposite end.

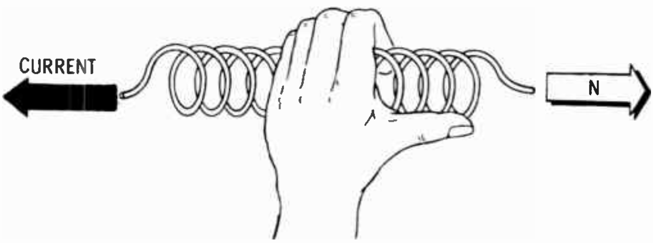
The strength of the magnetic field is directly proportional to the number of turns in the coil and the current passing



through them. A coil with a large number of turns has a magnetic field of greater strength than one with a small number of turns. The magnetic field is greater when a larger current flows through the coil.

Since all magnetic lines of force form a loop, poles similar to those of a permanent magnet are established on the coil. The poles form at each end of the coil and their polarities depend on the direction of current flow.

The left-hand rule is employed to determine the magnetic polarity. Grasp the coil in your left hand with your fingers pointing in the direction of current flow. Your thumb points in the direction of the north-seeking pole of the coil.



It was stated previously that the flux density is much greater in a block of iron than it is in air. Therefore, if an iron core is added to the current-carrying coil, the magnetic loops will concentrate through the core, increasing the flux density and strength of the electromagnet. The magnetic lines around the coil are called **induction lines.** Soft iron cores are used in electromagnets because of the high permeability of iron.

Q17. What is the field intensity at a distance of 5 inches from the center of a wire carrying 100 amps?

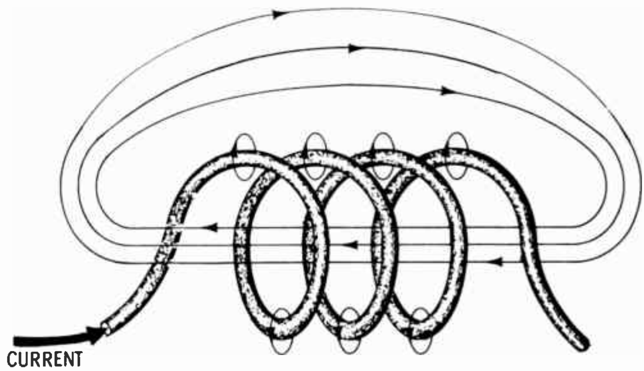
Q18. Why is the magnetic field around a coil stronger than the magnetic field around a straight wire?

Your Answers Should Be:

A17. The field intensity is **1.57 oersteds.**

$$H = \frac{I}{5d} = \frac{100}{5 \times 12.7 \text{ cm}} = \frac{100}{63.5} = 1.57 \text{ oersteds}$$

A18. When a straight wire is formed into a coil, the magnetic lines around each turn are reinforced.



The strength of an electromagnet can be determined by connecting a coil across a battery and placing an iron rod, suspended by a small hand scale, near the coil. When the circuit is energized, current flows through the coil and the magnetic field that is developed attracts the iron rod. The amount of pull can be read directly on the hand scale after subtracting the weight of the rod.

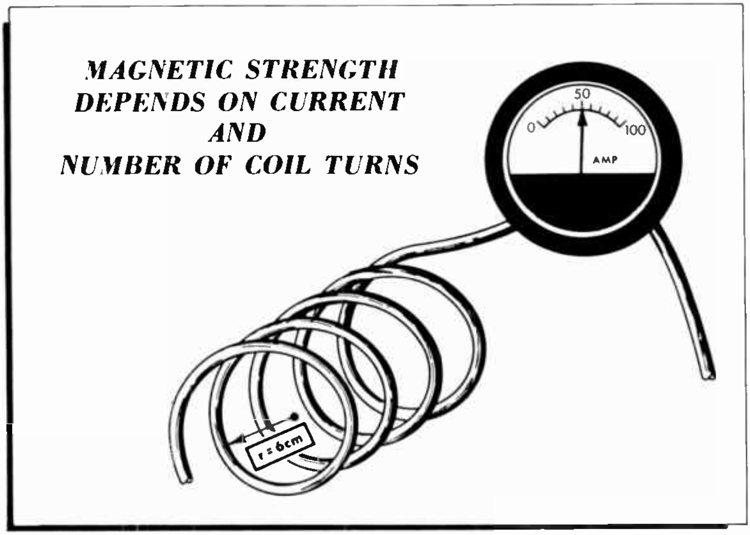
If the overall length of a coil is less than its diameter, the strength of the field can be calculated by the following expression.

$$H = \frac{2\pi NI}{10r}$$

where,

H is the field intensity in oersteds,
N is the number of turns in the coil,
I is the current through the coil in amperes,
r is the radius of the coil in centimeters,
π is a constant equal to 3.14.

The two main factors that determine the strength of an electromagnet are the current and the number of turns in the coil. The magnetic field can be varied by altering either factor. The combination of these two factors (I and N) is called **ampere turns.** An electromagnet with 200 turns of wire through which 1 amp is flowing has a field strength equal to an electromagnet with a 10-turn coil through which 20 amps is flowing. In both cases the number of ampere turns is 200.



Q19. What can be added to a coil of wire to make it a stronger electromagnet?

Q20. What is meant by permeable material?

Q21. Calculate the field strength of the coil shown in the figure on this page.

Q22. What determines the field strength of an electromagnet?

Q23. What is the field strength of a coil having 10 amps of current flowing through it, if the coil has a radius of 2 inches and contains 26 turns?

Q24. Find the current flowing in a coil having a field strength of 25 oersteds, 15 turns, and a radius of 2 cm.

Your Answers Should Be:

A19. Adding **an iron core** to a coil increases the strength of an electromagnet.

A20. Permeable material is **any material that can be easily magnetized.**

A21.

$$H = \frac{2\pi NI}{10r} = \frac{6.28 \times 4 \times 50}{10 \times 6} = \frac{1{,}256}{60} = \mathbf{20.93\ oersteds}$$

A22. The **current** and the **number of turns** in the coil.

A23.

$$H = \frac{2\pi NI}{10r} = \frac{6.28 \times 26 \times 10}{10 \times 2 \times 2.54} = \mathbf{32.14\ oersteds}$$

A24.

$$H = \frac{2\pi NI}{10r}$$

$$2\pi NI = H \times 10r$$

$$I = \frac{H \times 10r}{2\pi N} = \frac{25 \times 10 \times 2}{6.28 \times 15}$$

$$\mathbf{I = 5.30\ amps}$$

Magnetomotive Force

Magnetomotive force is defined as the force that produces a magnetic field, and is measured in **gilberts.** In the design of an electromagnet for a particular application, it is often desirable to determine just how much magnetomotive force is required to create a magnet with a specific field strength.

A convenient method of determining the magnetomotive force in a current-carrying air-core coil is to use the following expression.

$$\text{mmf} = 1.257 \times I \times N$$

where,

mmf is the magnetomotive force in gilberts,
I is the coil current in amps,
N is the number of coil turns.

The reluctance of air is 1.257 (this number will be different for an iron-core coil). As can be seen, magnetomotive force is directly proportional to the ampere turns.

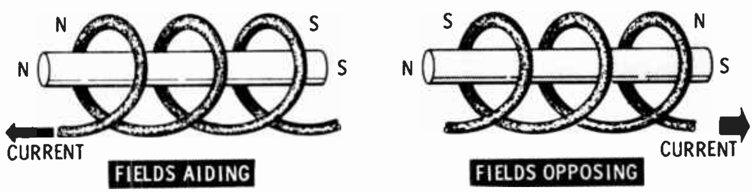
Residual Magnetism

When an electromagnet is de-energized, the magnetic field collapses, but a slight amount of magnetism remains in the core material. This is called **residual magnetism.**

When the magnetic lines of force surrounding the coil concentrate inside the center of the coil, the force magnetically aligns the molecules in the core material. This is similar to the process of magnetizing a metal bar. If the core material is a bar of steel, the results will be different from those for a bar of iron. Once the molecules are aligned in the steel bar, they tend to remain aligned. The core will then retain considerable residual magnetism after the current has ceased to flow through the coil.

Hysteresis

If the current is reversed in an electromagnet (perhaps many times a second), the magnetic field and the direction of polarization will also reverse. If the core material possesses any residual magnetism, the polarity change in the magnetic field will be somewhat delayed beyond the time when the current is reversed. It is necessary to overcome the residual magnetism before the core can be magnetized in the reverse direction.



When current flows through the coil in the direction shown, the north pole of the magnet is on the left, and the south pole is on the right (left-hand rule for a coil). The magnetic polarity of the core material is identical to the polarity of the coil. When the circuit is de-energized, the magnetic field collapses. Any residual magnetism remaining in the circuit retains its original polarity.

Q25. What is the magnetomotive force if 2 amperes flows through an 8-turn air-core coil?

Q26. What makes the best core material for an electromagnet?

Your Answers Should Be:

A25. The magnetomotive force is **20.112 gilberts.**

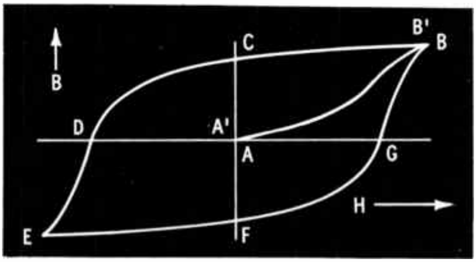
$$mmf = 1.257 \times I \times N = 1.257 \times 2 \times 8 = 20.112 \text{ gilberts}$$

A26. Soft iron makes the best core material because its molecules tend to rearrange themselves easily after the magnetizing force is removed.

If the current through a coil is reversed, the magnetic field also reverses. Before the reverse magnetic field can build up, however, it must first overcome the residual magnetism in the core material of the coil. The residual magnetism opposes the new field, so it is first necessary to reduce the residual magnetism to zero before the new field can be developed. Instead of the magnetic field being developed immediately as the current increases, there is a slight delay. The magnetic field lags the current slightly. This lag is called **hysteresis.**

Energy is required to align the molecules in the core material. If the current through the coil is reversed frequently, considerable energy is required to realign the molecules first in one direction and then in the other. This energy is lost in the form of heat and is called **hysteresis loss.**

The hysteresis lag becomes quite evident when a curve of magnetizing force (H) is plotted against flux density (B).



B-H CURVE

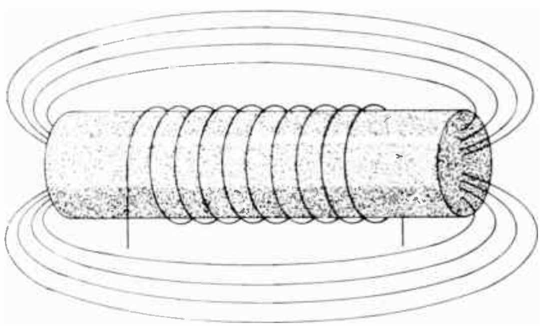
The figure above is referred to as the **B-H curve.** When current flows through a coil, the magnetic field around the coil builds up, as indicated by line A-B. When the current reaches its maximum level, the magnetic field also reaches maximum intensity, as indicated by point B. When the current ceases to flow, the magnetic field collapses along line B-C. When the current reaches zero, the amount of residual magnetism remaining in the circuit is indicated by line A-C.

If the current is reversed in the circuit, the residual magnetism must first be overcome. It falls to zero, as indicated by line C-D. The magnetic field then builds up in the opposite direction along line D-E, reaching maximum concentration at point E. When the current stops flowing in the reverse direction and falls to zero, the magnetic field collapses along line E-F. The distance between points A and F indicates the amount of residual magnetism remaining in the core at that time. If the current were to flow in its original direction, the magnetic field would collapse to zero, as shown by line F-G, and build up to its maximum level along line G-B.

Saturation

The magnetic field develops gradually as the current increases. There is a point, however, where the core material cannot accommodate additional lines of flux. When this point is reached, the core is said to be **saturated.** Any additional lines of force will have to flow through the air surrounding the core material. Since the reluctance of air is quite high compared to the reluctance of iron, it is difficult to increase the flux density beyond core saturation.

MAGNETIC SATURATION



CORE MATERIAL SATURATED

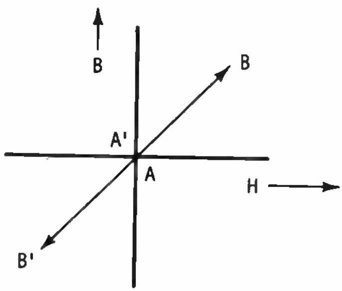
Q27. Will residual magnetism have any effect on the temperature of the core?

Q28. What would the effects be if the core material were removed?

Your Answers Should Be:

A27. **Yes,** the temperature will definitely be affected. When the molecular action increases, the material becomes hot, and energy is expended in the form of heat.

A28. If there were no core material **the B-H curve would increase and decrease in a linear fashion** and there would be no residual magnetism.

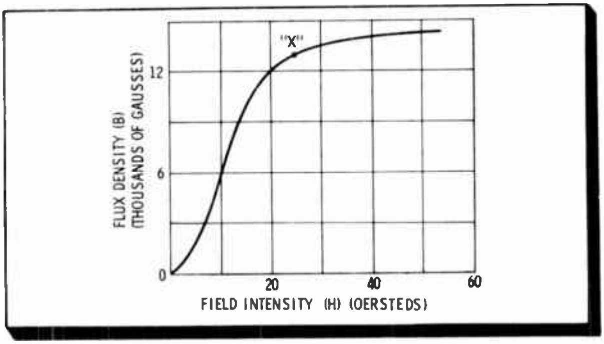


Magnetic Permeability

Compare the B-H curve on the preceding page with the curve above. Notice that the first curve does not vary in a linear fashion along line A-B or A′-B′. This is true because there is a slight variation in the process of core magnetization. Theoretically, the magnetic field gradually builds up by a definite quantity whenever the magnetizing force is varied by a specific amount.

For example, if the magnetizing force increases by 3 oersteds, the magnetic flux increases by 10,000 maxwells. This is true anywhere along the theoretical curve. In actual practice, however, there is a slight variation. At certain points along the curve an increase of 3 oersteds in the magnetizing force may increase the magnetic flux by only 9,800 maxwells. At other points on the curve, such an increase in the magnetizing force may increase the magnetic flux by 10,300 maxwells. This variation accounts for the nonlinearity of line A-B on the B-H curve.

The following graph compares magnetizing force and flux density when a steel bar is magnetized.



The flux density increases rapidly with only a slight increase in the magnetizing force when the core material is at a point of low field intensity (only a few thousand magnetic lines of force). At a point of high field intensity, a large change in the magnetizing force is required to cause a small change in flux density. Point X indicates the point of saturation.

Permeability can be determined by the following expression.

$$\mu = \frac{B}{H}$$

where,

μ is the permeability (has no unit of measure),
B is the flux density in gausses,
H is the magnetizing force in oersteds.

When the permeability of a material is low, the reluctance is high, requiring a large magnetizing force to increase the flux density. This can be seen from the following expression for determining flux.

$$\phi = \frac{mmf}{R}$$

where,

ϕ is the flux lines in maxwells,
mmf is the magnetomotive force in gilberts,
R is the reluctance.

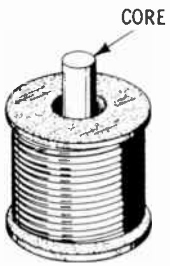
Q29. Referring to the graph above, would the permeability at the point of saturation be high or low?

> **Your Answer Should Be:**
>
> A29. The permeability of the core material at saturation would be very low.

Solenoids

A coil wound in the shape of a cylinder or tube is called a **solenoid.** A solenoid is often provided with a movable iron core, or plunger. In this arrangement, the iron core is pulled into the coil when current flows through the turns. Thus, the core can be used to mechanically move some device.

Solenoids are commonly used in relays or circuit breakers. The magnetic field built up in the center of the coil pulls the core into the solenoid, thereby breaking or making the relay contact(s).



A SOLENOID

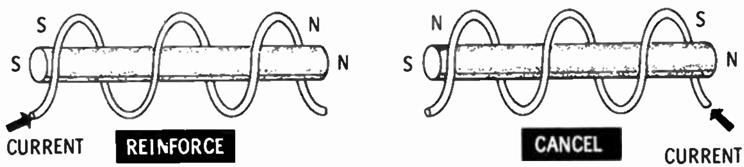
Toroids

Another type of coil that is used in some applications is the **toroid,** which has a ring-shaped core on which the turns of wire are wound to form a complete circle. This design concentrates all the lines of force inside the ring. With all the flux inside the ring, the toroid has no external polarity.

A TOROID

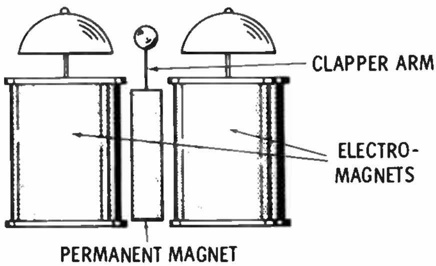
Polarized Electromagnets

A polarized electromagnet has a permanent magnet as its core, as shown in the figure below.



When current flows in the coil, the electromagnet will either add to, neutralize (cancel out), or subtract from the magnetic field of the permanent magnet. Polarized electromagnets are used in telephone and telegraph circuits. The figure below shows a diagram of a telephone-bell circuit.

A POLARIZED ELECTROMAGNET



The clapper arm, which extends down through the center of the electromagnet, is attached to a permanent magnet. The permanent magnet holds the clapper arm in a neutral position between the bells and provides the clapper with a specific polarity. Assume this position holds the clapper arm to the south-seeking pole of the permanent magnet. When current flows through the series-connected coils, the electromagnetic field thus developed adds to the field of the permanent magnet. This combined field pulls the clapper arm to the right, causing the clapper to strike the right-hand bell. When the current is reversed, the magnetizing force of the electromagnet subtracts from the force of the permanent magnet, and the clapper strikes the left-hand bell.

Q30. How would you determine which is the north-seeking pole of a solenoid?

Q31. In what position will the clapper arm be when current is not flowing through the electromagnet?

Your Answers Should Be:

A30. The magnetic field around a solenoid is similar to that around any coil. The **left-hand rule** used to find the polarity of a coil may also be used to determine the polarity of a solenoid.

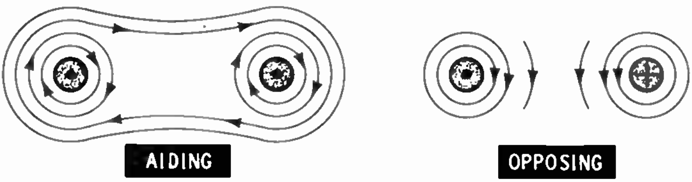
A31. The permanent magnet returns the clapper arm to **the center position** when the current stops flowing.

USES FOR MAGNETS

You may ask why the permanent magnet does not become demagnetized when the electromagnetic field opposes it. Once a permanent magnet becomes magnetized, a strong force is required to disarrange its molecules. The electromagnetic field might be strong enough to do this if it remained for a very long period of time. However, the current through the coil in a specific direction lasts for only a brief period and does not noticeably change the permanent magnetic field.

When current passes through parallel wires, the magnetic fields around these wires interact. If the currents flow in the same direction, the fields repel each other; if the currents flow in opposite directions, the fields attract each other.

PARALLEL WIRES CARRYING CURRENT

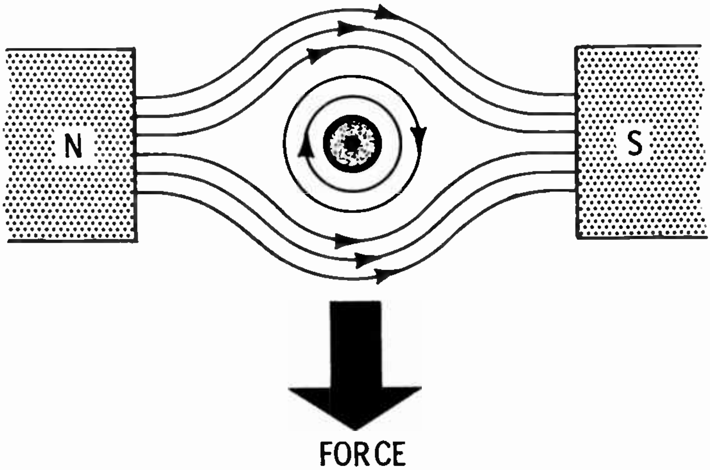


Electric Motors

The principle of attraction and repulsion just shown is used in electric motors and generators. Electric motors are used to provide a mechanical power output from an electrical input. Generators provide an electrical output from a mechanical input.

The force exerted on an electron in a magnetic field is at right angles to the magnetic field. When the electron is placed in both an electric and a magnetic field, the force exerted on the electron is perpendicular to both fields. A right-hand rule is used to determine the direction of force on electron flow in a magnetic and electric field.

FORCE EXERTED ON A CURRENT-CARRYING CONDUCTOR IN A MAGNETIC FIELD



The magnetic field around the conductor in the above figure is clockwise. The current appears to be coming out of the page. The direction of the magnetic field of the permanent magnet is from the north-seeking pole to the south-seeking pole, or from left to right in the figure above. Notice that the lines above the conductor and the lines around the conductor are going in the same direction, reinforcing the field above the electron path. Below the conductor the fields are opposing each other.

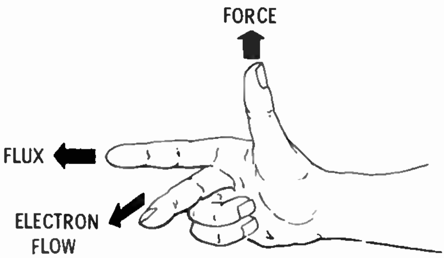
Q32. In the figure above, the field around the conductor and the magnetic field of the permanent magnet are opposing each other at a point below the electron path. What effect does this have on electron flow?

Your Answer Should Be:

A32. This weakens the fields and electron flow is forced in a downward direction.

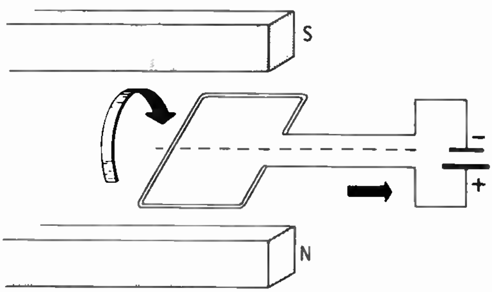
Right-Hand Rule

Arrange the thumb, index finger, and middle finger of your right hand as shown in the figure below. Point the index finger in the direction of magnetic flux and the middle finger in the direction of electron flow. The thumb indicates the direction of magnetic force on the electron (direction that the wire is repelled).



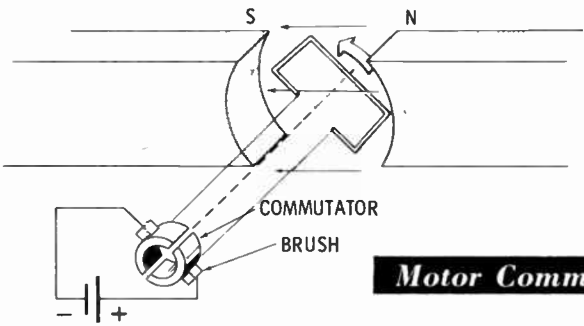
RIGHT-HAND RULE

If a loop of wire is positioned in a permanent magnetic field, a force acts on the wire each time current passes through it. This force causes the loop of wire to rotate, if it is free to turn, as shown in the figure below.



The simple motor shown in the figure above is not very practical. The coil cannot rotate very far because the current always moves through the wire in the same direction. When opposing poles appear opposite each other, the loop stops. Furthermore, any permanent connections to the loop of wire will not allow it to rotate very far.

To overcome these objections, the loop is terminated in two contacts that rotate with the loop. These contacts form the **commutator** of the motor. Electrical connections are made by carbon brushes pressing against the commutator.



Motor Commutation

When current flows through the wire loop, a magnetic field is set up so that the north-seeking pole appears above the loop and the south-seeking pole below. (Check this by employing the left-hand rule for a coil.) The magnetic poles thus created around the loop are attracted by the opposite poles of the permanent magnet; this causes the loop to rotate in a counterclockwise direction. (According to the right-hand rule, the force is downward on the left side of the loop and upward on the right side.)

The loop and commutator rotate together. When the loop has reached a position such that the opposing poles of the electromagnet are adjacent, the commutator will have rotated to a position where the applied voltage is reversed. The current through the loop will now reverse directions, reversing the magnetic field around the loop so that the north-seeking pole of the permanent magnet and the two south-seeking poles will be opposite. The like poles will oppose each other, and the loop will continue to rotate in a counterclockwise direction.

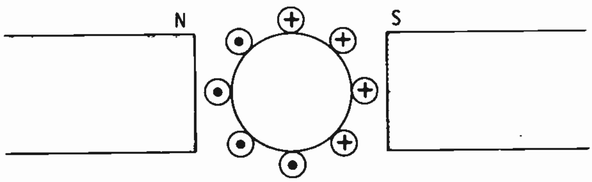
Q33. If a current-carrying conductor is placed in a magnetic field so that the current appears to be flowing into the page and the polarity of the permanent magnet is such that the north-seeking pole is on your right, what will be the direction of force on the electron stream?

Your Answer Should Be:

A33. The direction of force on the electron flow would be **downward.**

DC Motors and Generators

In electric motors many loops of wire are wound around a core. This assembly is called an **armature.** Each loop is connected to a commutator segment that makes contact with the carbon brushes as the armature rotates. The use of many loops provides smoother operation and considerably more power than a single loop. An end view of an armature is shown in the figure below.



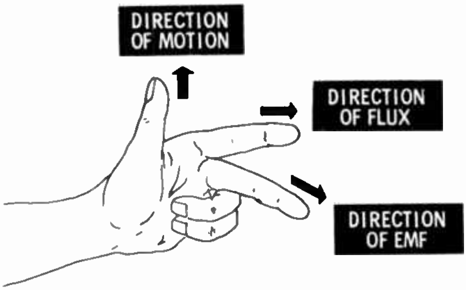
Large electric motors use electromagnets in place of permanent magnets. It is possible to obtain a stronger magnet for the same physical size by using the electromagnet.

If current flowing through a wire creates a magnetic field, it seems only reasonable that a wire moving through a magnetic field causes a current flow. The DC generator operates by use of this principle. An armature (similar to one in an electric motor) is rotated in a magnetic field. The turns of wire cut the lines of force, and a current is caused to flow in the wire loops of the armature. Connections to the commutator provide an electric current output.

Another left-hand rule is used to determine the direction of the induced electromotive force in a generator. Place the thumb, index finger, and middle finger of your left hand so that they are perpendicular and at right angles to each other. Point the thumb in the direction of motion (rotation) of the conductor (armature) and point the index finger in the direction of the magnetic flux. The middle finger will then indicate the direction of the induced current (electron flow).

This procedure is shown in the figure below.

LEFT-HAND RULE FOR GENERATORS

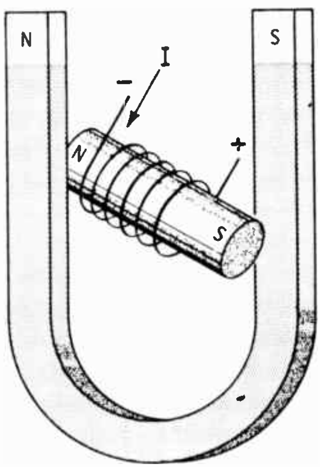


Meters

Both permanent magnets and electromagnets are used in meter movements. Their operation is similar to that of the electric motor previously described. In the meter movement the electromagnet does not rotate through 360° as it did in the motor; instead, it rotates through an arc of approximately 150°.

The electromagnet is positioned between the poles of a permanent horseshoe magnet, as shown in the figure below.

METER PRINCIPLE



Q34. How long will a single-loop motor rotate?

Q35. If the magnets in a generator are placed so that the north-seeking pole is on the right and the motion of the conductor is downward, what will be the direction of the induced current flow?

Your Answers Should Be:

A34. A single-loop motor will rotate **as long as current flows through the loop.**

A35. The direction of the induced current flow is **out of the page** (left-hand rule for generators).

When no current is flowing through the coil, a spring holds the coil in the position shown. When current does flow, a magnetic field is developed around the coil with the north-seeking pole on the left and the south-seeking pole on the right in the figure above (left-hand rule for coils). Thus, the two north-seeking poles and the two south-seeking poles are opposite each other. The like poles repel and the coil rotates. How far the coil rotates depends on the strength of the electromagnet and its ability to overcome the tension applied by the spring. A pointer connected to the moving coil moves across a calibrated scale, making it possible to use the meter as a measuring device.

WHAT YOU HAVE LEARNED

1. Magnetism is a property of certain materials to attract and repel each other.
2. Magnetized materials have north (north-seeking) and south (south-seeking) poles. Magnetic force lines flow from south to north inside the material and north to south outside.
3. Some materials may be magnetized by stroking them with a magnet or by passing current through a coil wrapped around them.
4. A permanent magnet has a high retentivity (retains its magnetism). A temporary magnet has low retentivity.
5. Permanent magnets should be stored in a manner which permits the external field to be concentrated in a path of low flux opposition. Bar magnets are stored with N and S poles adjacent. A keeper is placed across the poles of a horseshoe magnet.
6. Reluctance is the opposition offered to the flow of magnetic flux lines. Air has a higher reluctance than iron.

7. Number of flux lines (maxwells) is directly proportional to the magnetomotive force exerted and indirectly proportional to the reluctance of the material through which the flux lines pass.
8. Permeability of a material is a measure of its ability to be magnetized. Low reluctance indicates high permeability.
9. An electromagnet is a device that has been or is being magnetized electrically.
10. Current through a conductor generates a magnetic field. If the thumb of the left hand points in the direction of electron flow, the fingers curl in the direction taken by the flux lines.
11. A coil of wire develops a stronger magnetic field than a single conductor. Field strength is directly proportional to ampere-turns (number of coil turns and the amount of current flowing). Field strength is indirectly proportional to the diameter of the coil.
12. Magnetomotive force of a coil can be determined by multiplying ampere-turns by a reluctance constant. Reluctance for air is 1.257.
13. Residual magnetism is the amount of magnetism remaining in an electromagnet after current flow has ceased.
14. Hysteresis (difficulty in realigning magnetic direction of molecules) causes changes in the magnetic field to lag changes in the current.
15. Each magnetic material has a limit to which it can be magnetized. The limit of magnetic strength is called saturation, and is the point at which a maximum number of molecules have been aligned in the same magnetic direction.
16. Solenoids are electromagnets with movable iron cores.
17. Electromagnets are used in motors, generators, meters, and other devices that make use of the electrical effects of a magnetic field.
18. The right-hand rule for motors states: With thumb, index finger, and middle finger of the right hand at right angles to each other, the index finger pointing in

the direction of magnetic flux, and the middle finger pointing in the direction to current flow, the thumb will indicate the direction in which the conductor will move.

19. The left-hand rule for generators uses the same principle: If the left thumb points in the direction of the conductor movement, and the index finger points in the direction of the magnetic flux, the middle finger will indicate the direction of current flow in the conductor.

7

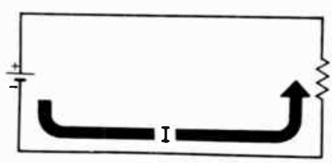
What Is Alternating Current?

What You Will Learn

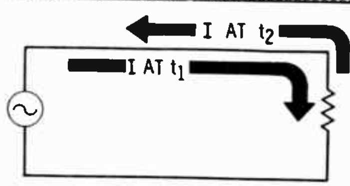
When you have finished this chapter you will be able to explain what alternating current is. You will not only know how AC currents are generated, but you will be able to recognize AC and pulse forms. In addition, you will be able to describe the different types of AC waveforms.

Alternating current (AC) differs from direct current (DC). The electrons in a direct current always flow in the same direction. Electrons in an alternating current reverse directions at periodic intervals.

Electrons Always Flow in the Same Direction in a DC Circuit



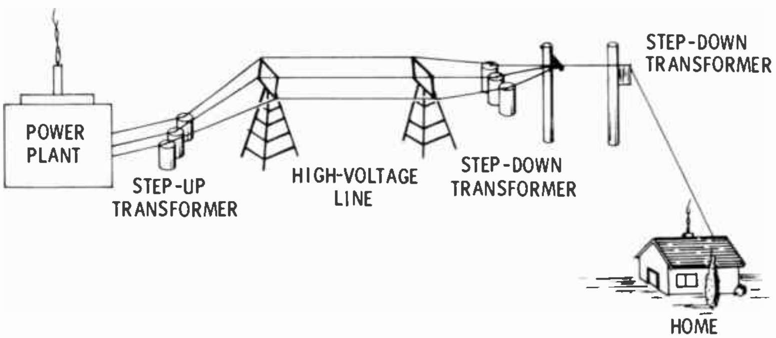
Electrons Reverse Direction Regularly in an AC Circuit



ALTERNATING CURRENT SOURCES

Alternating current is the most common type of electricity used. Because its electron flow reverses direction rapidly, the value of an alternating voltage is easily increased or decreased by passing it through a transformer. For example, when it is necessary to transmit electricity over great distances (from the power plant to a city miles away), the power-plant voltage is increased by a transformer to a very high value (such as 69,000 volts) and sent through a relatively small-diameter transmission line. If the AC electricity were sent at the power-plant voltage (such as 4,160 volts), the diameter of the transmission line would have to be much larger. This is because a lower voltage makes a higher current flow necessary. Thus, a larger-diameter line from the power plant to the user would be required. At the city end of the transmission lines the voltage is reduced by transformers, and then still further reduced to 240 and 120 volts by another transformer at the utility pole outside the user's house. It is far more difficult and costly to change DC voltages than to change AC voltages.

ALTERNATING CURRENT CAN BE TRANSMITTED LONG DISTANCES AT LOW COST



Alternating currents are generated in very large quantities in power plants. The electricity used in your home comes from a power plant. The total current capacity of a power plant can reach several thousand amperes at 4,160 volts.

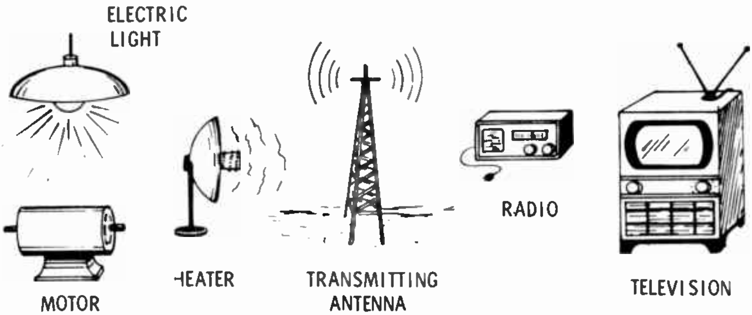
Another source of AC, usually for specialized purposes, is the **oscillator.** The current output of an oscillator is quite small, usually in the milliampere range. Oscillators are used primarily as signal sources in electronic equipment.

ALTERNATING-CURRENT APPLICATIONS

Large amounts of alternating current are used in homes for illumination, heating, cooking, and the operation of appliances. In industry, alternating current is used to operate motors and for many other applications.

Most of the alternating current used in homes and industry is produced by generators in large power plants. In most cases these generators are driven by turbines powered by either steam or falling water.

AC IS USED TO POWER MANY FAMILIAR DEVICES



Q1. The electricity usually used in homes is not DC current but __ current.

Q2. The electricity used in homes is produced by generators in power plants. Power plants are one important ______ of AC.

Q3. Name the most common kind of current used for lighting.

Q4. It is difficult and expensive to transmit DC current over long distances, or to raise or lower DC voltage. State two advantages of alternating current.

Q5. Alternating current is used in many applications in homes and in industry. Two sources of power used to generate this AC are _____ and ____________.

Your Answers Should Be:

A1. The electricity usually used in homes is not DC current but AC current.

A2. The electricity used in homes is produced by generators in power plants. Power plants are one important **source** of AC.

A3. The most common kind of current used for lighting is **AC.**

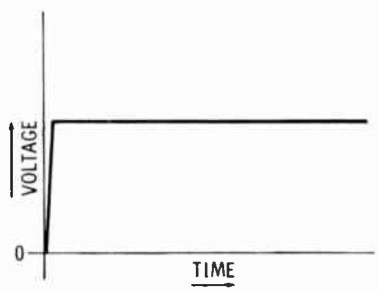
A4. Two advantages of alternating current are: **It is less expensive and easier to transmit over long distances, and it is easier to obtain and keep a constant voltage level.**

A5. Alternating current is used in many applications in homes and industry. Two sources of power used to generate this AC are **steam and falling water.**

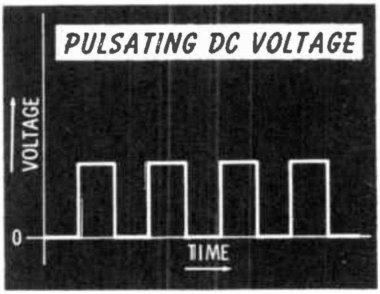
WAVEFORMS

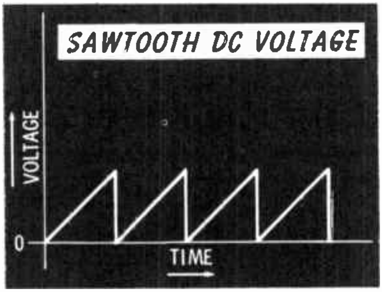
Waveforms are pictures showing how currents and voltages change over a period of time. The value of voltage or current is usually represented in the vertical direction, while time is represented in the horizontal direction. For example, the illustration below shows that most DC waveforms are straight lines.

DC WAVEFORMS ARE USUALLY STRAIGHT LINES



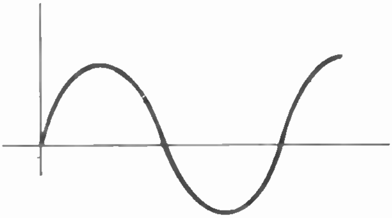
Pulsating DC voltages may have various shapes, but the two most common types are shown here.



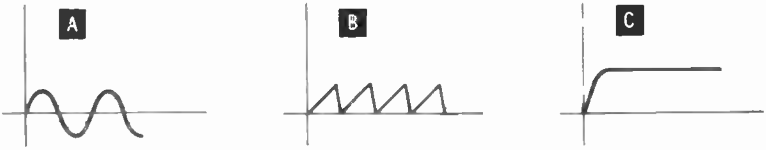


By far the most common AC waveform is the **sine wave.** In fact, the sine wave is so widely used that when we think of AC, we automatically think of sine waves.

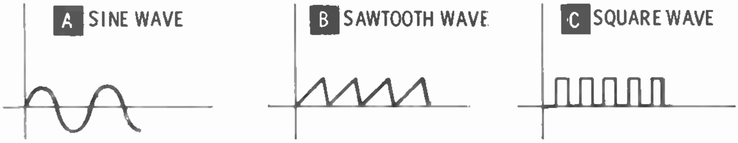
HOUSEHOLD AC IS A SINE WAVE



Q6. A waveform is a picture of how currents or voltages change over a period of time. DC waveforms usually look like which of the following?



Q7. AC currents and voltages usually change regularly in a smoothly curved form. Which of the following is the usual AC waveform?



Q8. The most common DC waveform is a ___________. The most common AC waveform is a ________.

Your Answers Should Be:

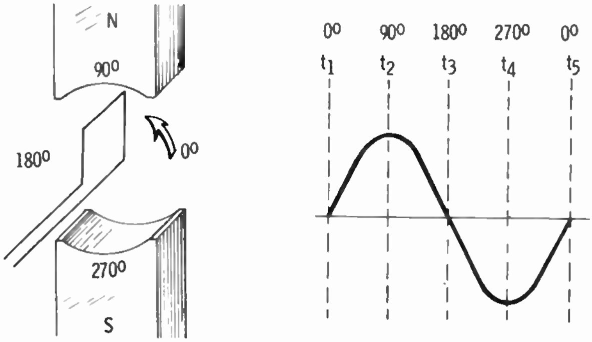
A6. The usual DC waveform is **(c)**, a straight line.

A7. The usual AC waveform is **(a)**, a sine wave.

A8. The most common DC waveform is a **straight line.** The most common AC waveform is a **sine wave.**

GENERATION OF A SINE WAVE

A sine wave is the most common AC waveform. It is also the simplest. You can visualize the way it is generated by looking at this illustration.



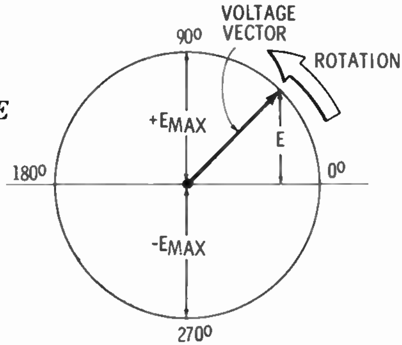
A ROTATING COIL CAN CREATE A SINE WAVE

As the coil cuts the lines of force between the magnetic poles, a voltage is produced that will cause current to flow if the coil is connected to a complete circuit. As the coil rotates at a constant speed, it cuts more and more lines of force in the magnetic field, and the voltage increases. At 90° it is moving at right angles to the lines of force, so it cuts the maximum number of lines per second. Therefore voltage is maximum.

At 180° (and at 0°) the coil is moving parallel to the lines of force and, therefore, cutting none. Thus, the voltage generated is zero. Beyond 180° the coil is cutting lines of force in the opposite direction, so the generated voltage has the opposite polarity—negative in this case. The output waveform of the generator is a sine wave like the one shown.

Imagine a line like the hand of a clock. This line is called a **voltage vector.** A voltage vector rotates counterclockwise through the full 360° of a circle. The distance measured from the end of the voltage vector to the base line at any time during the rotation of the vector represents the exact value of voltage at that instant. As you can see, the value of voltage is zero at 0° and 180°. At 90° the value of voltage is maximum positive, and at 270° it is maximum negative.

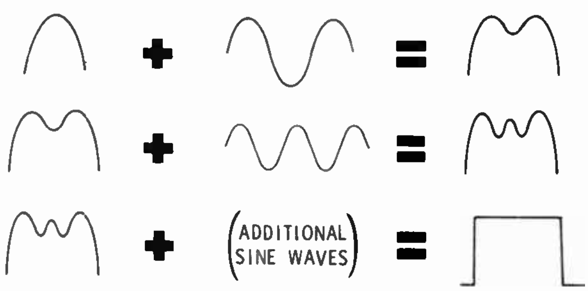
THE ROTATING VOLTAGE VECTOR CREATES A SINE WAVE



One complete cycle of a sine wave (from zero to a positive peak, down to a negative peak, and back to zero) simply represents one complete rotation of the voltage vector.

The simple sine wave is the building block from which all AC waveforms are constructed. Even sawtooth and square waves are really just complicated combinations of simple sine waves.

A SQUARE PULSE IS A COMBINATION OF MANY SINE WAVES



Q9. A sine wave represents the rotation of a line called a voltage ______.

Q10. With the right mixtures of sine waves, can saw-tooth and square waves be made?

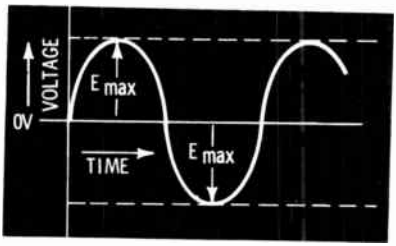
Your Answers Should Be:

A9. A sine wave represents the rotation of a line called a voltage **vector.**

A10. Any kind of AC waveform can be made with the right mixture of sine waves.

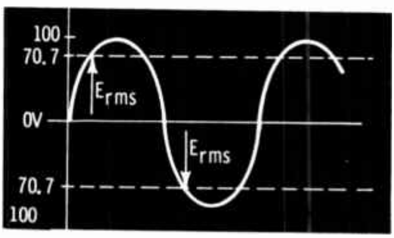
SINE-WAVE MEASUREMENT

In a previous chapter you learned that DC voltage has only one value. This value is measured in volts. In AC, however, the voltage is constantly changing, so no one voltage value exists for more than an instant. Looking at a sine wave you can see that it reaches a certain peak. That value is known as maximum voltage, or peak voltage (E_{max}). Notice that the waveform has the same shape and value both above and below the zero line.



A SINE-WAVE VOLTAGE REACHES A CERTAIN PEAK VALUE

A more practical value of AC voltage and current is the **rms** value (rms stands for root-mean-square). The rms value is the actual "working value" of a voltage or current.

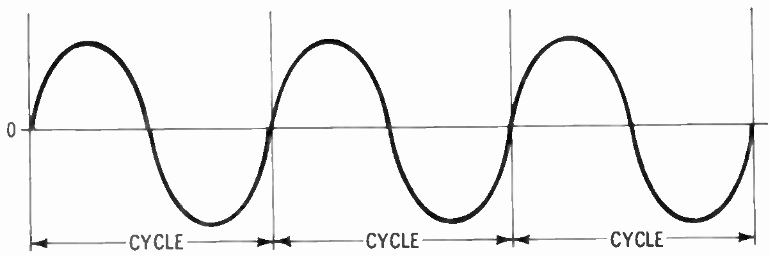


RMS VOLTAGE IS THE WORKING VOLTAGE

The current and voltage value most often used is rms. In fact, the standard household voltage of 120 volts is the rms value. An rms voltage of 120 volts corresponds to a peak voltage of 170 volts. In all sine waves the rms value is equal to 0.707 of the peak value. Conversely, the peak value is equal to 1.41 times the rms value.

You have seen how AC voltage first increases in value to a peak value, then decreases to zero, increases to a negative peak value, and then returns to zero. This sequence is known as a **cycle**. The cycle is normally repeated many times each second and is identical in waveform with the one before it and the one following it.

ALL SINE-WAVE CYCLES ARE NORMALLY IDENTICAL



Q11. Another name for peak voltage is _______ ________.

Q12. Rms is the working value of voltage. Which is less, rms or peak voltage?

Q13. Maximum voltage is also called ____ ________.

Q14. Working voltage is called ___ ________.

Q15. The symbol for maximum voltage is E_{max}. The symbol for rms voltage is _____.

Q16. Rms voltage is 0.707 times peak voltage. If peak voltage is 100, rms voltage is ____.

Q17. Peak voltage is 1.41 times rms voltage. That is, if rms voltage is 100, peak voltage is ____.

Q18. To change rms voltage to peak voltage (which is larger), multiply by ____. To change peak voltage to rms voltage, multiply by ____.

Q19. To give a complete picture of how an AC voltage (or current) changes, a waveform diagram must show at least ___ complete cycle(s).

Your Answers Should Be:

A11. Another name for peak voltage is **maximum voltage.**

A12. Rms is the working value of voltage. **Rms is less than peak voltage.**

A13. Maximum voltage is also called **peak voltage.**

A14. Working voltage is called **rms voltage.**

A15. The symbol for maximum voltage is E_{max}. The symbol for rms voltage is E_{rms}.

A16. Rms voltage is 0.707 times peak voltage. If peak voltage is 100, rms voltage is **70.7.**

A17. Peak voltage is 1.41 times rms voltage. That is, if rms voltage is 100, peak voltage is **141.**

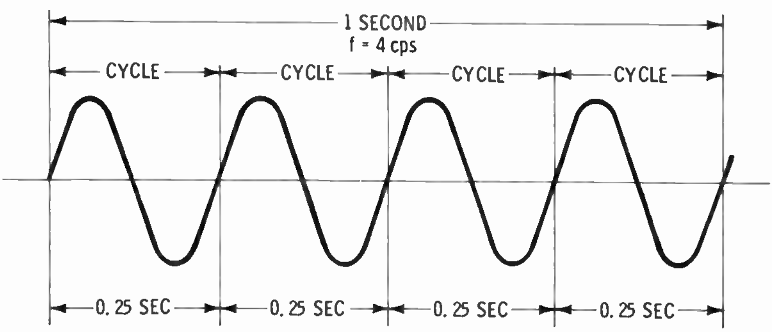
A18. To change rms voltage to peak voltage (which is larger), multiply by **1.41.** To change peak voltage to rms voltage, multiply by **0.707.**

A19. To give a complete picture of how an AC voltage (or current) changes, a waveform diagram must show at least **one** complete cycle.

Frequency

It is sometimes necessary to know how many times a cycle is repeated each second. The number of cycles completed each second by a given AC voltage is called the **frequency.**

FREQUENCY IS THE NUMBER OF CYCLES PER SECOND

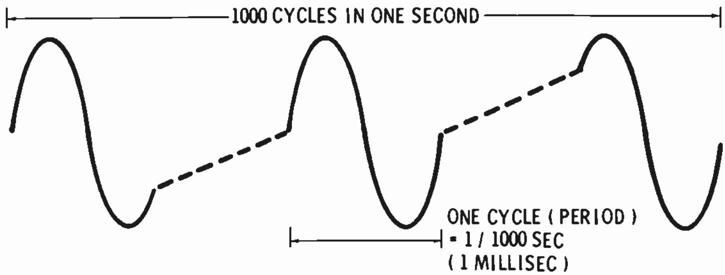


PERIOD IS THE TIME REQUIRED TO COMPLETE ONE CYCLE

Frequency is measured in **cycles per second** (cps). The symbol for frequency is **f**. The most common type of current (household current) has a frequency of 60 cps in most localities.

The time required for one cycle is called a **period.** A period is measured in **seconds, milliseconds,** or **microseconds.** A millisecond is 1/1,000 of a second, and a microsecond is 1/1,000,000 of a second. Since household electricity has a frequency of 60 cps, its period is 1/60 of a second, or 0.0167 second. This time can also be expressed as 16.7 milliseconds.

The period of a sine wave represents the time needed for the voltage vector to make one complete rotation. The frequency of a sine wave depends on how rapidly the voltage vector rotates.



Q20. The __________ of household current is 60 cps.

Q21. Frequency is usually measured in ______ per second.

Q22. If the frequency of a voltage is 60 cps, how would you find its period?

Q23. How many milliseconds are there in a second? How many microseconds are there in a millisecond?

Q24. If the frequency of an AC voltage is 1 million cycles per second, state its period in the most convenient unit.

Q25. In a certain sine wave the rms voltage is 20 volts. What is the peak voltage?

Q26. A sine wave has a peak value of 70.7 volts. What is the effective (rms) voltage?

Q27. If a current has a frequency of 100 cps, what is the period of one cycle? Give two answers—one in seconds and one in milliseconds.

Your Answers Should Be:

A20. The **frequency** of household current is 60 cps.

A21. Frequency is usually measured in **cycles** per second.

A22. **Divide 1 second by 60 cycles.** Thus the period of a 60-cps current is 1/60 of a second, or 0.0167 second.

A23. There are **1,000 milliseconds in a second,** and **1,000 microseconds in a millisecond.**

A24. **1 microsecond.**

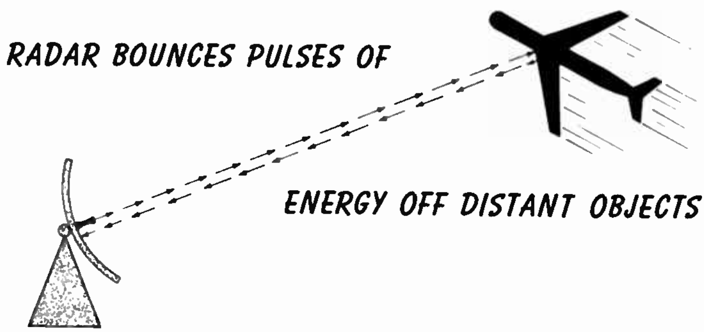
A25. $20V_{rms} \times 1.41 = 28.2V_{max}$

A26. $70.7V_{max} \times 0.707 = 50V_{rms}$

A27. **0.01 second, or 10 milliseconds.**

PULSES

You have been introduced to the definition and methods of pulse generation in DC electricity. In modern electronics, considerable use is made of these pulses. In the following paragraphs you will see two practical applications. Later, you will learn more about pulse behavior in electrical circuits.



A radar set sends a pulse of energy into space. This pulse travels at the speed of light. The pulse hits an object (an airplane, for instance) and is reflected back to the set. By measuring the time it takes for this signal to travel to the object and return, the distance between the set and the object can be calculated.

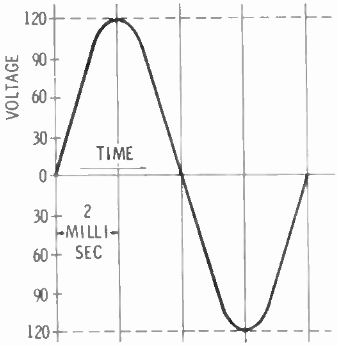
Digital computers are often used in calculating difficult problems. They are the so-called electronic brains. A very simple digital principle is an assembly line; for example, a series of cans moving on a conveyor belt. A light beam to a photoelectric cell is cut every time a can goes by, and the resulting signal is then counted. Computers employ various operations with pulses at very high speeds.

Q28. Look at the sine wave in the figure below and write down the values for:

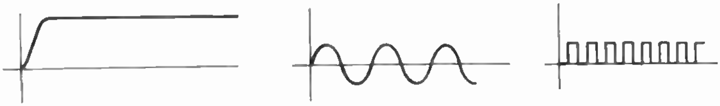
E_{rms} = ____ Period in seconds = ____ ---

E_{max} = ____ Frequency = ____ ---

Period = __ -------------

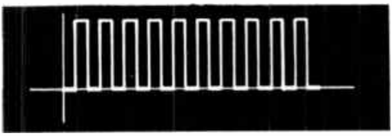


Q29. Which of the following waveforms would you especially expect to find in a digital computer?



A B C

Q30. The signal from a radar set looks like this:



What type of signal does a radar set send out?

Q31. Name one characteristic that a radar set and a digital computer have in common.

Your Answers Should Be:

A28. $E_{rms} = 84.4V$ Period = **0.008 sec**
$E_{max} = 120V$ Frequency = **125 cps**
Period = 8 **milliseconds**

A29. **(c)** is a pulse waveform which would be found in a digital computer. The other two might be found in the operation of some of its circuits.

A30. A **pulse** signal is the type of signal a radar set sends out.

A31. One characteristic that a radar set and a digital computer have in common is that both use **pulse waveforms.**

SAWTOOTH VOLTAGE

Most of the pulses described in the last section are of the regular square-wave type. Another very important type of pulse is the sawtooth waveform.

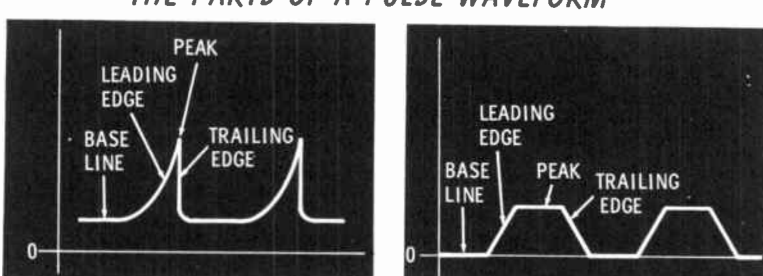
Sawtooth waves are primarily used in accurately timing the rate of sending square-wave pulses. In other words, sawtooth waveforms are used when time measurement is required, and they act as triggering devices.

Some of the most important uses of sawtooth pulses are in television sets and oscilloscopes, and for timing radar pulses.

PULSE MEASUREMENT

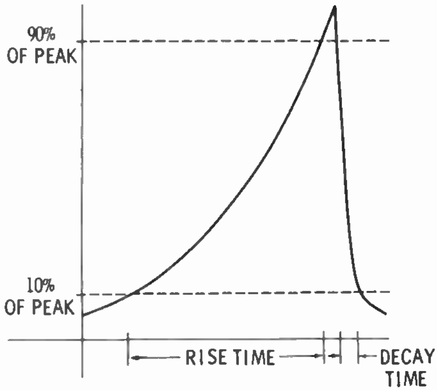
Pulses are usually described in terms of four parts—**base line, leading edge, peak,** and **trailing edge.** It is easiest to understand these parts by looking at them.

THE PARTS OF A PULSE WAVEFORM



It is often necessary to know how long it takes a pulse to rise from the base line to its peak **(rise time)** or to go from its peak value back to the base line **(decay time).** These times are measured between 10% and 90% of peak value.

Rise Time and Decay Time Are Measured Between 10% of Peak and 90% of Peak



Like AC sine waves, pulses have an rms value. Unfortunately, there is no simple formula to find the rms value of a pulse. The rms value of a pulse is its working value.

When pulses are repeated at a regular rate, the number of pulses per second is called the **repetition rate.**

Q32. Radar, television, and oscilloscopes use special pulses that look like the teeth of a saw. This kind of pulse is called a _________ voltage.

Q33. Radar uses both ordinary pulses and _________ _________.

Q34. Name three types of equipment which use saw-tooth voltages.

Q35. Rise time is the time during which the pulse goes from 10% of peak to _____ of peak. During decay the pulse decreases from _____ of peak to _____.

Q36. The time required for a pulse to go from 10% to 90% of peak is called ____ time. The same time along the trailing edge is called _____ time.

Q37. What is the working value of a pulse called?

Q38. The number of times a pulse is repeated per second is called its ___________ ____.

Your Answers Should Be:

A32. Radar, television, and oscilloscopes use special pulses that look like the teeth of a saw. This kind of pulse is called a **sawtooth** voltage.

A33. Radar uses both ordinary pulses and **sawtooth voltages.**

A34. Three types of equipment which use sawtooth voltages are **television, radar, and oscilloscopes.**

A35. Rise time is the time during which the pulse goes from 10% of peak to 90% of peak. During decay the pulse decreases from **90%** of peak to **10%.**

A36. The time required for a pulse to go from 10% of peak to 90% of peak is called **rise** time. The same time along the trailing edge is called **decay** time.

A37. The working value of a pulse is its **rms value.**

A38. The number of times a pulse is repeated per second is called its **repetition rate.**

WHAT YOU HAVE LEARNED

1. AC current changes direction regularly.
2. Most household appliances and electronic devices use AC electricity.
3. AC waveforms are usually sine waves.
4. AC is created by generators and oscillators.
5. The working voltage of a sine wave AC is the rms voltage, which is 0.707 times the peak voltage.
6. A cycle is one complete change from zero to the positive peak value, back through zero to the negative peak, and back to zero. This represents the rotation of a voltage vector around the 360° of a circle.
7. Frequency is the number of cycles generated in a second, and a period is the time it takes to complete one cycle.
8. The four main parts of a pulse waveform are the leading edge, the peak, the trailing edge, and the base line.

8

Calculating Resistance

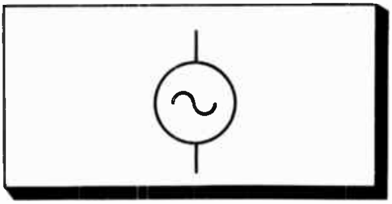
What You Will Learn

In this chapter you will learn how to draw the schematic of a basic AC circuit. You will determine when and how Ohm's law and the power formulas can be used in AC circuits. You will learn how to simplify combinations of resistances in an AC circuit to find the equivalent resistance. You will be able to tell when voltage and current are in phase. You will learn about skin effect and where and when it is found.

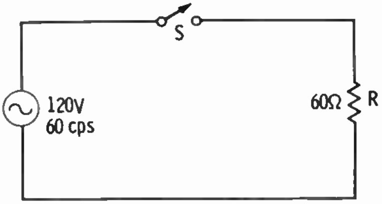
BASIC AC CIRCUIT

The basic AC circuit is very similar to the basic DC circuit. The only difference is that an AC generator is used as a voltage source instead of a battery.

AC-GENERATOR SYMBOL



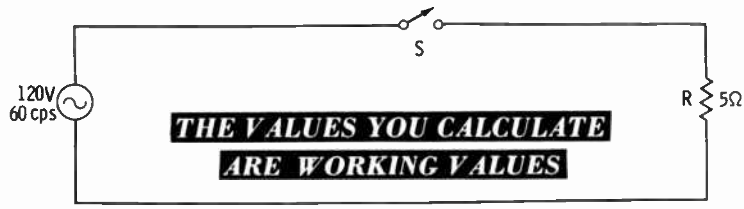
A BASIC AC CIRCUIT



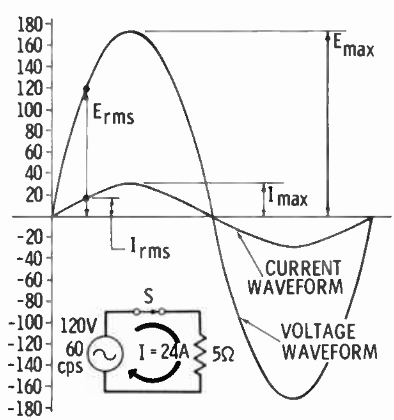
In any AC circuit the voltage shown at the generator is the rms voltage. The frequency shown is in cps (cycles per second), and the resistance is in ohms.

Ohm's law, as you learned it for DC, can also be used when AC is supplied to a resistive circuit. As stated previously, the rms voltage is the working voltage of AC electricity. In a basic AC circuit, all calculations will be made with rms voltage and current values, unless other values are specified. Ohm's law also applies to peak values, but peak values are not generally very useful.

Let us look at a basic AC circuit and see what happens as the switch is closed.



From Ohm's law we find that the current in the above circuit will be $I = \frac{120}{5} = 24$ amperes. But, since this is an AC circuit, we also know that both the 120 volts and the 24 amperes are rms values; that is, they are the working values. Since AC voltage and currents appear as sine waves, the voltage actually varies. The current also varies, but its numerical value is always five times smaller than that of the voltage.



VOLTAGE AND CURRENT IN A BASIC AC CIRCUIT

PHASE

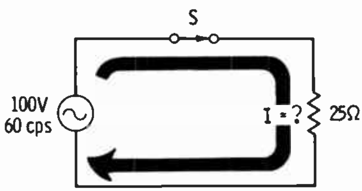
When both the voltage and the current rise and fall together in exactly the same fashion, they are said to be **in phase.** When they do not, they are **out of phase.**

When an AC circuit contains only pure resistance, the voltages and currents will always be **in phase.** When voltages and currents in an AC circuit are in phase, Ohm's law can be applied in the same manner as in DC circuits, provided you use the same kind of values (rms, etc.) for the voltages and currents.

Q1. A basic AC circuit consists of a ---------, ----------, ------, and ---- (----------).

Q2. Draw a basic AC circuit in which the generator has an rms voltage of 12 volts, a frequency of 60 cps, and the load is 10 ohms. Check your circuit against the correct one on the next page.

Q3. Find the current in this AC circuit, using Ohm's law.



Q4. Ohm's law applies to any AC circuit that contains only ----------.

Q5. When using Ohm's law with AC circuits, you will usually use the working value of voltage, which is ----.

Q6. When current and voltage are zero at the same time, maximum at the same time, and vary in the same fashion, they are -- -----.

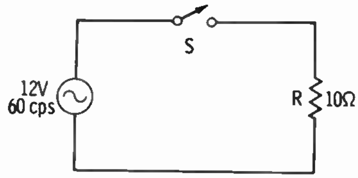
Q7. When voltage and current are in phase, they (have the same maximum value, reach zero at the same time).

Q8. Voltage and current are always in phase in AC circuits containing only ----------.

Your Answers Should Be:

A1. A basic AC circuit consists of a **generator, conductors, switch,** and **load (resistance).**

A2. Your basic AC circuit should look like this:



A3. Ohm's law is: $E = I \times R$, or $I = \frac{E}{R}$

In this case, $I = \frac{100}{25} =$ **4 amperes**

A4. Ohm's law applies to any AC circuit that contains only **resistance.**

A5. When using Ohm's law with AC circuits, you will usually use the working value of voltage, which is E_{rms}.

A6. When current and voltage are zero at the same time, maximum at the same time, and vary in the same fashion, they are **in phase.**

A7. When voltage and current are in phase, they **reach zero at the same time.**

A8. Voltage and current are always in phase in AC circuits containing only **resistance.**

POWER IN A BASIC AC CIRCUIT

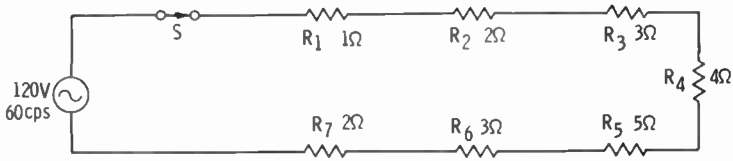
As you learned in the study of DC circuits, power is the work done by the current, and it is measured in watts. In DC circuits you have seen how power equals the voltage multiplied by the current. You also learned that the power in a resistance equals the value of the resistance multiplied by the current squared.

Voltage and current must be in phase if they are used together in an AC formula. For example, $E = I \times R$ is true only when voltage and current are in phase.

It is therefore a good idea when working with AC circuits to use only $P = I^2R$ for finding power. When using this formula, it makes no difference whether voltage and current are in phase or out of phase.

AC CIRCUITS WITH RESISTANCES IN SERIES

This is an AC circuit with resistances in series.



AN AC CIRCUIT WITH RESISTANCES IN SERIES

To find the current in this circuit, you must find the equivalent resistance of the resistors in series (the one resistance that can replace all the other resistances).

This AC series circuit can be treated in the same way as a DC series circuit. Since the resistors are all in series, the equivalent resistance is the sum of all the resistances.

$$R_{eq} = R_1 + R_2 + R_3 + R_4 + R_5 + R_6 + R_7$$

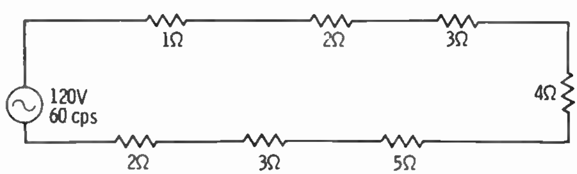
Q9. Which power formula can only be used when voltage and current are in phase?

Q10. Are voltage and current in phase in the basic AC circuit above? Explain how you know.

Q11. Which formula or formulas can be used to find power in the basic AC circuit above?

Q12. Write the power formula that can be used when voltage and current in an AC current are out of phase.

Q13. What is the equivalent resistance in the following circuit?



Your Answers Should Be:

A9. $P = I \times E$ can only be used when voltage and current are in phase.

A10. Yes, because voltage and current are always in phase in a circuit that contains only resistance.

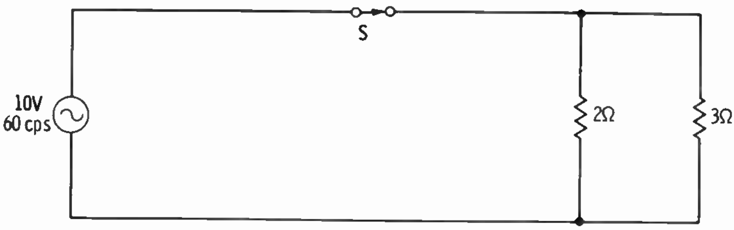
A11. Either $P = I \times E$ or $P = I^2R$.

A12. $P = I^2R$.

A13. 20 ohms.

AC CIRCUITS WITH RESISTANCES IN PARALLEL

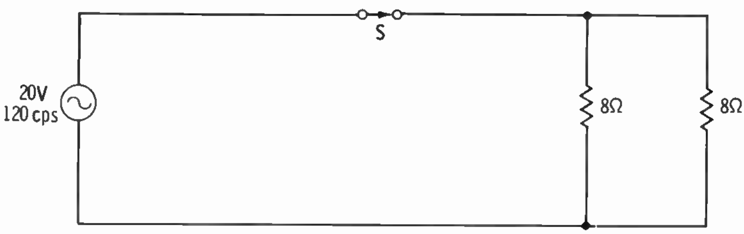
This is an AC circuit with resistances in parallel.



The formula for the equivalent resistance of two resistors in parallel is:

$$R_{eq} = \frac{R_1 \times R_2}{R_1 + R_2} = \frac{2 \times 3}{2 + 3} = \frac{6}{5} = 1.2 \text{ ohms}$$

Here is another AC circuit with two **equal** resistances in parallel.



The formula for the equivalent resistance of two **equal** resistors in parallel is:

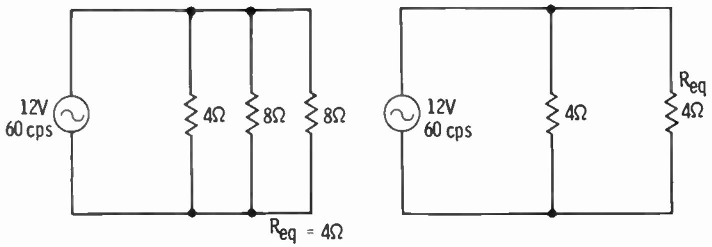
$$R_{eq} = \frac{R_1}{2} = \frac{8}{2} = 4 \text{ ohms}$$

Did you notice these three important facts about parallel resistances?

1. The equivalent resistance is always smaller than either of the parallel resistances.
2. When two parallel resistances are equal, the equivalent resistance is one half as large as either resistance.
3. Frequency does not enter into the calculations.

Here is an example of how to simplify a combination of parallel resistances.

Combinations of Resistances Can Be Simplified One Step at a Time



Q14. Can Ohm's law be used to find the current in the circuits on the opposite page?

Q15. What is the current through the generator in the first circuit on the opposite page?

Q16. What rule helps you check the calculation of the equivalent resistance of parallel resistors?

Q17. Two equal resistors in parallel have a total resistance of one half the value of one resistor. If you have a 1-ohm resistor and a 2-ohm resistor in parallel, does this rule apply?

Q18. What is the total resistance of two 7-ohm resistors in parallel?

Q19. An electric heater, an electric iron, and a lamp are fed from the same outlet (connected in parallel). Find the equivalent resistance if you know that the individual resistances are 4 ohms, 150 ohms, and 30 ohms respectively. Begin by drawing a schematic diagram of the circuit.

Your Answers Should Be:

A14. Yes, Ohm's law can be used.

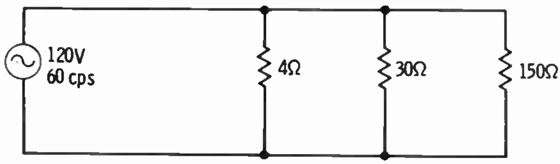
A15. $I = \frac{E}{R} = \frac{10}{1.2} = 8.3$ **amperes**

A16. When you calculate the equivalent resistance of a group of parallel resistors, the result must be smaller than the smallest single parallel resistor.

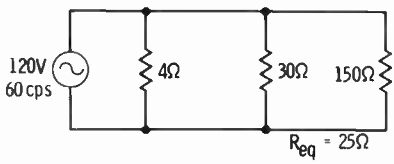
A17. No, the rule does not apply to resistances that are not equal.

A18. **3.5 ohms.**

A19. Your schematic should look like this:



You can simplify this as follows:

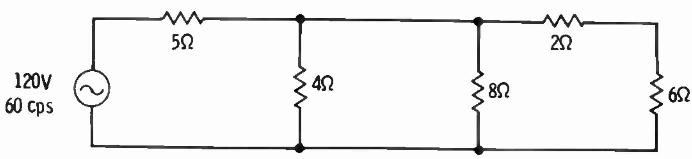


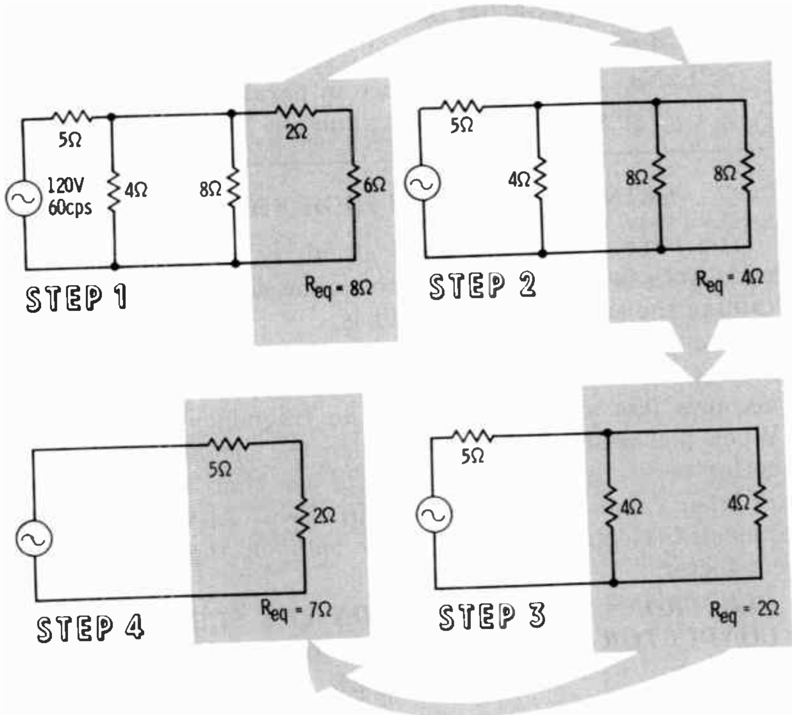
$$R_{eq} = \frac{4 \times 25}{4 + 25} = \frac{100}{29} = \mathbf{3.44\ ohms}$$

AC CIRCUITS WITH RESISTANCES IN SERIES AND PARALLEL

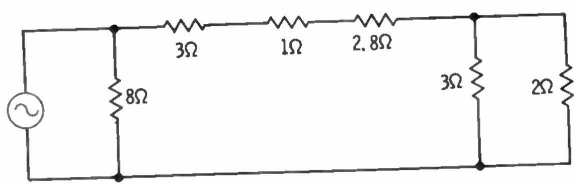
Now that you have learned how to handle resistors in series and pairs of resistors in parallel, it is easy to solve combinations by breaking them down into simple groups of resistors in series or pairs of resistors in parallel.

Here is an example of how to break down a combination of series and parallel resistances.

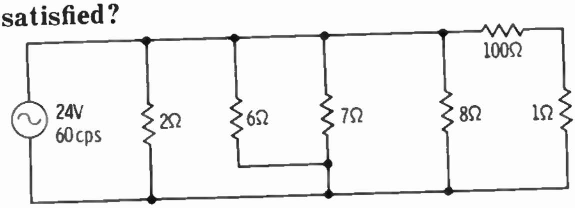




Q20. **Find the equivalent resistance of the following circuit.**



Q21. **If you calculated the equivalent resistance of the following circuit and got 6 ohms, would you be satisfied?**



Your Answers Should Be:

A20. 4 ohms.

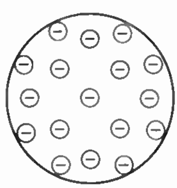
A21. No. A 2-ohm resistance in parallel with the rest of the circuit means R_{eq} must be less than 2 ohms.

SKIN EFFECT WITH HIGH FREQUENCY

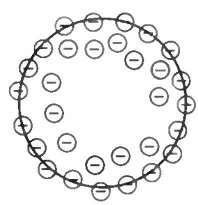
You have seen how an AC circuit containing only pure resistance is treated exactly the same as a DC circuit containing the same resistance values.

Usually a resistor represents the same value of resistance in both AC and DC circuits. You will find, however, that this becomes less and less true as the frequency is increased. When you deal with frequencies in the megacycle (million cycles per second) range, you will see that a resistor has a higher value. This is due to **skin effect.** At very high frequencies, electrons tend to flow only on the "skin" of a conductor.

ELECTRONS FLOW MAINLY ON THE SURFACE OF A CONDUCTOR AT HIGH FREQUENCIES—RESISTANCE IS HIGHER



60 cps



1,000,000 cps

Q22. The effect in the figure above is called the ____ ______.

Q23. When electrons flow only on the surface of a conductor, it is as though the conductor were smaller. Resistance is (higher, lower).

Q24. If a resistor has a value of 10 ohms when measured with an ohmmeter, what would you expect its resistance to be in a circuit using 2-megacycle AC?

Q25. At high frequencies of AC current, resistances become ______ because of ____ effect.

WHAT YOU HAVE LEARNED

1. You have learned how to draw the schematic of a basic AC circuit.
2. Calculations with Ohm's law, or the power formulas, use rms values of voltage and current.
3. Voltage and current sine waves are in phase when they vary in the same way at the same time.
4. Voltage and current are always in phase in an AC circuit that contains only resistance.
5. Voltage and current must be in phase when they are used together in a single formula.
6. The equivalent resistance of combinations of series and parallel resistors can be found in the same way for AC circuits as for DC circuits.
7. At very high frequencies the resistance of a conductor increases because the electrons tend to flow mainly on the surface of the conductor. This is called skin effect.

Your Answers Should Be:

A22. This effect is called the **skin effect.**

A23. Resistance is **higher.**

A24. If a resistor has a value of 10 ohms when measured with an ohmmeter, **its resistance in a circuit using 2-megacycle AC current should be more than 10 ohms.**

A25. At high frequencies of AC current, resistances become **higher** due to the **skin** effect.

9

Inductance

What You Will Learn

Inductance is one of the most important properties in electricity and electronics. Relays, transformers, coils, and many other devices all depend on inductance for their operation. When you have finished this chapter, you will know what factors influence inductance and how the inductance of a circuit affects AC voltage and current.

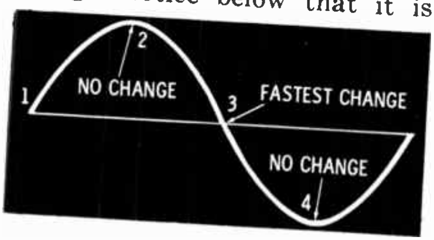
WHAT IS INDUCTANCE?

When current begins to flow in a conductor, a magnetic field builds up around it. As the magnetic field builds up, its expanding lines of force cut the conductor and generate a voltage that opposes the increasing current.

This opposing voltage, or **counter emf**, is greater when the current is changing more rapidly. In fact, the counter emf is proportional to the **rate of change** of the current, but it always opposes it. When current is decreasing, the counter emf attempts to keep the current flowing.

When a sine-wave current flows in an inductor (coil), the current is continually changing. Notice below that it is

CURRENT AT THE PEAKS IS STEADY FOR AN INSTANT



changing faster at the points where the sine wave crosses the zero line. It is not changing at all at the **instant** of each positive and negative peak.

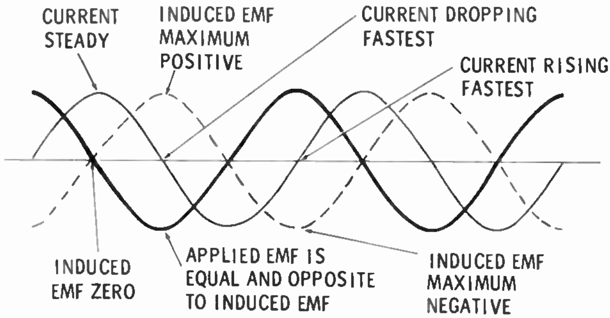
The voltage in the inductor follows the rule just given. At point 1 in the illustration, the current is rising at its fastest rate. Therefore the counter voltage, trying to keep the current from increasing, is at its negative peak. At point 2 on the wave, the current is not changing at all; at this point the counter voltage is zero. At point 3 the current is decreasing at its maximum rate, so the counter voltage, in trying to keep the current from decreasing, reaches its positive peak. At point 4 the current is at its negative peak and is not changing at all—counter voltage is zero.

We can follow the current sine wave point by point and, at every instant, calculate its rate of change and the resulting counter emf. The resulting voltage waveform is another sine wave, but this one is 90° out of phase with the current. This is the waveform of the **counter emf.**

In order to keep the current flowing, an external voltage that is exactly equal but opposite to the counter emf must be applied. This is the applied emf, and it is 90° ahead of the current.

We say that **in an inductance, the current sine wave lags the applied voltage wave by 90°.**

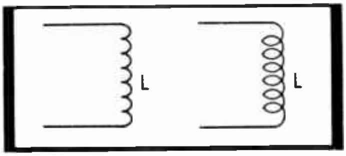
CURRENT LAGS THE APPLIED VOLTAGE BY 90°



In a DC circuit, inductance has an effect only when the direct current first starts to flow, and then again when you try to stop it. But in AC circuits the voltage is constantly changing and inductance constantly acts to retard the change in current.

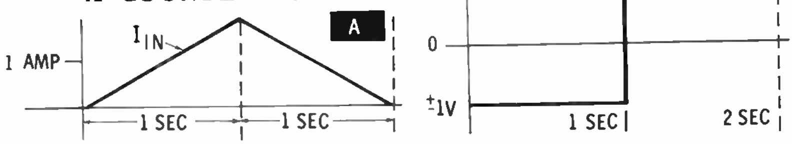
All conductors have some inductance. Straight wires have very small amounts, while coils have much more. In formulas, inductance is represented by the letter L. A coil or inductor is indicated on diagrams by one of the following.

SYMBOLS FOR INDUCTANCE



The unit of inductance is the **henry**. A coil is said to have an inductance of 1 henry if the current through it, changing at a rate of 1 ampere per second, encounters an opposition, or counter voltage, of 1 volt. This means that the **opposition to current change** shows up as a voltage opposing the applied voltage.

CHANGING CURRENT PRODUCES A COUNTER EMF



In part A above, with the current **increasing** at 1 ampere per second, a counter voltage of 1 volt appears and opposes the increase in current. In part B, as the current is **decreasing**, the inductive counter voltage of 1 volt is in a direction that tends to keep the current flowing. One henry is a very large value of inductance. Therefore, inductances in millihenrys (mh) and in microhenrys (μh) are more often found.

Q1. When current is trying to increase, inductance (makes it increase more quickly, slows down the increase).

Q2. Inductance opposes a change in ________.

Q3. Which kind of current will be most affected by inductance, AC or DC?

Q4. The usual symbol for inductance in formulas is the letter ____.

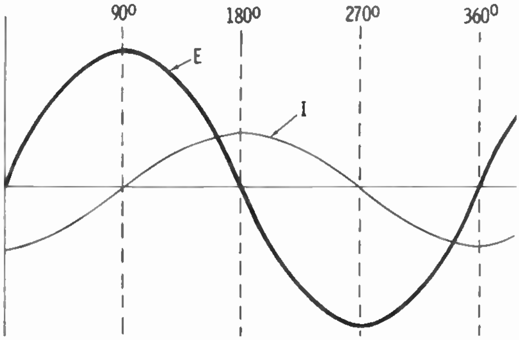
Q5. What units are used to measure the inductance of a coil?

> **Your Answers Should Be:**
>
> A1. When current is trying to increase, inductance **slows down the increase.**
>
> A2. Inductance opposes a change in **current.**
>
> A3. **AC** is most affected by inductance.
>
> A4. The usual symbol for inductance in formulas is L.
>
> A5. **Henrys, millihenrys,** and **microhenrys** are units used to measure inductance.

HOW DOES INDUCTANCE AFFECT AC?

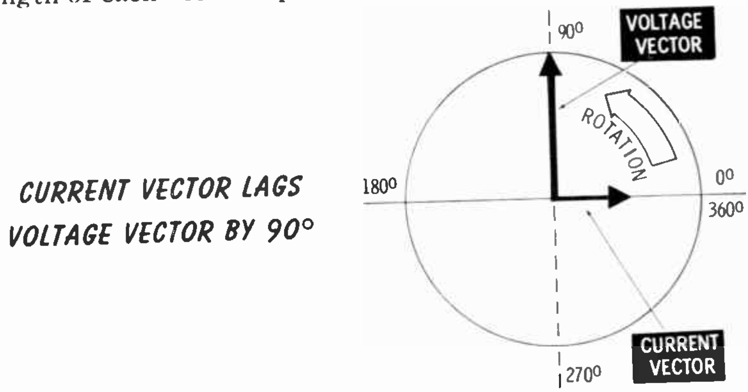
If a **sine**-wave voltage is applied across a resistor, the current through the resistor is also a sine wave. At every instant of the voltage wave, the current is determined by Ohm's law and equals E/R. The two sine waves, voltage and current, are exactly in step; they are said to be **in phase.**

Inductance **resists** a **change in current.** But the voltage of a sine wave is always changing, and therefore is always trying to change the current through an inductance. This means that inductance acts at all times in an AC circuit and **retards** the change in the current. This results in a **current** wave that is delayed after the applied voltage wave. The current wave **lags** the voltage wave by exactly 90°, or one quarter of the period of the sine wave. The two waves are **out of phase** by 90°.

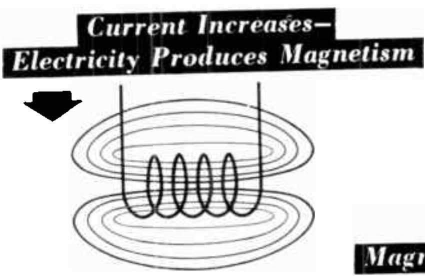


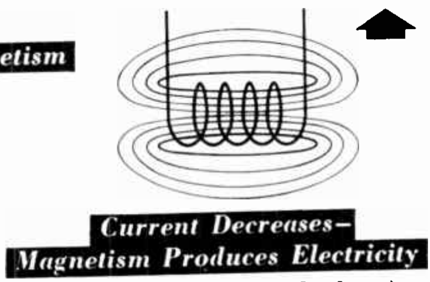
CURRENT LAGS THE VOLTAGE BY 90° IN AN INDUCTANCE

In a circuit containing only resistance, the voltage and current are in phase, and the voltage and current vectors have the same position. In a circuit having only inductance, the current vector is 90° behind the voltage vector. The length of each vector represents its magnitude.



Inductance, unlike resistance, **consumes no power.** When the current in the circuit is **increasing,** inductance **takes energy out of the circuit.** It converts this energy into a magnetic field. When the current in the circuit is **decreasing,** however, this magnetic field collapses, and **all the energy returns to the circuit.** Energy is borrowed, but none is used.





Q6. The current sine wave in an inductance (leads, lags) the voltage sine wave.

Q7. Current lags voltage by one-quarter cycle, or ____.

Q8. In an inductor, applied _______ leads _______ by 90°.

Q9. How much power is used in a pure inductive circuit?

Q10. An inductor stores electrical energy by producing a ________ _____.

Your Answers Should Be:

A6. The current sine wave in an inductor **lags** the voltage sine wave.

A7. Current lags voltage by one-quarter cycle, or **90°**.

A8. In an inductor, **voltage** leads **current** by 90°.

A9. **No power** is consumed in a circuit containing only inductance.

A10. An inductor stores electrical energy by producing a **magnetic field.**

FACTORS INFLUENCING INDUCTANCE VALUE

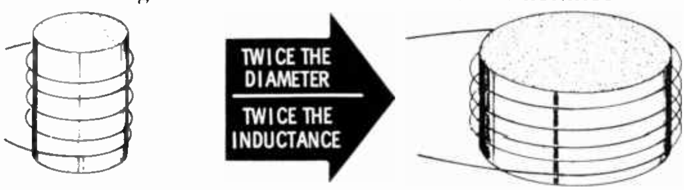
You have learned that inductance is a property of a circuit or of a component, and that a coil is the component with the most inductance.

Several factors determine the amount of inductance in a coil. One of the most important factors is the number of turns in the coil. The inductance of a coil is proportional to the **square of the number of its turns.** This means that if a certain coil has twice as many turns as another, it will have four times as much inductance; three times as many turns, it will have nine times as much inductance, etc.

— *Increasing Turns Increases Inductance* —

The diameter also affects the inductance of a coil. **The larger the diameter, the more inductance it will have.**

— *Increasing Coil Diameter Increases Inductance* —



Placing an iron core in the center of a coil is another way to increase inductance. **A coil wound on an iron rod has much more inductance** than an air-core coil. This is because an iron core can sustain a much greater magnetic field than air and, as you have learned, the inductance of a coil is related to the amount of magnetism it can produce.

CHANGING CORE MATERIAL CHANGES INDUCTANCE

There are formulas for calculating the inductance of various types of coils. There are also tables for simple, one-layer coils. Using these formulas, you can design a coil to have any desired value of inductance, or calculate the value of an unknown inductance.

Q11. The diameter of a coil and the kind of core it has are two factors that influence the amount of inductance a coil has. Name another important factor.

Q12. A coil with a large number of turns generally has (more, less) inductance than a coil with fewer turns.

Q13. Which has a greater inductance, an iron-core coil or an air-core coil? Why?

Q14. Which of the coils below do you think will have the greater inductance?

Q15. Name three factors that influence the inductance of a coil.

Your Answers Should Be:

A11. Another important factor influencing the inductance of a coil is **the number of turns it has.**

A12. A coil having a large number of turns generally has **more** inductance than a coil with fewer turns.

A13. An **iron-core coil** has a greater inductance **because the iron-core sustains a greater magnetic field** and **the coil can store more electrical energy in the magnetic field.**

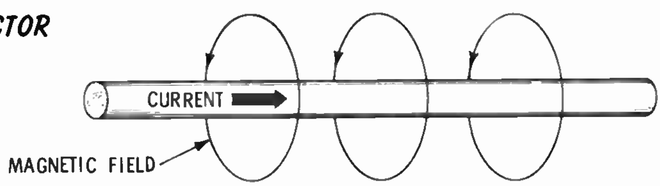
A14. **Coil B** probably has more inductance than coil A because it has an iron core.

A15. Three factors that influence the inductance of a coil are: **diameter, number of turns,** and **type of core.**

INDUCTANCE AND INDUCTION

Inductance is closely related to **induction.** Inductance is a circuit property. Induction, on the other hand, is the interaction between electric current and a magnetic field. Whenever a current flows in a conductor, its sets up a magnetic field around the conductor. This is how solenoids and electromagnets work.

CURRENT PRODUCES A MAGNETIC FIELD AROUND A CONDUCTOR

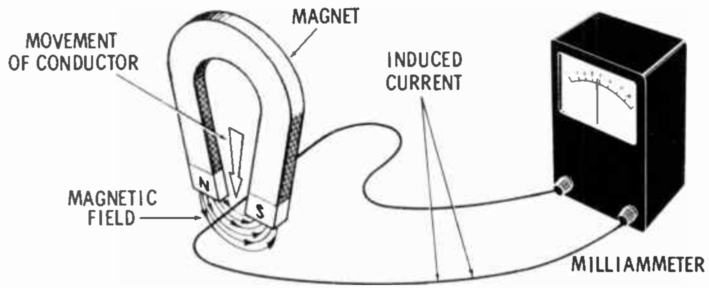


A good way to remember the direction of the induced magnetic field is the **left-hand rule.** With your left hand grasping the wire and your thumb pointing in the direction of the current, the curved fingers of your hand indicate the direction of the field. The direction of the magnetic field is always the direction toward the north-seeking pole of the magnet.

A coil with a direct current flowing through it in a particular direction acts as a magnet with a fixed polarity, just as if it were a bar magnet. When the current is AC instead of DC, the polarity of the magnetic field alternates in the same manner as the current.

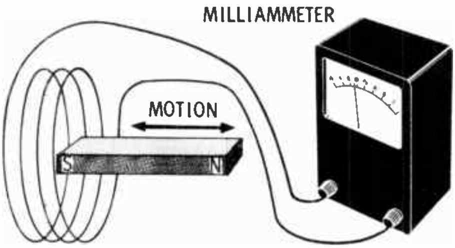
Conversely, if an electric conductor is moved through a magnetic field, an electric current is **induced** in the conductor. This is how generators work.

A Magnetic Field Induces Current in a Moving Conductor



If a coil is connected to an ammeter and a bar magnet is moved through the coil, the ammeter will show that an electric current flows. This current is **induced** by the magnetic field only. If you move the bar magnet back and forth through the coil continuously, the induced current will be AC. Use the lowest amperage range on the multimeter for this experiment.

A Magnet Moving in a Coil Produces an AC Current



Q16. An electric current flow produces a ________ _____.

Q17. Moving a conductor in a magnetic field ________ a current in the conductor.

Q18. Inductance is opposition to a(an) ______ __ _______.

Your Answers Should Be:

A16. An electric current flow produces a **magnetic field.**

A17. Moving a conductor in a magnetic field **induces** a current in the conductor.

A18. Inductance is opposition to a **change in current.**

INDUCTIVE REACTANCE

When current in an inductance is changing, the inductance opposes the change by generating a counter emf. In a DC circuit, this effect is present only at the time a switch is closed or opened, and it dies away in a few moments.

In AC circuits, however, current is constantly changing, so inductance is constantly acting to oppose it. The faster the current changes, the more opposition there will be. Obviously, the higher the frequency of a sine wave, the faster the current will change. Inductance, therefore, tends to offer more opposition at high frequencies than at low ones.

In an AC circuit this reaction to a changing current is present in addition to ordinary resistance. This opposition to the flow of an AC current through an inductance is called **inductive reactance.** The greater the inductance of the circuit, the greater is the inductive reactance. Inductive reactance does **not** oppose the flow of DC current (zero frequency).

The more rapidly the current is changing, the greater the opposition, or inductive reactance, will be. Since the rate of change in the current depends on the frequency of the sine wave, the higher the frequency, the greater the opposition to current flow will be. The symbol for inductive reactance is $\mathbf{X_L}$.

The formula for inductive reactance is:

$$X_L = 2\pi fL \quad (\pi = 3.14)$$

Inductive reactance (X_L) is measured in **ohms,** as resistance is (but don't confuse the two). In the above formula, L is the inductance in henrys, and f is the frequency in cycles per second.

From the formula, it is apparent that X_L increases with frequency. When the frequency is doubled, X_L doubles. Why is this? Because when the frequency is doubled, the current is reversing twice as fast, and the opposition to this change (caused by the inductance) also doubles. Notice, too, that if the frequency in the formula is equal to zero, inductive reactance disappears completely. A DC current has zero frequency and is not affected by inductance.

Inductance is very useful because every inductive circuit is **frequency-sensitive.** This principle is used in filters, antennas, and many other applications. It means that an inductive circuit passes direct current and low-frequency alternating current, but it impedes the higher frequencies.

Q19. The opposition of a coil to the flow of AC current is called ---------- ----------.

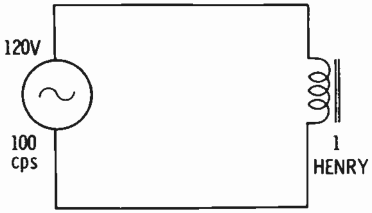
Q20. In what kind of units is X_L measured?

Q21. Inductive reactance depends on the value of inductance and ----------.

Q22. How is the inductance of a circuit affected by the input signal?

Q23. How is the inductive reactance of a circuit affected by the input signal?

Q24. What is the inductive reactance of the coil in the following circuit?



Q25. How much current is flowing in the above circuit?

Q26. If the frequency of the AC source in the above circuit is doubled, the inductive reactance will (decrease, increase, remain the same).

Q27. If an ohmmeter is used to measure a coil, the reading will indicate (DC resistance, inductive reactance).

Your Answers Should Be:

A19. The opposition of a coil to the flow of AC current is called **inductive reactance.**

A20. X_L is measured in **ohms.**

A21. Inductive reactance depends on the value of inductance and **frequency.**

A22. Inductance is **not affected** by the input signal.

A23. Inductive reactance **increases as the frequency of the input signal increases.**

A24.
$$
\begin{aligned}
X_L &= 2\pi fL \\
&= 2 \times 3.14 \times 100 \times 1 \\
&= \mathbf{628\ ohms}
\end{aligned}
$$

A25. $I = \frac{E}{X_L} = \frac{120}{628} = \mathbf{0.191\ ampere}$

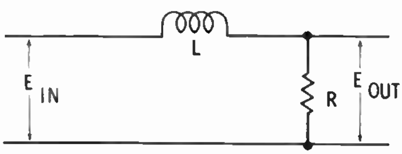
A26. If the frequency of the AC source is doubled, the inductive reactance will **increase.**

A27. If an ohmmeter is used to measure a coil, the reading will indicate **DC resistance.**

APPLICATION OF INDUCTANCE

Because inductive reactance depends on frequency, inductance is often used in **filters.** Filters are special circuits which have the property of allowing certain frequencies to pass while blocking others. There are, for example, **low-pass filters** which pass high frequencies and block low ones, and **band-pass filters** which pass only a certain band of frequencies.

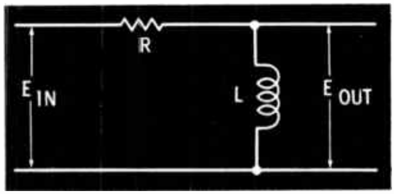
Here are two simple filters that depend only on inductance. The first one, which has an inductance in series, blocks high frequencies. It is a low-pass filter.



A LOW-PASS FILTER

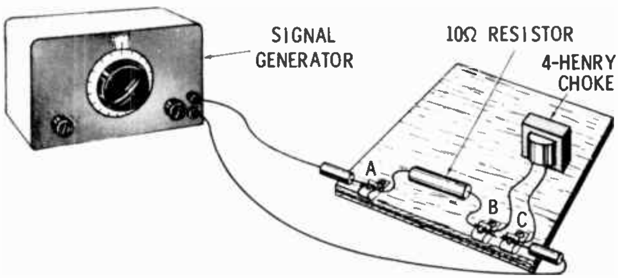
The second circuit has an inductance in parallel, or across it. This inductance will **bypass** the low frequencies. As the frequency increases, voltage across the inductor increases. Therefore, there is more output voltage at high frequencies, and the circuit acts as a **high-pass** filter.

A HIGH-PASS FILTER



If you have a signal generator, you can build a simple filter circuit like the one shown below and see how it reacts to different frequencies.

FILTERS USE INDUCTANCE



Voltages can be measured between points A and C, A and B, and B and C. Pick about 12 equally spaced frequencies. Using each as an input, measure and record both the input and output voltages.

Q28. A filter that allows only high frequencies to pass is called a ____ ____ ______.

Q29. A ____ ____ ______ is designed to allow only a certain band of frequencies to pass.

Q30. Draw a schematic of a simple low-pass filter.

Q31. Between which points would you measure the input voltage to the filter circuit in the second illustration above?

Q32. Between which points would you measure the low-pass output of the filter?

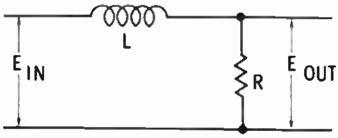
Q33. Between which points would you measure the high-pass output of the filter?

Your Answers Should Be:

A28. A filter that allows only high frequencies to pass is called a **high-pass filter.**

A29. A **band-pass filter** is designed to allow only a certain band of frequencies to pass.

A30. Your schematic should look like this:



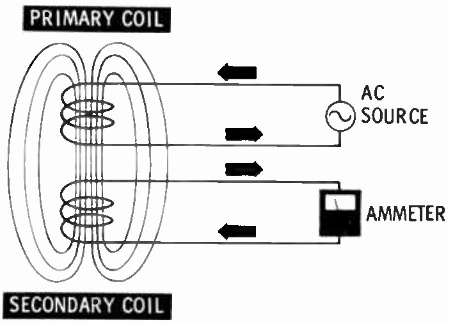
A31. Measure input voltage **between points A and C.**

A32. Measure the low-pass output **between A and B.**

A33. Measure the high-pass output **between B and C.**

TRANSFORMERS

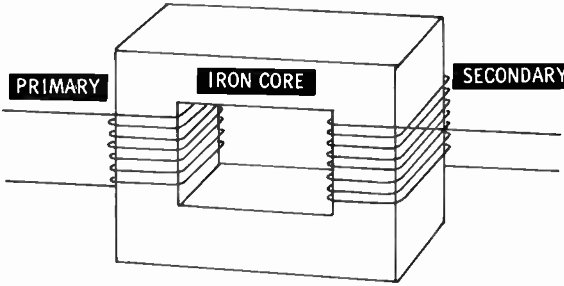
You are now aware that a moving magnetic field generates an electric current in a conductor, and also that current flowing in a conductor produces a magnetic field. These two effects can be combined in a circuit such as this.



THE TRANSFORMER PRINCIPLE

One coil has a current flowing in it. It is an AC current that sets up an alternating magnetic field in and near the coil. If another coil is placed next to it, there will be a second alternating current induced in the second coil. The first coil is the **primary**, the second coil is the **secondary**, and the combination of the two is a **transformer.** Most commercial transformers appear as shown on the next page.

MOST TRANSFORMERS HAVE AN IRON CORE



An iron core is used to increase the magnetic flux and to channel it to the secondary coil. The primary coil sets up a magnetic field in the core, and the secondary coil converts the field back to electric current. Power is actually transferred from the primary to the secondary. A lamp or other load placed in the secondary circuit will operate.

One of the main advantages of using transformers is that they can **change voltage.** They do this because the voltage induced in the secondary depends on the number of turns in the secondary as compared to the number of turns in the primary coil. If the turns in the secondary are doubled, the induced voltage will also be doubled (but no more power, because the current will be halved). The **voltage ratio** of the secondary to primary is the same as the **turns ratio.** So, if the primary of a transformer has 1,000 turns and the secondary has 100 turns, it is a **step-down transformer** because it steps down the primary voltage by 10 (1,000/100). If the connections are reversed, it becomes a **step-up transformer** with the same ratio.

Q34. In the primary coil of a transformer, electric current produces a ________ _____.

Q35. In the secondary coil of a transformer, a moving magnetic field produces a(an) ________ ________.

Q36. How does a transformer work?

Q37. Will a transformer work with DC electricity?

Q38. If a transformer has 100 turns in one coil and 200 turns in the other, how could you get a 240-volt output using ordinary household current?

Your Answers Should Be:

A34. In the primary coil of a transformer, electric current produces a **magnetic field.**

A35. In the secondary coil of a transformer, a moving magnetic field produces an **electric current.**

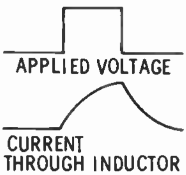
A36. An AC current produces a changing magnetic field in the primary coil of a transformer. This changing field produces an AC electric current in the secondary coil of the transformer.

A37. No. A transformer will work only with AC.

A38. **Apply the 120V household current to the 100-turn coil** and you will get 240V from the 200-turn coil.

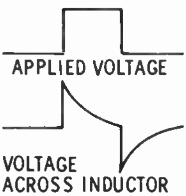
PULSE RESPONSE

When pulses are applied to a circuit containing an inductor, the inductor opposes a change of current in its usual way. The effect of this is to distort the waveform of the current through the inductor by rounding off the corners on the leading edge.



An Inductor Rounds Off a Current Waveform

The voltage across the inductor is affected in just the opposite way. An increase in current tends to cause a sharp increase of voltage in the **positive** direction. A decrease in current causes an increase of voltage in the **negative** direction.



An Inductor Exaggerates a Voltage Waveform

Inductive circuits are used in practically all electronic equipment. The frequency-sensitive characteristics of an inductor find practical uses in a TV receiver, for example. High video frequencies are not amplified as much as low video frequencies as they pass through the various stages of the set. However, the quality of the picture displayed on the screen depends to a large extent on an equal amplification of both the high and low frequencies. **Peaking** coils are therefore used in the better-quality receivers to equalize the amplification of high and low frequencies. The high frequencies cause a larger voltage drop across the peaking coils than the low frequencies. This tends to compensate for the unbalance in amplification, resulting in a better picture.

Inductors are also used in some hi-fi speaker systems to improve sound reproduction quality. The low audio frequencies are separated from the high audio frequencies by an inductive filter circuit. The lows are then fed to the larger speakers (woofers) and the highs to the smaller speakers (tweeters). Thus, each speaker reproduces only those frequencies which it can handle without distortion. This results in a more faithful and distortion-free reproduction of the amplified sound.

Q39. Inductance opposes a change in current. It tends to round off the corners on the leading edge of the _______ waveform of a pulse.

Q40. The effect of inductance on the voltage waveform of a pulse is the opposite of its effect on the current waveform; it will turn a corner into a sharp spike in the _______ waveform.

Q41. In the figure at the bottom of the opposite page, what happens to the inductor voltage when the current increases?

Q42. What happens to the inductor voltage when the current decreases?

Q43. Why must a TV receiver amplify the high video frequencies as much as it amplifies the low video frequencies?

Q44. What is the name of the components that are used to equalize the gain for high and low video frequencies in many TV receivers?

Your Answers Should Be:

A39. Inductance opposes a change in current. It tends to round off the corners on the leading edge of the **current** waveform of a pulse.

A40. The effect of inductance on the voltage waveform of a pulse is the opposite of its effect on the current waveform; it will turn a corner into a sharp spike in the **voltage** waveform.

A41. The voltage increases in the **positive** direction.

A42. The voltage increases in the **negative** direction.

A43. The gain must be uniform **to provide** a **good-quality picture.**

A44. **Peaking coils** are used to equalize the video gain.

WHAT YOU HAVE LEARNED

1. Inductance opposes a change in current and makes the waveform of an AC current lag the voltage by 90°.
2. Inductance is measured in henrys, millihenrys, or microhenrys.
3. Inductance uses no power; it only "borrows" energy for a short time.
4. Three factors that influence the inductance of a coil are number of turns, diameter of the coil, and type of core.
5. Induction is the creation of a magnetic field by an electric current or of an electric current by a magnetic field.
6. Transformers work by induction.
7. Inductive reactance acts similarly to resistance in an AC circuit and is measured in ohms.
8. The formula for inductive reactance is:

$$X_L = 2\pi fL$$

9. You have learned how to use inductance to construct a simple filter circuit.
10. You have learned how inductance affects the waveform of pulses.

10

RL Circuits

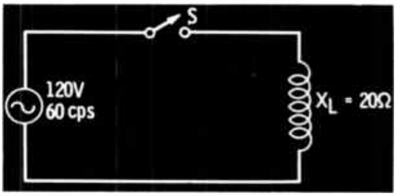
What You Will Learn

You are now going to learn how to find the equivalent reactance of inductors in series and in parallel. You will become acquainted with some of the ways to measure the relative importance of R and L in a component or circuit and how to find the time constant of a circuit. You will be able to add reactance and resistance to find impedance. You will discover how the combination of resistance and inductance affects the phase relations of voltage and current. You will also learn how to calculate current and power in RL circuits.

INDUCTIVE CIRCUITS

A good way to understand circuits containing inductance is to work through a simple problem. For example, the following illustration shows a schematic of a basic inductive-reactance AC circuit.

A BASIC INDUCTIVE —RESISTIVE CIRCUIT



Assume that the resistance in the leads and the coil is negligible. The problem is to find the rms value of the current in this circuit.

Ohm's law still applies.

$$I = \frac{E}{X_L} = \frac{120}{20} = 6 \text{ amperes}$$

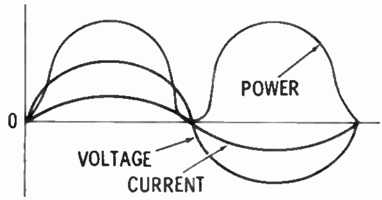
You have learned that power in a circuit is:

$$P = EI$$

where,

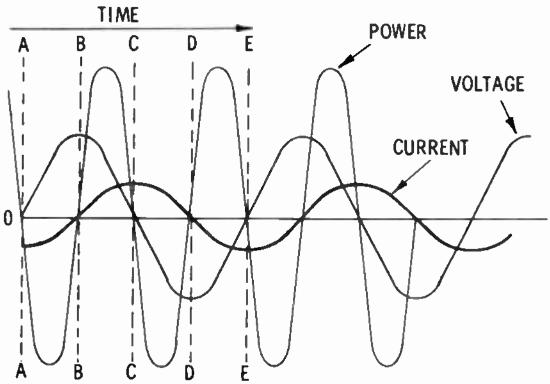
E is the voltage,
I is the current.

With a sine wave the power at any time during the cycle is the product of the voltage and the current at that moment. In a resistive circuit, power has a pulsating waveshape.



POWER IN A RESISTIVE CIRCUIT

You have already learned that no power is dissipated in a circuit that contains only inductance. A look at the waveforms below will help you understand this.



POWER IN AN INDUCTIVE CIRCUIT

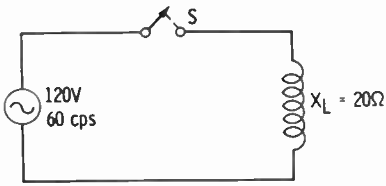
Between points B and C, both current and voltage are positive. If you multiply their values, it appears that power is being dissipated exactly as in a resistive circuit. Between points D and E, both current and voltage are negative, and again you have exactly the same situation as in a resistive circuit—power appears to be dissipated. But between points A and B and points C and D there is a situation that never exists in a resistive circuit.

As you can see, there are pulses of negative power as well as positive power. The positive-power pulses represent the time when the circuit is utilizing power to produce a magnetic field. The negative-power pulses represent the time when the circuit is absorbing power from the magnetic field. The negative pulses and the positive pulses are equal and cancel each other, so the total power dissipated is zero.

An important rule that you must remember is:

When you multiply positive values by positive values, or negative values by negative values, the results are positive values.

When you multiply positive values by negative values, the results are negative values.



Inductive reactance in a circuit changes with frequency, but inductance stays the same. To find how the above circuit behaves at other frequencies, you must determine the inductance. Use the formula:

$$L = \frac{X_L}{2\pi f} \text{ (this is a form of } X_L = 2\pi fL)$$

Q1. Is voltage positive or negative between points A and B in the figure at the bottom of the opposite page?

Q2. Is current positive or negative between A and B?

Q3. Is power positive or negative between A and B?

Q4. What is the amount of inductance in the circuit shown above?

Q5. How much current will flow in this circuit if the applied voltage is 100V at a frequency of 100 cps?

Your Answers Should Be:

A1. Voltage is **positive.**

A2. Current is **negative.**

A3. Power is **negative.**

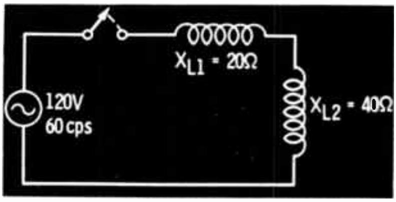
A4. About **0.053 henry.**

A5. X_L is 33.3 ohms.

$$I = \frac{E}{X_L} = \frac{100}{33.3} = 3 \text{ amperes}$$

Inductors in Series

The simplest form of a series inductive circuit is one with two inductors in series.



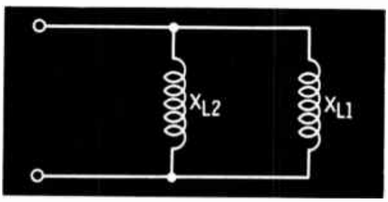
A SERIES INDUCTIVE CIRCUIT

To find the current in the circuit, add X_{L1} and X_{L2}, and then use Ohm's law with the equivalent X_L.

If the value of each inductance (L) is known, add the individual inductances to find the total inductance and then calculate X_{Leq} for the circuit.

Parallel Inductive Circuits

A circuit containing pure inductances in parallel can be treated much like a parallel resistance circuit.



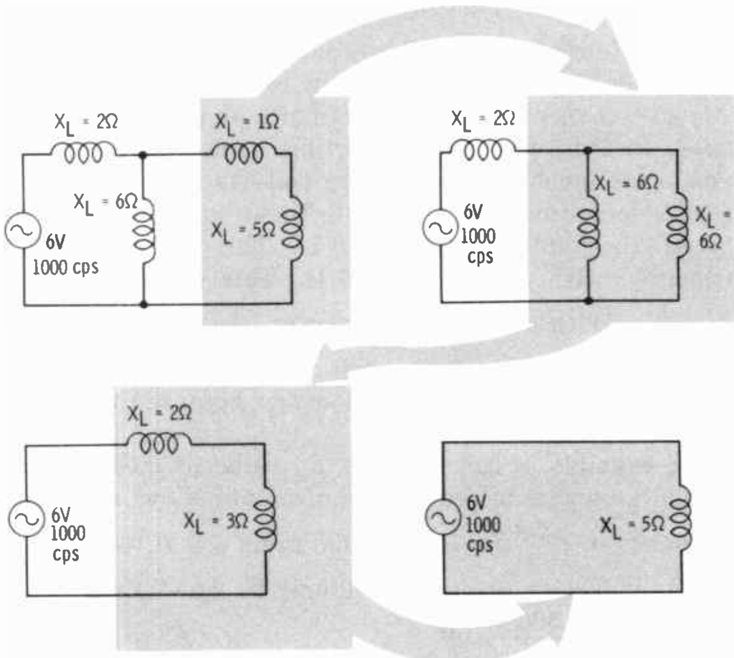
INDUCTANCES IN PARALLEL

This simple parallel circuit can be solved by the formula:

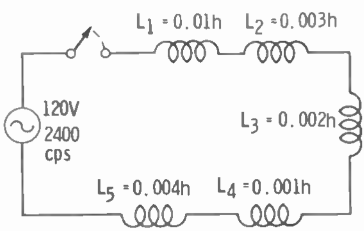
$$X_{Leq} = \frac{X_{L1} \times X_{L2}}{X_{L1} + X_{L2}}$$

As with resistance, the equivalent inductive reactance of two inductors in parallel is always smaller than that of either single inductor. Combined series and parallel circuits, or large groups of inductors in parallel, can be simplified in steps by the same method you have used with resistances.

A CIRCUIT CONTAINING SERIES AND PARALLEL INDUCTANCES CAN BE SIMPLIFIED



Q6. What is the equivalent X_L in the following circuit?



Q7. How much current will flow in this circuit?

Q8. How much power will be dissipated in this circuit?

Your Answers Should Be:

A6. $X_L = 2\pi fL = 2 \times 3.14 \times 2{,}400 \times .02 = 301$ **ohms**

A7. $I = \frac{E}{X_L} = \frac{120}{301} = .399$ **ampere**

A8. No power will be dissipated.

Q FACTOR

An RL circuit is one that contains both resistance and inductance. You are more likely to encounter circuits of this sort than pure inductive circuits or pure resistive circuits. In fact, even the connecting conductors in a circuit have some inductance, and every coil has some resistance.

It is sometimes important to know how "good" or how "pure" the inductance of a coil is. This quality is usually measured with a factor called Q. This is simply a ratio, $Q = \frac{X_L}{R}$. With a large Q, the power loss in the coil will be small, and the inductance will be more efficient. Notice, however, that Q varies with frequency, because the inductive reactance varies.

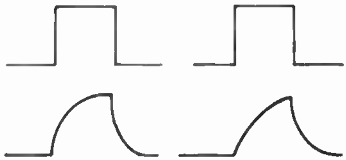
For example, a coil with an X_L value of 5,000 ohms at 10,000 cps and a DC resistance of 50 ohms has a Q at that frequency of $\frac{5{,}000}{50} = 100$. If this same coil is used at 5,000 cps, its inductive reactance will only be 2,500 ohms, and its Q will equal $\frac{2{,}500}{50} = 50$.

TIME CONSTANT

A different measure of the relative amounts of resistance and inductance is very important when dealing with pulse circuits. The shape of a pulse is changed by inductance.

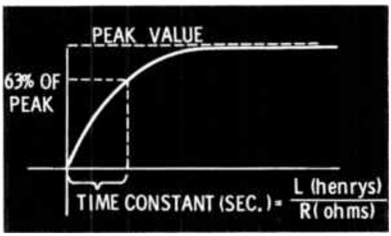
When a pulse is passed through an RL series circuit, the roundness of the current rise and the time it takes for the current to rise to its final value depend on the amounts of inductance and resistance in the circuit. As you would expect, the greater the value of inductance, the slower the current will build up. At the same time, the resistance in the circuit has the opposite effect—the smaller the resistance, the longer the current takes to reach the steady-state condition. (The reason is that when the resistance is smaller, the final current will be larger, and it will therefore take longer to reach this final value.)

INCREASING THE TIME CONSTANT INCREASES THE AMOUNT OF DISTORTION



When dealing with filters and pulse circuits, circuits containing L and R in series are often described by their **time constant.** This is a measure of how quickly the current in the circuit reaches its final peak value. The time constant equals L/R and is expressed in seconds. If a circuit has an L/R time constant of one-half second, the current will reach 63% of its maximum (peak) value in one-half second when a voltage is applied to the circuit.

L/R Tells How Long It Takes a Pulse to Reach 63% of Its Peak



Q9. A "pure" inductance (which has no resistance) would have a (high, low) Q.

Q10. If you purchased a coil with a low Q, you would expect it to have a relatively (high, low) DC resistance.

Q11. If a coil has a high Q at 1,000 cps, would you expect it to have a higher or lower Q at 5,000 cps?

Q12. If the inductance of a circuit is 3 henrys and the resistance of the circuit is 5 ohms, how long will it take for a pulse to reach 63% of its maximum value?

Q13. The time constant of a circuit indicates the time it takes a pulse to reach ___% of its maximum value in that circuit.

Your Answers Should Be:

A9. A "pure" inductance would have a **high** Q.

A10. A coil with low Q would have a relatively **high** DC resistance.

A11. At an increased frequency, you would expect Q to **increase.**

A12. It would take a pulse $\frac{L}{R} = \frac{3}{5} =$ **0.6 second** to reach 63% of its maximum value.

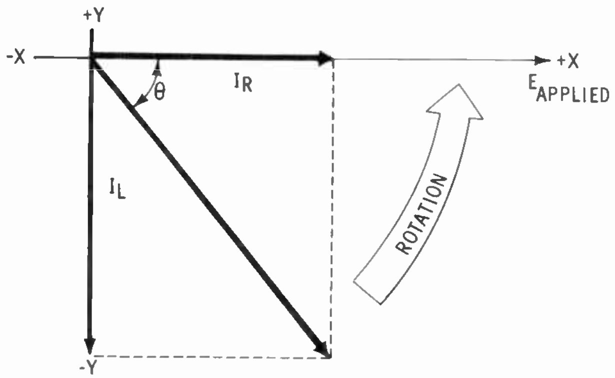
A13. The time constant of a circuit indicates the time it takes a pulse to reach **63%** of its maximum value in that circuit.

PHASE

It has been previously explained that AC voltage and current are always in phase in a purely resistive circuit and that AC current through an inductance always lags the applied voltage by 90°. When resistance and inductance are combined in a single circuit, the amount of phase difference between the current and voltage depends on which (resistance or inductance) has the greater value; that is, it depends on the Q of the circuit.

If the applied voltage is a sine wave, the current through an RL circuit will also be a sine wave. Therefore, you can

One Current Vector Can Represent the Combined Effect of Resistive and Inductive Currents



think of it as being generated by a rotating current vector.

However, this vector is a combination (or resultant) of the resistive and inductive current vectors.

As you see, these two vectors form the two sides of a rectangle, and the overall (resultant) current vector is the diagonal of the rectangle. The angle labeled with the symbol θ is the **phase angle**, the number of degrees by which the overall current lags voltage.

IMPEDANCE

To find the current flowing in a purely inductive circuit, you apply Ohm's law, using inductive reactance instead of resistance ($I = E/X_L$). Inductive reactance, of course, equals $2\pi fL$ and varies with frequency and inductance.

What happens when both resistance and inductance are in series in the same circuit? Say, for example, that the resistance is 3 ohms, and the inductive reactance (for a specific frequency) is 4 ohms.

As you know by now, the current through the resistance in an AC circuit is **in phase** with the applied voltage sine wave, while the current in the inductance **lags 90° behind** the voltage. Just as the rms value of resistive current cannot be added to the rms value of the inductive current to find the overall current, the 3 ohms of resistance cannot be added to the 4 ohms of inductive reactance. Instead, the overall effect of the two must be found in the same way that the overall current vector is found. The overall effect of resistance and reactance working together is called **impedance.** The symbol for impedance is **Z.**

Q14. If the current lags the voltage by 85° in a circuit with an input at 1,000 cps, do you think an input at 450 cps is more likely to cause the current to (a) lag by 89°, (b) lead by 45°, (c) lag by 15°?

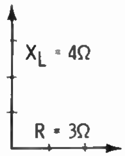
Q15. Draw vector lines representing 3 ohms of resistance (R) and 4 ohms of inductive reactance (X_L) on a sheet of paper.

Q16. Complete your vector diagram to find the impedance presented by the 3 ohms of resistance and 4 ohms of inductive reactance. Measure the diagonal.

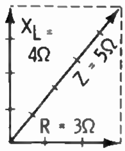
Your Answers Should Be:

A14. Current is most likely to **(c) lag by 15°.**

A15. You should have drawn vector lines that look like this.



A16. Your vector diagram should look like this. Z is **5 ohms.**



Relationship of X_L, R, and Z

One simple way to find the overall effect of 3 ohms of resistance and 4 ohms of inductive reactance is to draw a line 4 units long pointing downward. This line represents the inductive reactance. Then draw a line to the right 3 units long. This line represents the resistance. The two lines form two sides of a rectangle. The diagonal of this rectangle will represent the impedance.

Notice the angle between the R and X_L vectors. This angle is usually indicated by the Greek letter **theta** (θ) and is referred to as the phase angle.

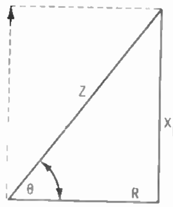
It is not enough to say that a circuit has an impedance of 5 ohms; you must also know the angle by which the current and voltage are out of phase. There are two ways to do this. You can express impedance in **polar** form, $Z\angle\theta$. In the example above, Z is 5. Or you can express the impedance as the sum of 3 ohms resistance plus 4 ohms inductive reactance. A short way of saying this is $3 + j4$. The j tells you that the 4 is 90° behind the 3. In general

$Z = R + jX_L$. This is the **rectangular** form of impedance. Although you can find impedance by drawing vector diagrams and measuring, there are other ways of finding the value of impedance.

As long as θ remains the same, the proportion between reactance and impedance will be the same. The proportion between resistance and impedance and between reactance and resistance will also be the same.

When any two facts about a combination of X_L and R are known, the other facts can be found by using a table of **trigonometric functions.** An example of such a table is shown on page 270.

Trigonometric relationships of X_L, R, and Z.



$$\tan\theta = \frac{X_L}{R} \text{ or } R = \frac{X_L}{\tan\theta}$$

$$\sin\theta = \frac{X_L}{Z} \text{ or } Z = \frac{X_L}{\sin\theta}$$

$$\cos\theta = \frac{R}{Z} \text{ or } Z = \frac{R}{\cos\theta}$$

Using the above relationships, the impedance of an inductive circuit for which X_L is 7 ohms and R is 10 ohms can be found.

$$\tan\theta = \frac{X_L}{R} = \frac{7}{10} = 0.700$$

$\theta = 35^\circ$ (from table on page 270) ; $\sin\theta = 0.574$

$$Z = \frac{X_L}{\sin\theta} = \frac{7}{0.574} = 12.2 \underline{/35^\circ} \text{ ohms}$$

Q17. What happens to θ if both R and X_L are doubled?

Q18. What happens to Z if both R and X_L are doubled?

Q19. What happens to R and X_L if Z stays the same but θ is increased?

Q20. What is θ if R is 17.33 ohms and X_L is 10 ohms?

Q21. What is Z for Q20?

Q22. If R is 12 ohms and θ is 30°, what is Z?

Q23. If X_L is 20 ohms and θ is 30°, what is Z?

Your Answers Should Be:

A17. If you double both R and X_L, θ **remains the same.**

A18. If you double both R and X_L, Z **is doubled.**

A19. If θ is increased, X_L **becomes larger and R smaller.**

A20. $\tan \theta = X_L/R = 30°$

A21. $Z = X_L/\sin \theta = 20 \angle 30°$ **ohms**

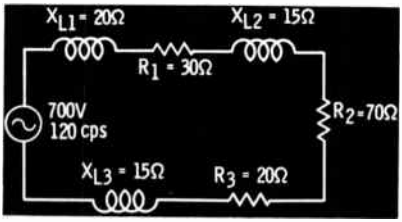
A22. $Z = R/\cos \theta = 13.9 \angle 30°$ **ohms**

A23. $Z = X_L/\sin \theta = 40 \angle 30°$ **ohms**

Current in an RL Circuit

When inductors and resistors are connected in series in a circuit, simply add all the inductive reactances and all the resistances separately to get an equivalent circuit with one inductive reactance and one resistance.

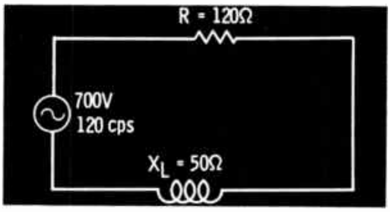
If it is necessary to find the impedance of this circuit, begin by simplifying it.



Even though X_L and R values are scattered through the series circuit, they may be added directly. Thus,

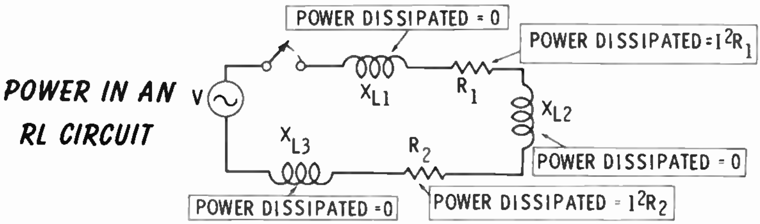
$$X_{L\ TOTAL} = X_{L1} + X_{L2} + X_{L3} = 20 + 15 + 15 = 50 \text{ ohms}$$
$$R_{TOTAL} = R_1 + R_2 + R_3 = 30 + 70 + 20 = 120 \text{ ohms}$$

The circuit above is equal to this equivalent circuit.

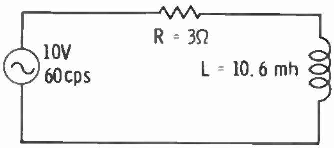


POWER IN RL CIRCUITS

All power is dissipated in resistance. You have also learned that the formula for power is $P = I^2R$. This is the only formula that should be used to find power in AC systems.



Go through all the steps necessary to find the power dissipated in the following circuit. (See Q24 through Q27.)



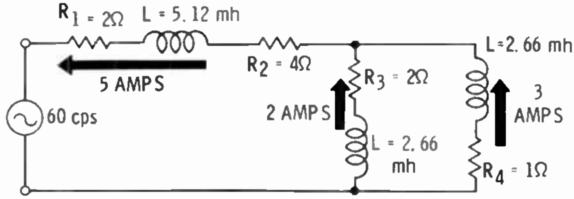
Q24. What is the inductive reactance of the coil?

Q25. What is the impedance of the circuit?

Q26. How much current flows through the circuit?

Q27. How much power is dissipated in the circuit?

Q28. Here is a more complicated circuit. Notice how the current divides in the parallel parts. Kirchhoff's law is used to determine how the current divides. How much power is dissipated in this circuit?



Q29. Suppose a 4-henry filter choke and a 2,630-ohm resistor are wired in series across the terminals of a transformer that supplies 15 volts at 60 cps. Draw a schematic of the circuit.

Q30. How much current will flow in the circuit?

Q31. How much power will be dissipated by the resistor?

Your Answers Should Be:

A24. $X_L = 2\pi fL = 4$ **ohms (approx)**

A25. $Z = 5\angle 33^\circ$ **ohms**

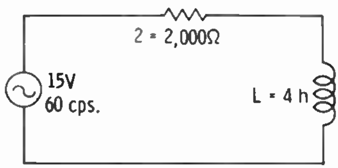
A26. $I = \frac{E}{Z} = 2$ **amperes**

A27. The power dissipated is: $P = I^2R = 12$ **watts**

A28. Since the current is known, the inductors can be disregarded. Use $P = I^2R$ to find the power dissipated in each resistor.

$$P_1 = 5 \times 5 \times 2 = 50 \text{ watts}$$
$$P_2 = 5 \times 5 \times 4 = 100 \text{ watts}$$
$$P_3 = 2 \times 2 \times 2 = 8 \text{ watts}$$
$$P_4 = 3 \times 3 \times 1 = 9 \text{ watts}$$
$$\text{TOTAL} \quad \text{167 watts}$$

A29.



A30. $X_L = 1{,}507$ ohms $\quad I = \frac{E}{Z} = \frac{15}{3{,}000} = 5$ **ma** (approx.)

$R = 2{,}630$ ohms

$Z = 3{,}000\ \angle 30^\circ$ ohms (approx.)

A31. $P = I^2R = 0.072$ **watt**

WHAT YOU HAVE LEARNED

1. Series and parallel inductive reactances can be combined in the same way as resistances.
2. L/R is the time constant of an RL circuit and indicates the time in seconds it takes a pulse to reach 63% of its maximum value.
3. Q is the ratio of X_L to R in a coil.
4. The phase angle in an AC circuit is determined by the proportions of X_L and R.
5. X_L and R are added vectorially to find impedance.
6. Impedance may be expressed as $Z\angle\theta$ or $R + jX_L$.

11

The Effect of Capacitance

What You Will Learn

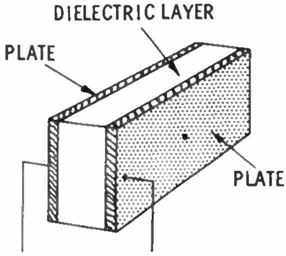
When you have finished this chapter, you will know how capacitance affects AC and pulses. You will learn how capacitance blocks DC but allows AC to pass more and more easily as the frequency increases. An explanation of how capacitance causes applied voltage to lag the current and how it distorts the voltage waveforms of pulses is given. You will become familiar with the units in which capacitance is measured and the factors that influence the value of a capacitor. You will be able to calculate capacitive reactance.

WHAT IS CAPACITANCE?

Capacitance is the property of an electrical circuit that **opposes a change in voltage.** Capacitance has the same reaction to voltage that inductance has to current. This means that if the voltage applied across a circuit is increased, capacitance will resist that change. If the voltage applied to a circuit is decreased, capacitance will oppose the decrease and try to maintain the original voltage.

In a DC circuit, capacitance has an effect only when voltage is first applied, and then again when it is removed. **Note that current cannot flow through a capacitance.** However, AC current **appears** to flow through a capacitance—you will learn how later. Since voltage is constantly changing in AC circuits, capacitance acts at all times to retard these changes in voltage.

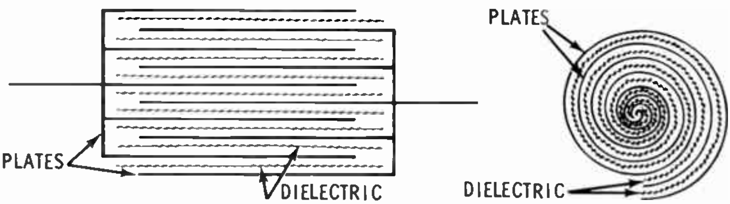
A basic capacitor (sometimes called a condenser) is shown below. It consists of two conducting metal plates separated by a layer of air or other insulating material, such as paper, glass, mica, oil, etc. The insulating layer is called the **dielectric.**



A BASIC CAPACITOR

All capacitors have these two plates and a separating layer. In practice, these are often stacked or even rolled into a compact form. Sometimes the dielectric is a paste or a liquid instead of a solid.

Capacitor Plates Are Often Stacked or Rolled To Save Space



This is the circuit symbol for a capacitor.

CIRCUIT SYMBOLS FOR A CAPACITOR

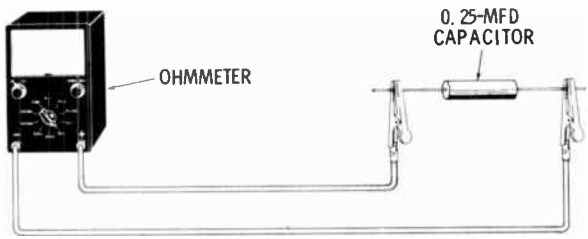
When a capacitor is first connected to a battery, electrons from the negative terminal of the battery flow to the nearest capacitor plate and remain there. They can go no farther, since the opposite plate is separated from the first by an insulating layer. Electrons are moved from the opposite capacitor plate and flow into the positive terminal of the battery. After this initial movement of electrons, one plate is filled with all the electrons that the battery voltage can force into it, and the other plate loses the same number of electrons. This means that one plate has a negative charge and the other plate has an equal positive charge. No further current flows; the capacitor is "charged."

Positive and negative charges attract each other, so there will be a force between the plates of the capacitor. There is also a voltage between them that is equal to and opposes the voltage of the battery.

Because it takes a certain specific number of electrons to fill the negative plate, we say that the capacitor has a certain capacity, or **capacitance.**

You can see this happen if you take a capacitor (say 0.25 mfd, 600V) and connect the probes of an ohmmeter to the capacitor leads or terminals, using a very high-ohms range (R × 1 MEG). Notice that as soon as the connection is made, there is a sudden drop in the ohms reading as the battery in the ohmmeter provides current to charge the capacitor. Immediately following this decrease, the reading increases toward infinity. This shows there is some current at first (the charging current), but it quickly disappears and the resistance becomes infinitely large.

OBSERVING THE CHARGE OF A CAPACITOR



Q1. Name two differences between capacitance and inductance.

Q2. Draw a circuit diagram of a capacitor connected across the terminals of a battery.

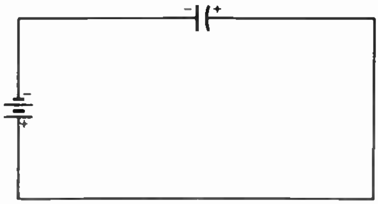
Q3. Explain what happens when you remove the battery from across a charged capacitor and place a shorting wire across the leads of the capacitor.

Q4. What would happen if you tried to repeat the above experiment without first discharging the capacitor?

Your Answers Should Be:

A1. **Capacitance opposes a change in voltage** while inductance opposes a change in current. **Capacitance blocks DC** while inductance does not.

A2. Your circuit diagram should look like this.



A3. The **electrons** from the negative plate **rush through the shorting wire to the positive plate** until both plates have the same number of electrons. The **voltage across the plates is then zero.**

A4. Once the capacitor has been charged, **there is no "kick"** (needle movement) when you connect the ohmmeter probes. The capacitor is already full and can take no more charge.

CAPACITANCE MEASUREMENTS

The usual symbol for capacitance is C. Capacitance is measured in **farads.** The amount of capacitance in a capacitor is the quantity of electrical charges (in coulombs) which must be moved from one plate to the other in order to create a potential difference of 1 volt between the plates. The number of coulombs transferred is called the **charge.**

One farad is the capacitance in which a charge of 1 coulomb produces a difference of 1 volt between the plates. The larger the capacitance of a capacitor, the more charge it will hold with the same voltage applied across the plates.

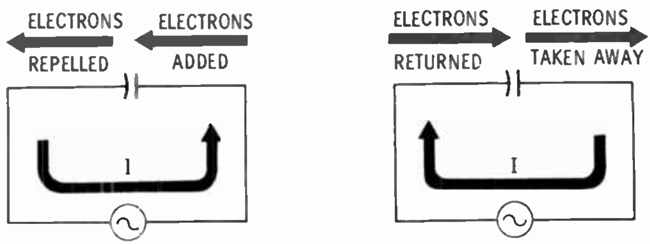
Capacitance values are usually specified in microfarads (millionths of a farad, abbreviated mfd or μf) or in micromicrofarads. Micromicrofarads are also called picofarads (millionths of a microfarad, abbreviated **mmf, $\mu\mu f$, or pf**).

HOW DOES CAPACITANCE AFFECT AC?

Although current cannot flow through a capacitor, an AC current appears to do just that. The reason lies in the nature of capacitance. If the voltage across the plates is continuously varied, the number of electrons on the plates varies.

Increasing the number of electrons on one plate of a capacitor repels electrons from the other plate. Decreasing the number of electrons on the first plate allows electrons to be attracted back to the other plate.

AC CAN PASS THROUGH A CAPACITOR



An AC voltage can, in effect, get across the dielectric; since the voltage is alternating, it causes an AC current on the other side. In other words, **voltage changes** are transmitted across the gap.

If a capacitor has the same voltage as the applied voltage, no current will flow to or from it. If the applied voltage changes, the capacitor voltage will no longer equal the applied voltage. Current will flow trying to equalize the two.

In a circuit this means that if an AC sine-wave voltage is applied across a capacitor, an AC sine-wave current will appear on the opposite side, even though no electrons cross the dielectric layer.

Q5. The capacitance of a capacitor is measured in ______.

Q6. A millionth of a farad is called a __________ and is abbreviated as ___ or __.

Q7. A ________________ is a millionth of a microfarad and is abbreviated ___, ___ or __.

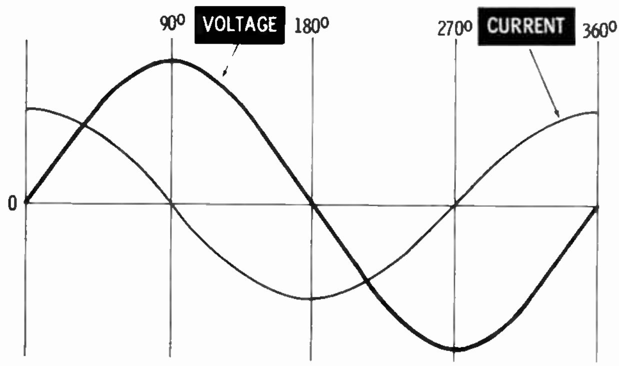
Q8. Current will flow from one plate of a capacitor to the other plate only when ________ is changing.

> **Your Answers Should Be:**
>
> A5. The capacitance of a capacitor is measured in **farads.**
>
> A6. A millionth of a farad is called a **microfarad** and is abbreviated as **mfd** or **μf.**
>
> A7. A **micromicrofarad** is a millionth of a microfarad and is abbreviated **mmf, $\mu\mu$f,** or **pf.**
>
> A8. Current will flow through a capacitor only when **voltage** is changing.

PHASE

Just as with inductance, current and voltage are not in phase in a capacitive circuit. The voltage lags the current (current leads the voltage) by 90°.

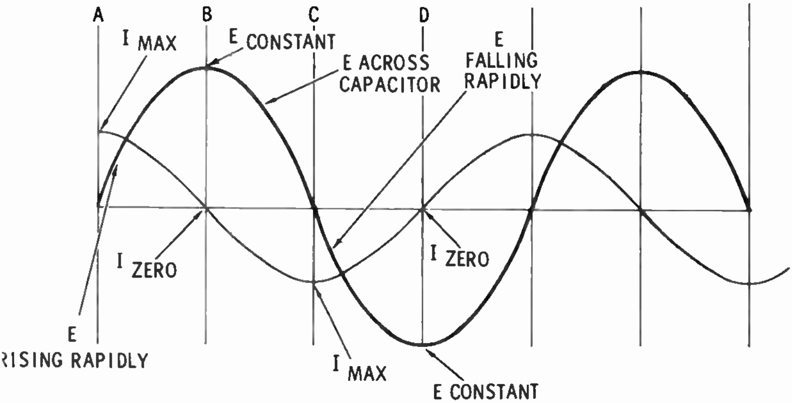
CURRENT LEADS VOLTAGE IN A CAPACITOR



At any instant, the current flowing into or out of a capacitor is proportional to the rate of change of the applied voltage. This can be seen in the illustration on the next page. The applied voltage is changing most rapidly at time A, the beginning of the sine-wave cycle. Therefore current flow is maximum. At time B the voltage across the capacitor has reached its peak and, for the moment, is not changing. Therefore current at this instant is zero. At time C, voltage across the capacitor again is changing quite rapidly (but in the negative direction), and so the current is at its negative peak. At time D, when the voltage reaches its negative peak and is momentarily not changing, the current waveform passes through zero once more.

If we trace the current from point to point along the voltage waveform, the result is a sine wave, but it is one that **leads the voltage by exactly 90°**. This shows that if the voltage across the capacitor is a continuous sine wave with a constant amplitude, the current through the capacitor circuit is a sine wave that is 90° ahead of the voltage.

CURRENT IS DETERMINED BY THE VOLTAGE CHANGE

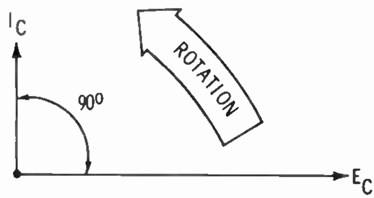


Current and voltage vectors in a capacitive circuit are 90° out of phase. In this case the current vector is **ahead** of the voltage vector by 90°.

THE CURRENT VECTOR

LEADS

THE VOLTAGE VECTOR



Q9. When an AC voltage across a capacitor is maximum, AC current through the circuit is ____.

Q10. When an AC current through a capacitor circuit is maximum, AC voltage across the capacitor is ____.

Q11. Contrast the phase relationship of AC voltage and AC current in an inductor and in a capacitor.

Your Answers Should Be:

A9. When an AC voltage across a capacitor is maximum, AC current through the circuit is **zero.**

A10. When an AC current through a capacitor circuit is maximum, AC voltage across the capacitor is **zero.**

A11. In an inductor, voltage **leads** current by 90°; in a capacitor, voltage **lags** current by 90°.

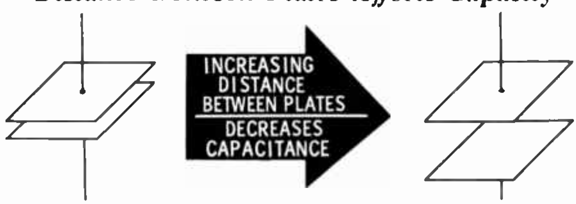
FACTORS AFFECTING CAPACITANCE VALUE

The amount of electrical charge that can be stored in a capacitor (the number of electrons that can be placed on the plate) varies with the area of the plates. Consequently, capacitance varies directly with area—if the area is doubled, the capacitance is doubled. When the area is doubled or twice as many plates are connected in parallel, there is twice as much area to store electrons, and the capacitance is therefore twice as great.

Plate Area Affects Capacity

Capacitance can also be increased by placing the plates closer together. When the plates are closer, the attraction

Distance Between Plates Affects Capacity



between the negative charges on one side and the positive charges on the other side is greater, and thus more charge can be stored. It is, of course, necessary to keep the plates far enough apart so that the charge does not cross the gap.

Higher values of capacitance can be obtained by using an insulating material (dielectric) other than air. This allows the plates to be closer together without the charge crossing the gap.

Dielectric Material Affects Capacitor

Dielectrics such as mica, glass, oil, and Mylar are a few of the materials that can sustain a high electric stress without breaking down. This property is called **dielectric constant.** The higher the dielectric constant is, the better the dielectric. Air has a dielectric constant of 1, glass about 5, and mica 2.5 to 6.6.

Besides allowing the plates to be placed closer together, a dielectric has another effect on capacitance. Dielectric material contains a large number of electrons and other carriers of electrical charge. Although electrons cannot flow as in a conductor, they are held rather loosely in the structure and can move slightly. The distortion of the structure of the dielectric, which is caused by charging the capacitor, has a large effect on the forces of attraction and repulsion that aid or oppose the flow of the electrons. This factor has a substantial effect on capacitance.

When materials such as mica or glass are used as the dielectric, the capacitors have a much higher value than the same size units with an air dielectric.

Q12. If you had two capacitors of low value, how could you combine them to get a larger capacitance?

Q13. How does a mica capacitor differ from an air capacitor of the same physical size?

Q14. What are three factors that affect the capacitance of a capacitor?

Q15. A screw-type variable capacitor is made with an adjusting screw that is used to vary the distance between the capacitor plates. How would you increase its capacitance?

Your Answers Should Be:

A12. Combining two capacitors in parallel would produce the same effect as a single capacitor with more plates, and therefore **would result in a higher capacitance.**

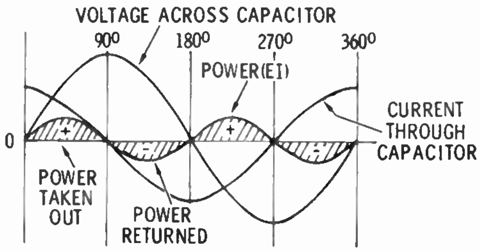
A13. A mica capacitor has a **higher capacitance** than an air capacitor of the same physical size.

A14. The capacitance of a capacitor depends on these three factors: the **area** of the plates, the **spacing** between the plates, and the nature of the **dielectric material.**

A15. Tightening the screw moves the plates closer together and **increases capacitance.** Loosening the screw **decreases the capacitance.**

POWER

Just like inductance, capacitance consumes no power. During the sine-wave cycle, the capacitor takes energy out of the circuit and stores it in the form of an electric field during a quarter cycle and returns it to the circuit in the next quarter cycle. **Energy is borrowed, but it is always returned.**



POWER IN A CAPACITOR

If the product of E times I is taken at every instant of the cycle, the power waveform will show that energy is taken out and returned in alternate quarter cycles.

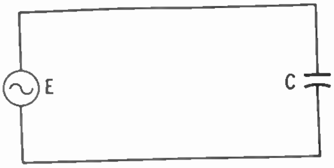
To find the amount of energy (in **coulombs**) stored in a capacitor, multiply the capacity in farads by the applied voltage. In a circuit containing only pure capacitance, it makes no difference how long the voltage is applied—the same amount of energy will always be stored at a given voltage.

CAPACITIVE REACTANCE

Like inductance, capacitance has a reactance—an opposition to the flow of AC. But capacitive reactance **decreases** as frequency increases.

Suppose a capacitor is connected in series with an alternating voltage source. There is no resistance in the circuit.

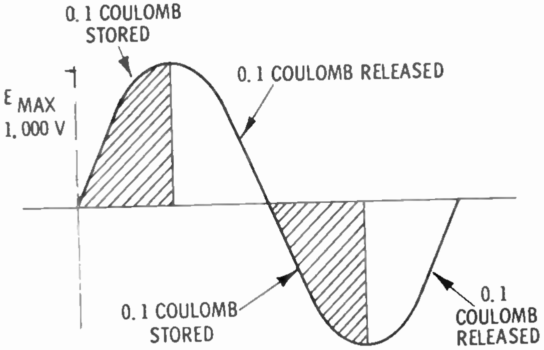
A BASIC CAPACITIVE CIRCUIT



Because the circuit above contains no resistance, the voltage across the capacitor will be the same value as the source voltage at every instant.

When a capacitor is charged up to voltage E, it stores an amount of energy equal to the capacitance times the voltage. If the peak voltage of the AC source is E, the capacitor will have stored a particular amount of energy every time the voltage sine wave hits its peak, and again stores that amount whenever the voltage reaches it negative peak. The energy depends only on capacitance and peak voltage.

Equal Amounts of Energy Must Flow in Each Cycle



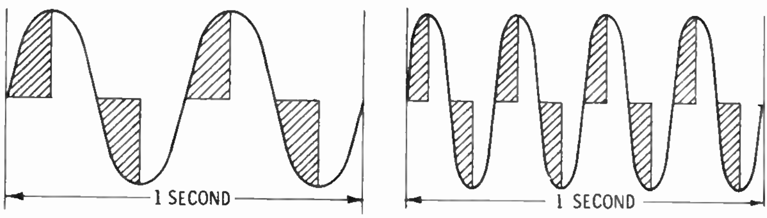
Q16. How much energy will be stored in a 100-mfd capacitor in the first quarter cycle of an applied AC voltage of 1,000 volts maximum?

Your Answer Should Be:

A16. 1,000 volts × .0001 farad = **0.1 coulomb**

What happens when the frequency of the power source is doubled? If the peak voltage (E) is unchanged, the capacitor will charge every half cycle to the same amount as before. But it will have to do this twice as fast because the energy is doubled. This means that the same amount of energy must flow into the capacitor in only half the time. And since the voltage is the same, we must have twice the current to supply this same amount of energy.

A Capacitor Stores the Same Amount of Energy Each Time It Reaches E_{MAX}



What does this mean? The frequency was doubled, and this doubled the current flowing into the capacitor—yet, the input voltage remained the same. A pure capacitance lets twice as much current flow if the frequency is doubled.

Capacitive reactance is the opposition that pure capacitance offers to the flow of current. It is expressed in **ohms**, and its symbol is $\mathbf{X_C}$. Capacitive reactance depends on frequency. As the frequency increases, the rate of change of applied voltage increases, and the current flowing also increases. As the frequency is reduced, the rate of change of voltage goes down, and less current flows.

At this point you can more easily see why capacitor current leads the voltage across the capacitor. It is necessary for the capacitor to charge up to the given voltage, and this charging is done by the current. Hence, the charging current will reach its maximum value at the time the charging is going on at the greatest rate; that is, when the rate of change of voltage is the most rapid.

As the capacitor approaches full charge, the voltage rate of change slows down, and the current decreases. When the capacitor is fully charged and its voltage has reached maximum, there is no charging current flowing at all—the current has already dropped to zero at this time. A similar process occurs during discharging. At all times, current leads the voltage by 90°, or one quarter of the cycle. In a steady-state AC situation, when the applied voltage is a sine wave, both voltage and current will be sine waves.

Capacitive reactance depends on frequency. Since it lets more current flow as frequency increases, capacitive reactance must decrease as the frequency increases.

Capacitive reactance also depends on the size of the capacitance. As capacitance increases, more current must flow into the capacitor to charge it to the same voltage (since the amount of energy stored equals C × E). As a result, capacitive reactance decreases when capacitance increases.

The formula for capacitive reactance is:

$$X_C = \frac{1}{2\pi fC} \text{ ohms}$$

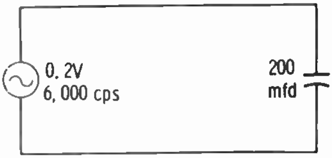
where,

f is the frequency in cps,
C is the capacitance in farads.

Capacitive reactance can be used in calculating current in a purely capacitive circuit by Ohm's law.

$$I = \frac{E}{X_C}$$

Q17. What is X_C if f = 6,000 cps and C = 200 mfd?



Q18. What is the current in this circuit?

Q19. What would the current in the above circuit be if the input signal were 0.01 volt at 120 kc?

Your Answers Should Be:

A17. $X_C = \frac{1}{2\pi fC} = \frac{1}{2 \times 3.14 \times 6{,}000 \times 200 \times 10^{-6}}$

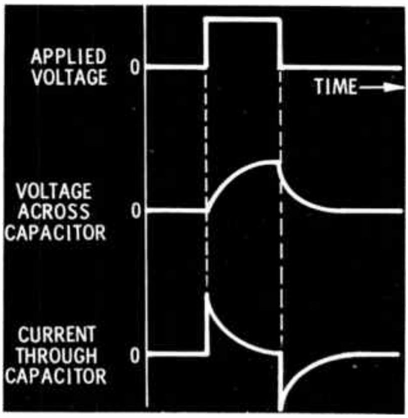
$= \frac{1}{7.53} =$ **0.133 ohm**

A18. $I = \frac{E}{X_C} = \frac{0.2}{0.133} =$ **1.5 amps**

A19. $I = \frac{0.01}{0.0066} =$ **1.52 amps**

PULSE RESPONSE OF CAPACITANCE

When a sharp pulse, such as a square wave, is applied to a circuit containing capacitance, the capacitance opposes the sudden change of voltage. This results in a rounding off of the sudden voltage rise. Similarly, when the pulse voltage is suddenly decreased, the voltage across the capacitor does not decrease suddenly, but it trails off. Current is greatest when the change of voltage is greatest, so the current waveform will have a peak when the voltage rises suddenly, and another peak (but in the opposite direction) when it drops.



CURRENT IS GREATER WHEN VOLTAGE CHANGE IS GREATEST

There is always some resistance in a circuit. By choosing the right value of capacitance and resistance, a circuit can be designed in which the voltage takes a predetermined length of time to reach a certain value. This type of circuit can thus provide a time delay.

APPLICATION OF CAPACITANCE

You have already learned how inductance can be used in lters. Capacitance can also be used to block DC or to by-ass AC. You have also learned that capacitance can be used or time delays. Another use for capacitance is to store nergy. For example, capacitors are often used to store nergy in photoflash units. In these photographic devices, battery that produces a relatively small current can be sed to gradually charge a capacitor. The capacitor releases large store of energy very quickly when it is discharged hrough the flashbulb.

STRAY CAPACITANCE

Capacitive reactance decreases as frequency increases. n communications, pulse, and radar work, where very high requencies are used, **stray capacitance** can present quite a roblem.

In a vacuum tube, an antenna, or a receiver chassis, there re always very small capacitances between adjacent con-uctors and between conductors and nearby objects which re meant to be isolated from each other. With the lower adio frequencies these capacitances are not important, but s the frequency increases, the capacitive reactances of hese very small capacitances decrease. A decrease in react-nce can actually cause leakage of the signal.

It is important to know, therefore, that at high frequen-ies, placement of wires and components is very important n order to keep the effects of stray capacitances to a ninimum.

Q20. How do the effects of capacitance on pulses differ from the effects of inductance?

Q21. Compare and contrast capacitive reactance and inductive reactance on these points:

1. Effect of an increase in frequency on reactance.

2. Effect of reactance on DC.

3. Effect of phase relations in AC.

Q22. What constant value appears in the formulas for both capacitive and inductive reactance?

Your Answers Should Be:

A20. Capacitance rounds off the voltage waveform and produces spikes in the current waveform. Inductance rounds off the current waveform and produces spikes in the voltage waveform.

A21. 1. X_C decreases as frequency increases, while X_L increases.

2. X_C blocks DC, while X_L passes DC.

3. Capacitance causes current to lead the applied voltage, while inductance causes it to lag.

A22. 2π appears as a constant in both formulas.

WHAT YOU HAVE LEARNED

1. Capacitance offers an opposition to a change in voltage.
2. A basic capacitor consists of metal plates separated by a dielectric.
3. A capacitor stores electrical energy in the form of an electric field as the capacitor charges, and releases this energy when it discharges.
4. Capacitance is a measure of the energy storage capacity of a capacitor. This capacity is measured in farads.
5. A capacitor blocks DC but allows AC to flow.
6. Pure capacitance in a circuit causes current to lead the applied voltage by 90°.
7. The amount of capacitance is determined by the area of the plates, the distance between them, and the dielectric material.
8. A capacitor stores energy and returns it to the circuit.
9. The opposition of capacitance to the flow of AC is called capacitive reactance.
10. The formula for capacitive reactance is:

$$X_C = \frac{1}{2\pi fC}$$

11. Capacitance rounds off the voltage waveform of a pulse.
12. Stray capacitance can cause signal leakage at high frequencies.

12

RC Circuits

What You Will Learn

When you have finished this chapter you will know how to find the equivalent capacitance of combinations of capacitors in series and in parallel. You will be able to add capacitive reactance and resistance vectorially in order to find impedance. You will be able to analyze RC circuits and to explain how they affect various voltages and currents. You will know how to find RC time constants and how they are used.

A BASIC CAPACITIVE CIRCUIT

First, let's review what you have learned about capacitance by applying it to this basic capacitive circuit.

A BASIC CAPACITIVE CIRCUIT

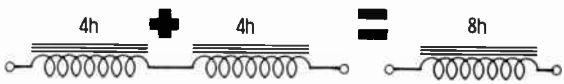
You have already learned that when a sine-wave AC voltage is applied, the current in a capacitor always leads the voltage by 90°. You have also learned that a capacitance consumes no power; all the energy it takes out of a circuit in one quarter cycle is returned in the next quarter cycle.

Both of the above statements are true, not only for a single capacitance, but also for any combination of capacitors. In fact, any circuit that contains only pure capacitances, no matter how many, can be simplified to include only one representative equivalent capacitance.

CAPACITORS IN COMBINATION

As you know, resistors and inductors add in series. Two resistors or inductors in series have the same effect as a single, larger resistor or inductor.

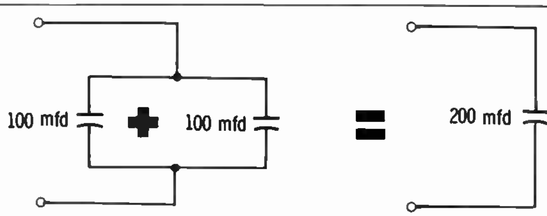
RESISTORS AND INDUCTORS ADD IN SERIES



Capacitors in Parallel

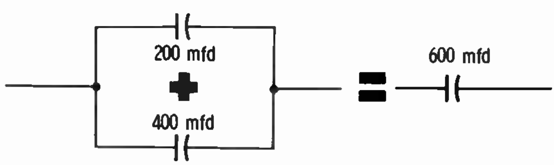
Capacitors add in parallel. It is easy to understand why this is true if you remember that the more plates a capacitor has, the greater is its capacitance.

The More Plates a Capacitor Has, the Greater Is Its Capacity



If two capacitors are connected in parallel, you can find their equivalent capacitance by adding their values.

Capacitors Add in Parallel



If a 200-mfd and a 400-mfd capacitor are connected in parallel, the equivalent capacitance of the combination is

200 mfd plus 400 mfd, or 600 mfd. This is also true with three, four, or any other number of capacitances in parallel.

Capacitors in Series

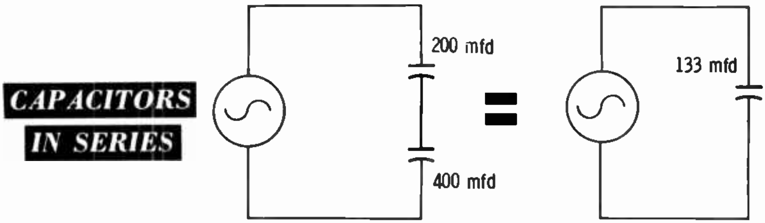
If two capacitors are connected in series, what is their equivalent capacitance? We cannot simply add C_1 and C_2 together. Instead, we use the relationship:

$$C_{eq} = \frac{C_1 \times C_2}{C_1 + C_2}$$

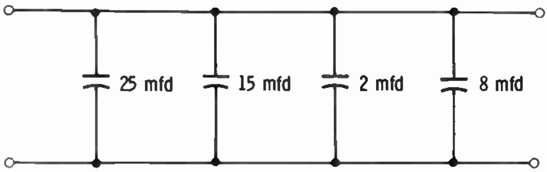
What is the total capacitance of 200 mfd and 400 mfd connected in series? Using the above relationship, the total capacitance is calculated to be:

$$C_{eq} = \frac{200 \times 400}{200 + 400} = 133 \text{ mfd}$$

Notice that this equivalent value is smaller than either of the two individual capacitor values.



Q1. What is the equivalent capacitance of the following circuit?



Q2. How would you replace a 500-mfd capacitor if you had available only 200-mfd and 300-mfd capacitors?

Q3. Would you expect two capacitors in series to have greater or less capacitance than the same two capacitors in parallel?

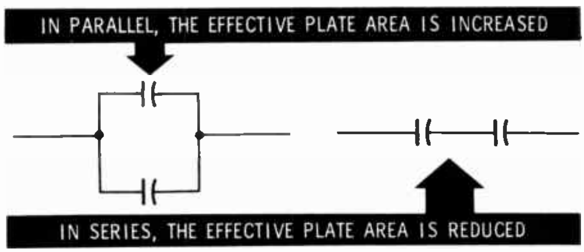
Q4. What is the equivalent capacitance of two equal capacitors in series?

Your Answers Should Be:

A1. C_{eq} is $25 + 15 + 2 + 8 =$ **50 mfd.**

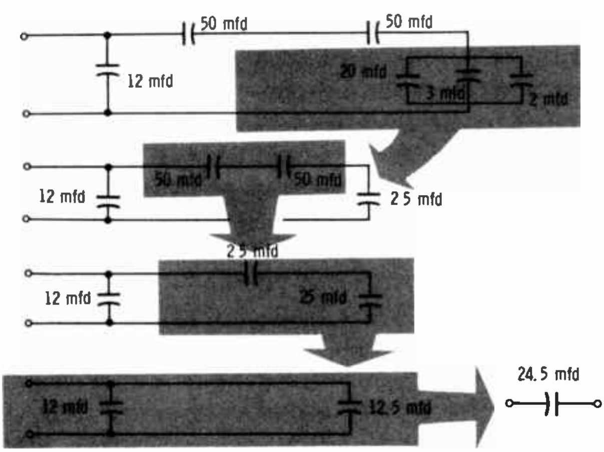
A2. Connect a 200-mfd and a 300-mfd capacitor **in parallel** to get an equivalent capacitance of 500 mfd.

A3. Two capacitors in series would have **less capacitance** than the same two capacitors in parallel.



A4. The equivalent capacitance of two equal capacitors in series is always **one half** the capacitance of either one of them.

Complicated circuits can be simplified by analyzing them in steps as shown below.

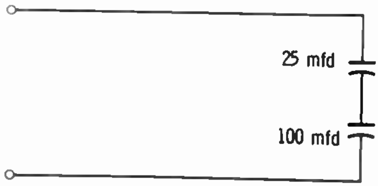


On the preceding pages, capacitance values were combined, not capacitive-reactance values. You must not confuse the two. To combine capacitive reactances, whether in series or in parallel, use the same rules that apply to resistance—add series values and combine parallel values by the formula:

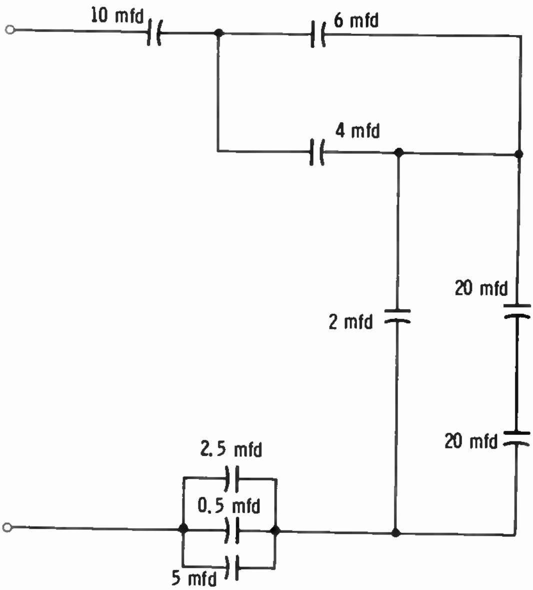
$$X_{eq} = \frac{X_1 \times X_2}{X_1 + X_2}$$

Always check to make sure that all the capacitive-reactance values are computed for the same frequency—otherwise the result will be wrong. In order to calculate the reactance of a capacitive circuit, it is usually better to compute the equivalent capacitance first, and calculate the capacitive reactance of the equivalent capacitance.

Q5. What is the equivalent capacitance of this circuit?



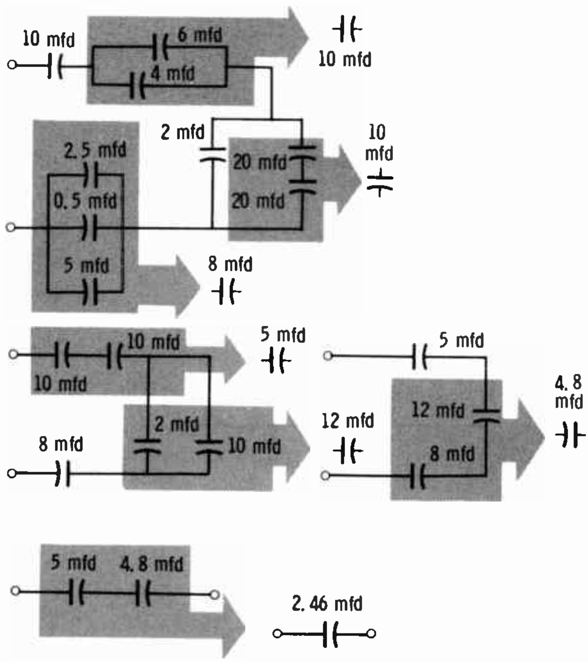
Q6. What is the equivalent capacitance of this circuit?



Your Answers Should Be:

A5. $C_{eq} = \frac{25 \times 100}{25 + 100} = \frac{2{,}500}{125} = \mathbf{20\ mfd}$

A6. You should have simplified the circuit to something like this:

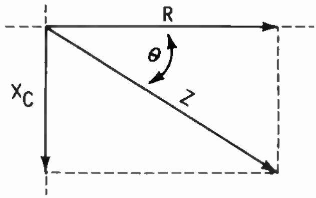


RC CIRCUITS

Actually, an entirely pure capacitance does not exist. The leads of capacitors have some small value of resistance. Also, the dielectric layer is never quite perfect; it has some extremely high value of resistance. So if you wanted to be very accurate, you would represent these unwanted resistances by inserting their values in your circuit diagram, and treating them just as if they were actual resistors. For most practical purposes, however, you can disregard them.

Now let's see what happens if we put capacitors and resistors in the same circuit. As you already know, we cannot add resistance and capacitance, because they are two different quantities (resistance is measured in ohms, capacitance in farads). Instead, it is necessary to use capacitive reactance, which you learned about in the previous chapter. However, just as with inductance, to add resistance to capacitive reactance it must be remembered that resistive current is in phase with the voltage, while capacitive current leads the voltage by 90°. So the two cannot be added directly—they must be added vectorially.

CAPACITIVE REACTANCE AND RESISTANCE MUST BE ADDED AS VECTORS



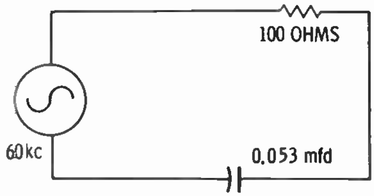
IMPEDANCE

The capacitive-reactance vector is 90° **ahead** of the resistance vector. The resulting quantity, an **impedance**, is somewhere between the two, and its length (quantity) is the diagonal of the rectangle they form. This is **capacitive impedance,** which is different from inductive impedance because it leads the resistance vector. The way to write capacitive impedance is R — jX; the minus sign tells the story. All inductive impedances are represented by a + j, and all capacitive impedances by a —j in front of the X.

Q7. Inductive impedance (leads, lags) resistance.

Q8. Would an impedance of 15 — j20 ohms be inductive or capacitive?

Q9.



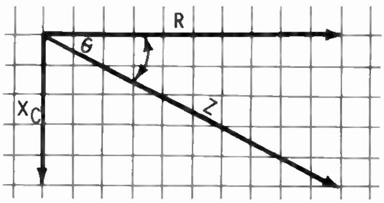
Draw a vector diagram on graph paper to find the impedance in the circuit above. Measure the phase angle with a protractor.

Your Answers Should Be:

A7. Inductive impedance **lags** resistance.

A8. An impedance of 15 — j20 ohms would be **capacitive.**

A9. The capacitive reactance is 50 ohms.
Your vector diagram should look like this.



Z = 100 — j 50 ohms

or 112 /—27° ohms

If you have a table of trigonometric functions, you can get more accurate measurements of impedance, using the same formulas you used to find inductive impedance. Remember, these formulas apply to both inductive and capacitive impedance.

$$R = Z\cos\theta \qquad X = R\tan\theta \qquad X = Z\sin\theta$$

$$R = \frac{X}{\tan\theta} \qquad \frac{X}{R} = \tan\theta \qquad Z = \frac{R}{\cos\theta}$$

$$\frac{R}{Z} = \cos\theta \qquad \frac{X}{Z} = \sin\theta \qquad Z = \frac{X}{\sin\theta}$$

Table of Trigonometric Functions

Angle	Sin	Cos	Tan	Angle	Sin	Cos	Tan
5°	.087	.996	.087	50°	.766	.643	1.192
10°	.174	.985	.176	55°	.819	.574	1.428
15°	.259	.966	.268	60°	.866	.500	1.732
20°	.342	.940	.364	65°	.906	.423	2.144
25°	.423	.906	.466	70°	.940	.342	2.747
30°	.500	.866	.577	75°	.966	.259	3.732
35°	.574	.819	.700	80°	.985	.174	5.671
40°	.643	.766	.839	85°	.996	.087	11.430
45°	.707	.707	1.000	90°	1.000	.000	∞

Use the partial table of trigonometric functions on the opposite page to solve the following problems.

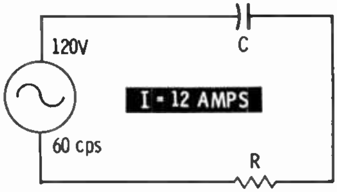
Q10. Find Z and θ for these values of X_C and R.
(a) $X_C = 3$ ohms, R = 4 ohms.
(b) $X_C = 4$ ohms, R = 3 ohms.
(c) $X_C = 10$ ohms, R = 10 ohms.
(d) $X_C = 87$ ohms, R = 50 ohms.

Q11. Find X_C and R for these values of θ and Z.
(a) $\theta = 45°$, Z = 10 ohms.
(b) $\theta = 37°$, Z = 0.5 ohms.
(c) $\theta = 15°$, Z = 1,000 ohms.

Q12. If θ is 60°, will R be larger or smaller than X_C?

Q13. If θ is 37°, will R be larger or smaller than X_C?

Q14. Will a circuit with an impedance of 100 ohms and a phase angle of 75° dissipate more or less power than a circuit with the same impedance and a phase angle of 45°?



Suppose you know the input voltage, the frequency, and the current flowing in the above circuit. Also, suppose you know that the phase angle of the circuit is 60°.

Q15. What is the DC resistance of this circuit?

Q16. What is the impedance of the circuit?

Q17. What is the capacitive reactance of the circuit?

Q18. What is the resistance of the circuit?

Q19. How much power is dissipated in the circuit?

Q20. What will happen to the capacitive reactance of the circuit if the frequency of the input is decreased?

Q21. What will happen to the phase angle of the circuit if the frequency of the input is increased?

Your Answers Should Be:

A10. (a) **$Z = 5$ ohms, $\theta = 37°$**

(b) **$Z = 5$ ohms, $\theta = 53°$**

(c) **$Z = 14.14$ ohms, $\theta = 45°$**

(d) **$Z = 100$ ohms, $\theta = 60°$**

A11. (a) **$X_C = 7.07$ ohms, $R = 7.07$ ohms.**

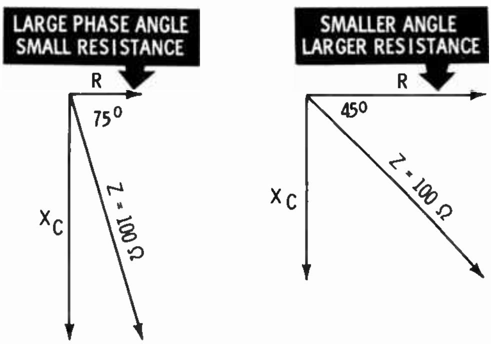
(b) **$X_C = 0.3$ ohm, $R = 0.4$ ohm.**

(c) **$X_C = 259$ ohms, $R = 966$ ohms.**

A12. If θ is 60°, **R will be less than X_C.**

A13. If θ is 37°, **R will be more than X_C.**

A14. An impedance of 100 ohms will contain less resistance and **dissipate less power** at **a** phase angle of 75° than at a phase angle of 45°.



A15. The DC resistance will be **infinite** because the capacitor blocks DC.

A16. The impedance can be found by using the formula $Z = \frac{E}{I}$. **$Z = 10$ ohms.**

A17. $X_C = Z \sin \theta =$ **8.66 ohms.**

A18. $R = Z \cos \theta =$ **5 ohms.**

A19. $P = I^2R =$ **720 watts.**

A20. X_C will **increase** if the frequency decreases.

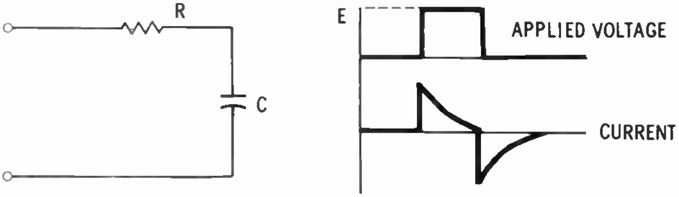
A21. The phase angle will **decrease** if the frequency increases, because X_C will decrease.

RC TIME CONSTANT

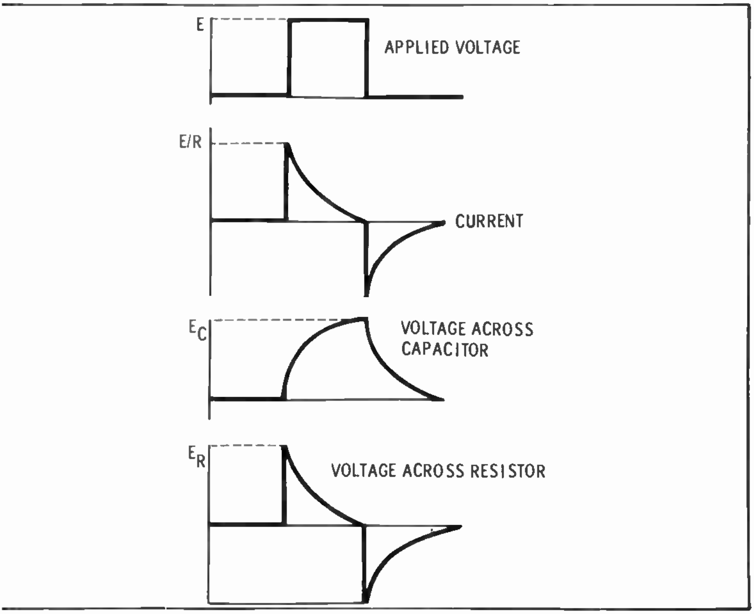
The ratio between R and C has an important effect on ıe characteristics of a circuit. The way this ratio affects C voltages and currents is indicated by a **time constant,** ı much the same way that the effects of combined inductnce and resistance were indicated.

What happens if you apply a pulse, such as a square wave,) a series RC circuit? The capacitor will oppose the sudden

A SQUARE PULSE THROUGH AN RC CIRCUIT



ıange of voltage and will gradually **charge** to source voltge E. The rate of charge (the initial current that will flow) limited by resistance R. In fact, the initial current will e $I = E/R$ and will gradually decrease to zero as the voltge **builds up** across the capacitor.



The voltage across the capacitor will start at zero and will build up smoothly until it equals source voltage E. The voltage across the resistor will, at any instant, equal the difference between the source voltage and the voltage across the capacitor; it will also be a spike as shown.

The rate of charging—the steepness of the capacitor voltage curve—depends on how much current the resistor will allow to flow. The higher the resistance, the less the current flow and the slower the charging rate will be.

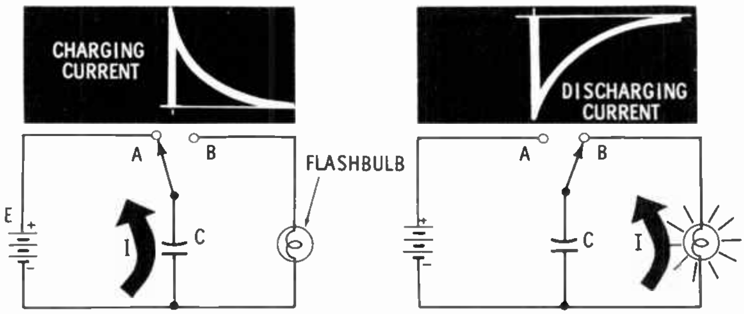
This fact is expressed in numbers by the **time constant** of the circuit. The time constant of a series RC circuit is simply R $\times$ C, where R is in ohms, C is in farads, and the time constant is in seconds. **RC** is the time it takes the capacitor to charge to 63.2% of the source voltage.

For example, if R is 10,000 ohms and C is 10 microfarads,

$$RC \text{ is } 10{,}000 \times \frac{10}{1{,}000{,}000} = 0.1 \text{ second.}$$

When a capacitor has been charged, it actually contains a certain amount of stored energy. The stored energy is C times E coulombs, where C is the capacitance in farads and E is the voltage to which the capacitor is charged.

If a charged capacitor is connected in a circuit, its stored energy is released into the circuit. An example of this is a battery-capacitor, photographic-flash circuit.

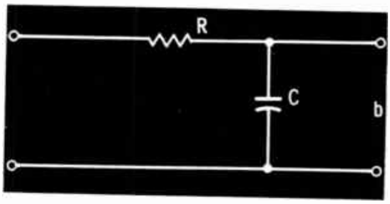


CHARGING FROM BATTERY *DISCHARGING THROUGH BULB*

Capacitor C is charged up to the battery voltage by throwing the switch to position A. The rate of charge depends on the resistance in the battery circuit (wire resistance and internal resistance of the battery). When a flash is desired, the switch is moved over to position B. The capacitor, which is charged to full battery voltage (E), has no opposing voltage in the new circuit, and its discharge is limited only by the resistance of the flash bulb. The stored energy flows through the flash bulb and, in doing so, fires the bulb. The discharging current follows the curve shown in the figure; the speed of discharge again depends on the time constant of the circuit.

An RC series circuit can be used as a timing device. It is, in fact, often used this way (e.g., in television receivers).

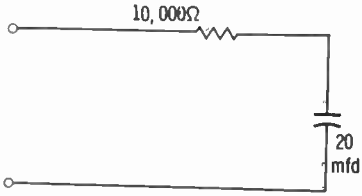
A TIMING CIRCUIT



In the above circuit, the length of time it will take for the capacitor voltage to rise to some given value can be calculated. If some device, which will be triggered only when this given value of voltage is reached, is connected across the output terminals b, the device, such as a gas diode, will be triggered after a predictable time delay from the time the input voltage (E) is applied.

The length of the time delay can be controlled by varying either the resistance or the capacitance. However, if the amount of energy stored is important, the delay can only be varied by changing the capacitance.

Q22. What is the time constant of the following circuit?



Q23. How long will it take the circuit above to charge to 63.2 volts if a 100-volt input is continuously applied?

Q24. What will the time constant be if R is 1 megohm and C is 50 mfd?

Your Answers Should Be:

A22. RC = 10,000 ohms × 0.00002 farad = **0.2 second**

A23. It will take **0.2 second** for the circuit to charge to 63.2 volts.

A24. $RC = \frac{50}{1{,}000{,}000} \times 1{,}000{,}000 =$ **50 seconds**

WHAT YOU HAVE LEARNED

1. Capacitances add in parallel. They combine in series according to the formula:

$$C_{eq} = \frac{C_1 \times C_2}{C_1 + C_2}$$

2. Capacitive reactances add in series and combine in parallel exactly like resistances and inductances.
3. A circuit containing a complicated combination of capacitors can be converted to a simple equivalent circuit by a series of steps.
4. Capacitive reactance and resistance add vectorially.
5. The capacitive-reactance vector is in the opposite direction from the inductive-reactance vector and is represented in the impedance formula by —j.
6. Capacitive impedance can be calculated using trigonometric functions.
7. The time constant of a series RC circuit is found by multiplying R times C.
8. RC circuits can be used to store energy and/or to provide a time delay.
9. RC is the time in seconds it takes the capacitor to charge to 63.2% of the source voltage.

13

RLC Circuits

What You Will Learn

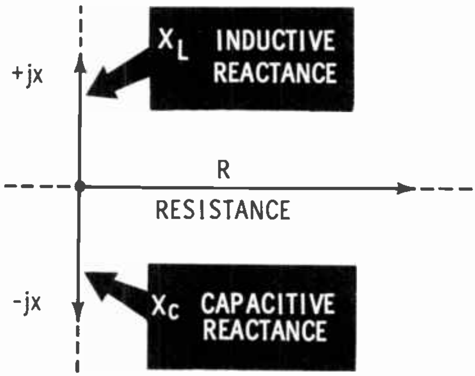
You will now learn how to combine the two reactive effects (inductive and capacitive) with and without resistance. A number of important special circuits, called tuned circuits, depend on the RLC combination. When you have finished this chapter, you will know how to calculate their effects in circuits having inputs of various frequencies. You will also learn a general rule about phase and power in AC circuits, as well as how the power factor of a circuit affects the amount of power dissipated. You will be able to analyze the effects of RLC circuits on pulse inputs in terms of frequency response. You will know how to use a universal time-constant chart to analyze the reaction that RC and RL circuits have to step voltages and square waves.

RLC IMPEDANCE

When vector diagrams are used to find the impedance and phase angle (as in the previous chapters), +jX is always drawn upward, while —jX is always drawn downward. This leads to the idea that inductance and capacitance provide opposite reactions.

What happens if a circuit contains both inductance and capacitance in series? The two reactances cannot be just arithmetically added to find the total reactance. +jX and —jX tend to offset each other, and the total effect is their difference.

The Vectors for Inductive and Capacitive Reactance Are Opposite



This difference is in the direction of the greater of the two reactances. So, if a circuit contains a capacitor, the reactance of which is —j50 ohms, and an inductor, the reactance of which is +j100 ohms, the net result is equivalent to an inductive reactance of +j50 ohms.

If a resistor is connected in series with an LC circuit, the impedance of the circuit will simply be the resultant reactance (whether inductive or capacitive) in series with the resistor.

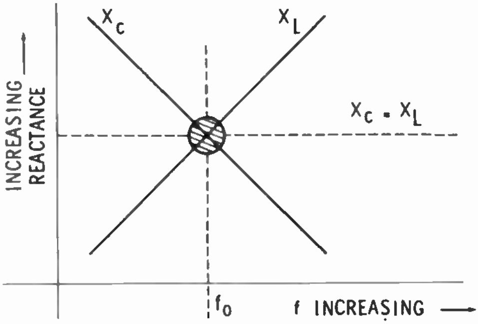
A series circuit containing L and C behaves either as a capacitor or as an inductor, whichever of the two components has the greater reactance at the operating frequency.

RESONANCE

A special case arises when the capacitive reactance and the inductive reactance are equal. When this condition exists, the reactances cancel each other and the circuit appears to be purely resistive. This can happen at only one frequency, however, for each particular set of inductive and capacitive values. At a low frequency, the inductive reactance is low and the capacitive reactance is high. The circuit, therefore, behaves as a capacitance. If the frequency of the applied voltage is gradually increased, the inductive reactance will gradually increase and the capacitive reactance will gradually decrease. At some point the two reactances become equal, and thus cancel. This point is called the resonant frequency of the circuit. If the frequency is increased further, the inductive reactance becomes greater than the capacitive reactance, and the circuit will behave as an inductor.

Every L and C combination has one, and only one, resonant frequency. It is the frequency at which the inductive and capacitive reactances are equal.

EVERY LC COMBINATION HAS ONE RESONANT FREQUENCY



Q1. Capacitance and inductance both store energy. Capacitance stores energy in a(an) ________ field. Inductance stores energy in a(an) ________ field.

Q2. How do capacitance and inductance affect a DC input?

Q3. What are the formulas for finding capacitive and inductive reactances?

Q4. How does an increase in the frequency of the input affect capacitive reactance? Inductive reactance?

Q5. Capacitive impedance is expressed in component form as R — jX. Inductive impedance is expressed as ______.

Q6. What is the total reactance of a circuit that has an X_L of 100 ohms and an X_C of 25 ohms? Is the total reactance capacitive or inductive?

Q7. The condition existing when capacitive reactance is equal to inductive reactance is known as __________.

Q8. Any circuit containing inductance and capacitance has only one ________ frequency.

Your Answers Should Be:

A1. Capacitance stores energy in an **electric** field. Inductance stores energy in a **magnetic** field.

A2. **Capacitance blocks DC. Inductance offers no opposition to DC.**

A3. $X_C = \frac{1}{2\pi fC}$; $X_L = 2\pi fL$

A4. An increase in frequency results in a **decreased capacitive reactance,** and an **increased inductive reactance.**

A5. Inductive impedance is expressed as **R + jX.**

A6. **75 ohms of inductive reactance.**

A7. The condition existing when capacitive reactance is equal to inductive reactance is known as **resonance.**

A8. Any circuit containing inductance and capacitance has only one **resonant** frequency.

Resonant Frequency Calculation

The resonant frequency (f_o) formula is derived as follows:

$$2\pi f_o L = \frac{1}{2\pi f_o C}$$

Multiplying by f_o,

$$2\pi f_o^2 L = \frac{1}{2\pi C}$$

Dividing by $2\pi L$,

$$f_o^2 = \frac{1}{4\pi^2 LC}$$

Taking the square root of both sides,

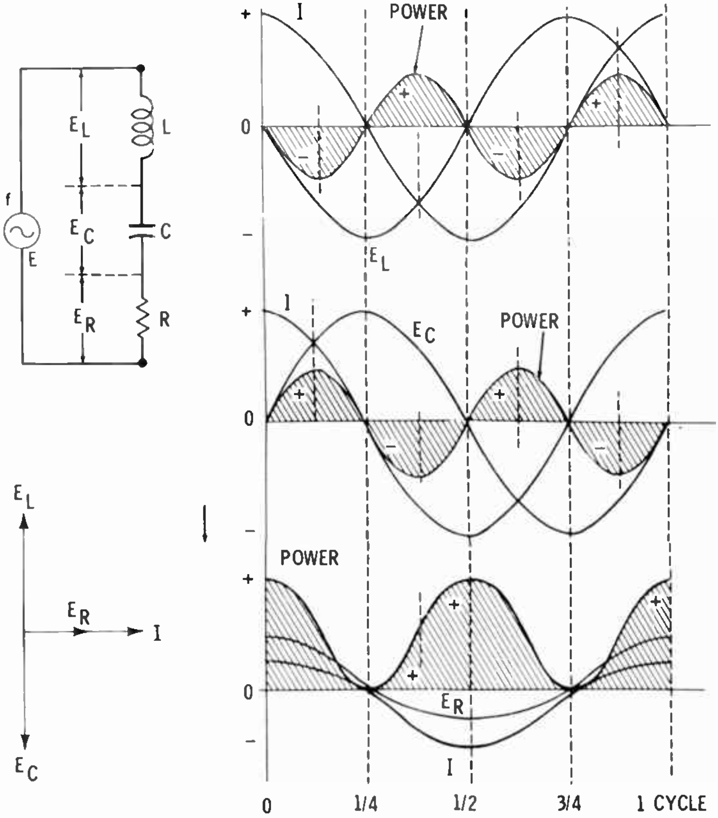
$$f_o = \frac{1}{2\pi\sqrt{LC}}$$

Now see what actually happens in a series resonant circuit. Current I, which is in phase with the applied AC voltage, flows through all three components—L, C, and R. During the first quarter cycle (of each sine wave) the inductance is returning energy **to** the circuit and the capacitance is taking energy **from** the circuit at the same rate.

During the second quarter cycle, the situation is reversed—the capacitor is returning energy, and the inductor is taking it out. This sequence occurs during each cycle.

The voltage across the capacitance is equal and opposite to the voltage across the coil at all times, and the two cancel. One voltage (E_C) is 90° behind the current and the other voltage (E_L) is 90° ahead. No power is consumed in the L and C elements—only the resistor consumes power.

SERIES RESONANCE



Q9. What is the resonant frequency of a circuit containing 2 henrys in series with 2 mfd?

Q10. If a 100-ohm resistor is placed in series with the two components of Question 9, what happens to the resonant frequency of the circuit?

Your Answers Should Be:

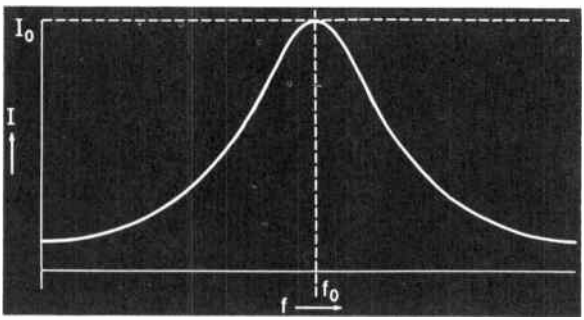
A9. $$f_0 = \frac{1}{6.28 \times \sqrt{2 \times 0.000002}} = 79.6 \text{ cps}$$

A10. If a 100-ohm resistor is placed in series with the two components of Question 9, the resonant frequency of the circuit will **remain the same.**

Q of a Resonant Circuit

At resonance, the voltage across the capacitor and across the inductor is greater than at any other frequency. The effective current in the circuit is also higher at the resonant frequency than it is below or above resonance.

Current in a Series Circuit Is Maximum at the Resonant Frequency

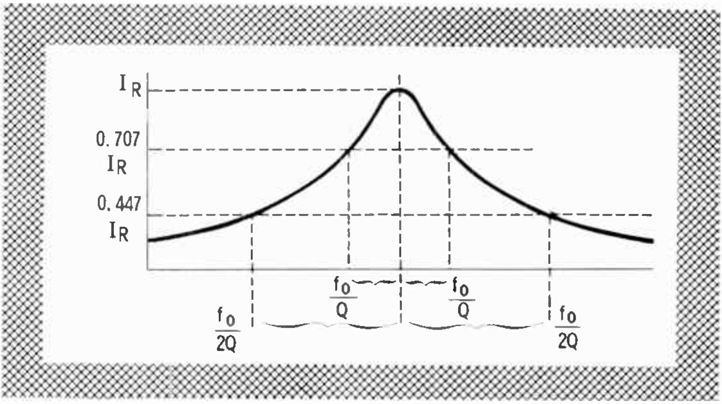


The quality of a resonant circuit can be measured by the Q factor. Q is the ratio of the energy stored in the capacitor and inductor divided by the energy dissipated in the resistor.

The amount of reactive opposition to current flow at a given frequency is not affected by the Q of the circuit. The resistive opposition, however, does vary according to the Q. This means that the shape of the resonance curve depends on this factor. If the frequency is changed from f_0 to a frequency where the reactance is low, and if the Q is high (resistance is only a few ohms), the total impedance will be halved. If the Q is low (resistance is high), the total impedance will be increased by only a small amount, and the current decrease will be very small.

The Q determines the exact shape of the resonance curve of a circuit. For example, if the resonant frequency is multiplied by $\frac{1}{Q}$, and the frequency of the input is changed from the resonant frequency by this amount, the current will be 0.707 times the resonant current. If the frequency is changed by $\frac{1}{2Q}$ times the resonant frequency, the current will be 0.447 times the resonant current.

THE Q DETERMINES THE SHAPE OF THE RESONANCE CURVE



Q11. Both the capacitor and the inductor in a resonant circuit store energy. Do both store energy at the same time?

Q12. Do they both store the same maximum amount of energy?

Q13. At what frequency would you measure the Q of a circuit?

Q14. What is the Q of a circuit whose resonant frequency is 1,000 cps, inductance is 0.5 henry, and resistance is 10 ohms?

Q15. If two resonant circuits are identical except that one has a greater R (and therefore a lower Q) than the other, which one will pass a greater effective current at a given voltage?

Q16. Draw a curve representing current for various frequencies in a low-Q, series resonant circuit.

Your Answers Should Be:

A11. **No.** The inductor stores energy when the capacitor is releasing it, and vice versa.

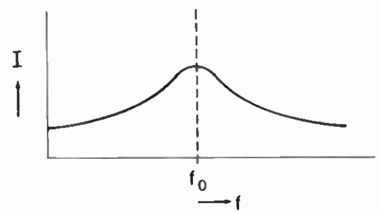
A12. **Yes.** When maximum energy is stored in the inductor, the capacitor has stored no energy.

A13. At its **resonant frequency.**

A14. $Q = \frac{X_L}{R} = \frac{2\pi fL}{R} = \frac{3{,}140}{10} = 314$

A15. **The one with the higher Q** will pass the greater current.

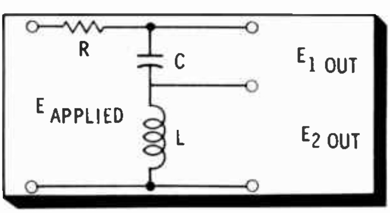
A16. Your curve should look something like this:



APPLICATIONS

Frequency-selective properties of series resonant circuits are useful in applications where it is desired to pass one particular frequency with more ease than others. The circuit can act as a filter.

A BANDPASS FILTER



If the voltage across either L or C is used for the output, the voltage will be much greater for signals having the resonant frequency than for signals above or below this frequency. Such a circuit is called a **bandpass filter.**

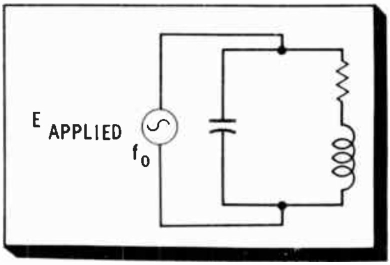
The width of the bandpass depends on the circuit Q—the higher the Q, the sharper the resonance curve, and the narrower the bandpass.

In a radio-frequency circuit a high-Q tuned circuit can be used to select the desired station and reject all others. In a power supply, a circuit using fairly large L and C values may be used to reject undesired frequencies.

PARALLEL RESONANT CIRCUITS

A parallel resonant circuit is made up of inductance and each of the two branches shows reactance. The capacitive losses are usually associated with the coil rather than with the capacitor, the resistance is usually shown as being in series with the inductance.

A PARALLEL RESONANT CIRCUIT



Q17. **What is the phase relationship between the applied voltage and the output voltage across the capacitor in the circuit on the opposite page?**

Q18. **What is the phase relationship between the applied voltage and the output voltage across the inductor?**

Q19. **What is the phase relationship between the applied voltage and the current through the circuit?**

Q20. **Analyze what will happen in the circuit on this page. Assume that R is negligible. What effect will C have on the phase of the current through the C branch?**

Q21. **What effect will L have on the phase of the current through the L branch?**

Q22. **Draw a sketch of the applied voltage sine wave and then of the inductive and capacitive currents to show their phase relationships.**

Your Answers Should Be:

A17. Output voltage across the capacitor **lags** the applied voltage by 90°.

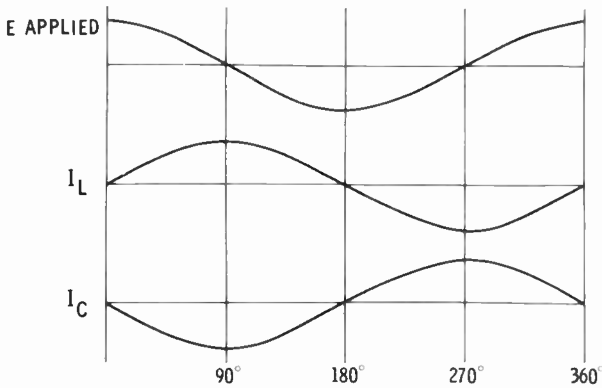
A18. Output voltage across the inductor **leads** the applied voltage by 90°.

A19. Current is **in phase** with the applied voltage.

A20. In the C branch, current will **lead** the applied voltage by 90°.

A21. In the L branch, current will lag the applied voltage by 90° (if R is negligible).

A22. Your sketch should look like this:

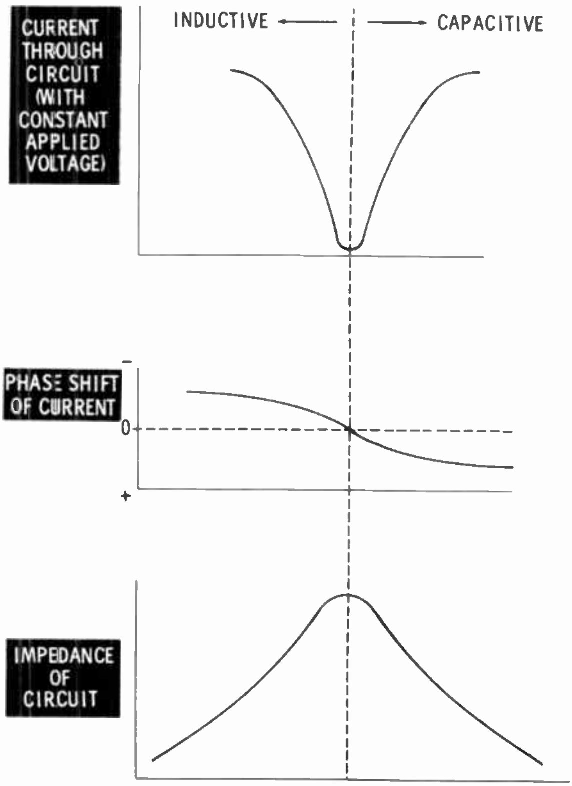


Parallel RLC Circuits

When an AC voltage is applied to a parallel RLC circuit, each of the two branches shows reactance. The capacitive reactance in the capacitor branch is high at low frequencies, and decreases as the frequency increases. Similarly, the inductive reactance of the inductor branch is low at low frequencies, and increases as the frequency increases.

The capacitor has a high reactance and the inductor a low reactance at frequencies below resonance. Consequently, most of the current flows through the inductive branch and lags the applied voltage. Similarly, if the frequency is above resonance, most of the current will flow in the capacitive branch and will lead the applied voltage.

At some particular frequency the two reactances in a parallel resonant circuit are exactly equal. Since there is an AC voltage applied across each branch, both kinds of current are present—an inductive current in the inductive branch and a capacitive current in the capacitive branch. At resonance the two currents are equal.

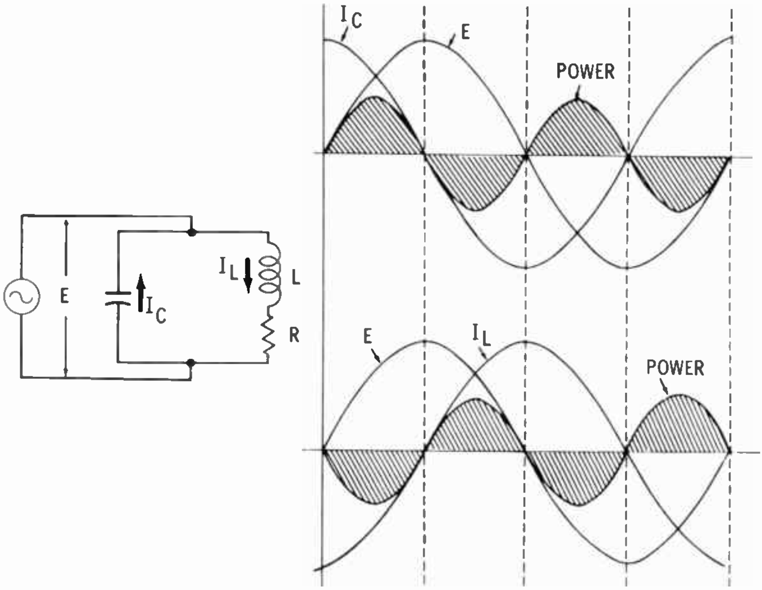


But, because one of the currents **leads** the applied voltage by 90° and the other **lags** the voltage by 90°, the two currents are 180° out of phase with each other. This means that they cancel (add up to zero).

The applied voltage was kept constant as the frequency was varied. Since current is minimum through the circuit at resonance, a parallel circuit has a higher impedance at the resonant frequency than at any other.

Now, let's look at what happens inside the loop formed by the inductance and capacitance.

Current, Voltage, and Power Relationship in a Parallel Resonant Circuit



The two large currents—inductive and capacitive—still flow, but only inside the loop. Energy alternately flows from capacitor to inductor and back again, twice each cycle. The capacitor alternately charges and discharges, first in one direction and then in the other. The inductive magnetic field alternately builds up and collapses, changing polarity twice each cycle. But all this flow back and forth is contained in the loop, and none appears in the external circuit. The outside circuit only has to replenish the energy lost in any resistance the inductor has, and this constitutes the entire external current.

The Q of the circuit, just as in the series resonant circuit, is the inductive reactance at resonance divided by the resistance of the inductor ($\frac{X_L}{R}$). In a parallel resonant circuit the loop current flowing between inductor and capacitor is Q times the external (resistive) current.

A parallel resonant circuit is, in a way, the opposite of a series resonant circuit. A series circuit has low impedance at resonance (maximum current); a parallel circuit has high impedance (minimum current). The total impedance will be greater as X_L and X_C become greater relative to resistance. It will decrease as R increases and draws more current. The impedance of a parallel circuit at its resonant frequency can be found by this formula:

$$Z_o = \frac{X_L X_C}{R}$$

If you use the formulas for X_L and X_C, you can also develop another formula.

$$X_L\, X_C = 2\pi fL \times \frac{1}{2\pi fC} = \frac{2\pi fL}{2\pi fC} = \frac{L}{C}$$

Substituting in the above impedance formula,

$$Z_o = \frac{X_L X_C}{R} = \frac{L}{CR}$$

Another useful formula can be developed if you notice that X_L/R is the Q of the circuit. This means that the impedance at resonance is simply X_C (or X_L since they are equal) times the Q of the circuit.

$$Z_o = X_L Q = 2\pi fLQ$$

The impedance curve for a parallel resonant circuit is the same shape as the current curve for a series resonant circuit. Its shape depends on the Q of the circuit in the same way.

Parallel tuned circuits are used in receivers, transmitters, and similar equipment. For instance, the five-tube radio receiver has parallel tuned circuits in its IF amplifiers. Their function is to select certain frequencies and reject others.

Q23. What is the impedance at resonance of a parallel resonant circuit consisting of a 1-henry inductor with 1 ohm of DC resistance, and a 1-mfd capacitor?

Q24. If the resonant frequency of a circuit is 1,000 cps, L is 1 henry, and the Q of the circuit is 80, what is the impedance of the circuit at resonance?

Your Answers Should Be:

A23. $Z_0 = \frac{L}{CR} = \frac{1}{0.000001 \times 1} = 1$ **megohm**

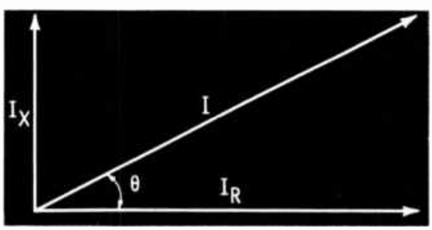
A24. $Z_0 = 2\pi fLQ = 6.28 \times 1{,}000 \times 1 \times 80 = 502{,}400$ ohms

POWER IN RLC CIRCUITS

To calculate the power dissipated in a circuit containing only resistance, either $P = I^2R$ or $P = EI$ can be used. Either will yield the same result. However, $P = EI$ applies only to resistive circuits (circuits in which the voltage and current are in phase).

In a parallel circuit that contains resistance and either capacitance or inductance, $P = EI$ gives the **apparent power.** This, however, is not the true power—apparent power is always larger. The reason is that the overall current in a reactive circuit is not in phase with the voltage. The total current is actually the vector sum of the resistive current (which is in phase with voltage) and the reactive current (which leads or lags by 90°). To use $P = EI$, multiply the voltage by only that portion of the current that is in phase—the resistive current. In order to calculate the true consumed power, the resistive and reactive currents must be taken separately.

The Overall Current Is The Vector Sum of the Reactive Current and the Resistive Current



The overall current is the vector sum of the reactive current and the resistive current. This overall current leads or lags the applied voltage by an angle θ.

The true power dissipated in a circuit is found by multiplying the apparent power by cos θ.

$$\frac{EI \cos \theta}{EI} = \cos \theta$$

True power divided by apparent power equals cos θ and is called the **power factor** of the circuit. There are several things to consider about power factor. The more reactance there is in a circuit (compared to the resistance present), the more out of phase the current will be with the voltage, and the smaller the power factor will be.

It is possible to represent the total current flowing as two separate component currents at right angles to each other. The resistive current produces power (does the work). The reactive current merely flows in and out of the capacitance or inductance as it charges and discharges, but it does no work.

Even though the reactive current produces no power in the circuit, the wires must be large enough to carry it. Power lines are designed to carry the total current, not just the resistive component.

A low power factor sometimes leads to problems. For example, when a plant that uses induction motors draws a large reactive current (has a low power factor), equipment must be provided to supply it with more current than it actually consumes. The large inductive component can be canceled in such cases by placing large capacitors in series with the load. The capacitors draw reactive current 180° out of phase with the inductive current, and thus the capacitors cancel the inductive component. This is called "power factor improvement" and can save considerable money in large power installations. Another method sometimes employed by power companies to improve a low power factor is to persuade the consumer to use synchronous instead of induction-type motors. This results in an overall saving to the power company because less power need be generated and supplied to the consumer.

Q25. Is a high or a low power factor desirable in electrical circuits used to transmit power?

Q26. How can inductive reactance be canceled to increase the power factor in an inductive circuit?

Your Answers Should Be:

A25. A **high** power factor.

A26. Inductive reactance can be canceled by **capacitive reactance.**

PULSES IN RLC CIRCUITS

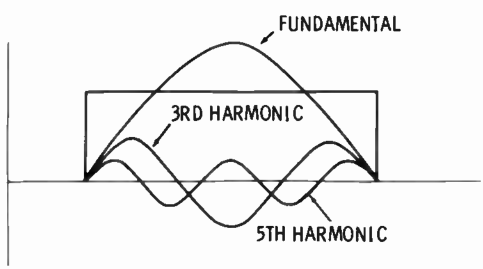
Pulses are a special type of AC, even though they often have a DC component as well, and are very important in modern electronics. Radar systems are based on pulses of RF energy reflected from targets. Digital computers, counters, and other data-processing circuits employ pulses. Pulses are also used in telemetry and remote control to switch circuits on and off. Trains of pulses are used to transmit information between satellites, spaceships, and the earth.

All these applications create a need for circuits that can generate, amplify, send, receive, count, recognize, and/or process pulses. Because pulses are composed of a combination of many sine-wave frequencies, pulse-handling circuits have very severe requirements placed on them.

Frequency Response

All pulse waveforms are made up of a combination of sine waves.

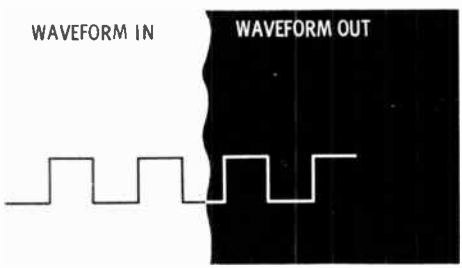
A SQUARE WAVE IS COMPOSED OF SINE WAVES



The lowest frequency contained in a train of rectangular pulses is called the fundamental frequency. This frequency has a period equal to that of the square wave. All the other frequencies contained in the square wave are **harmonics**, or multiples, of the fundamental frequency. In the case of a square or rectangular wave, only the **odd harmonics** are included. The next higher frequency is three times the fundamental (the third harmonic), then five times the fundamental (the fifth harmonic), etc. A perfectly square waveform contains an infinite number of odd harmonics, from the fundamental up.

To pass or amplify a square wave without distortion, a circuit must be able to pass all the frequencies contained in the wave. In practice, an infinitely high frequency response is not possible, nor is it necessary. This less-than-perfect response is because all circuits have some frequency-sensitive characteristics due to such factors as stray capacitance, the inability of vacuum tubes or transistors to amplify signals above certain limits, etc. All of these frequency-sensitive characteristics result in the corners of the square wave being rounded off.

THE CIRCUIT RESPONDS THE SAME WAY TO ALL FREQUENCIES ABOVE THE FUNDAMENTAL



Q27. In a pulse circuit, inductance opposes a change in ________.

Q28. In a pulse circuit, capacitance opposes a change in ________.

Q29. What sine-wave frequency contributes most of the amplitude of the flat-top, or straight-line, portion of a square wave?

Q30. What sine-wave frequencies are responsible for the steep leading and trailing edges of a square wave?

Your Answers Should Be:

A27. In a pulse circuit, inductance opposes a change in **current.**

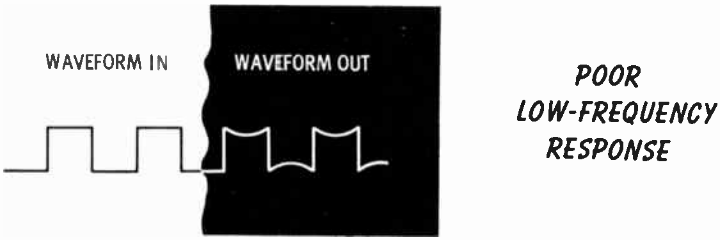
A28. In a pulse circuit, capacitance opposes a change in **voltage.**

A29. The **fundamental** frequency.

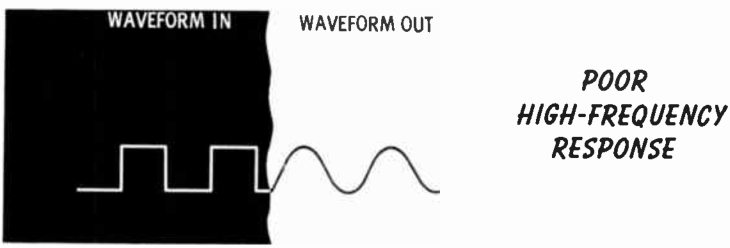
A30. The **higher** harmonic frequencies.

Pulse Circuit Applications

If a circuit has poor low-frequency response, there will be a visible sag in the level portion of the output waveform.



If the circuit has good low-frequency response but poor high-frequency response, the corners of the output waveform will be rounded off.

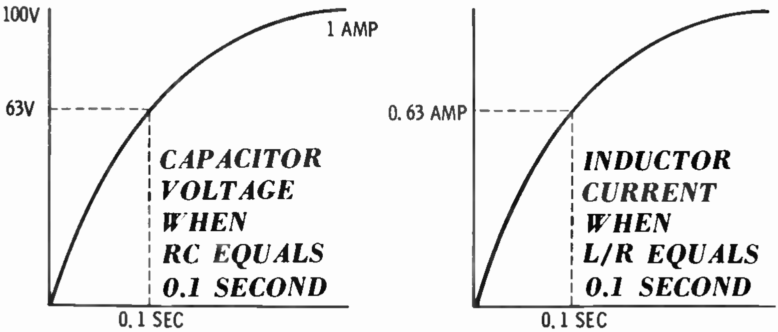


It depends on the application of the pulse whether a particular circuit is good enough or not. In a telegraph system, it may only be necessary to detect the presence or absence of pulses with no concern as to their exact shape. So, the high-frequency response of the circuit would not be critical.

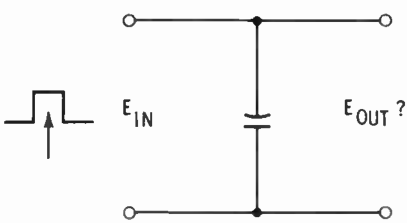
If precise location of the start of a pulse is necessary (as in a precision radar, or a timing circuit), then the high-frequency response of the circuit is extremely critical.

TIME CONSTANTS

L/R and RC time constants indicate how quickly current or voltage builds up when a sudden increase in DC voltage (such as a square wave) is applied to a particular combination of L and R or C and R. One time constant is the time required for voltage (or current, depending on the circuit) to reach 63% of its peak value. The percentage of the peak value can be calculated for any elapsed time if the time constant of the circuit is known. The curves for the voltage increase across a capacitor, or the current increase through an inductor, are exactly the same if the time constants of the two circuits are the same.



Q31. If a square wave is applied to the circuit below, the capacitor will tend to bypass what frequencies? What frequencies will be emphasized in the voltage across the capacitor? How will this affect the shape of the output waveform?

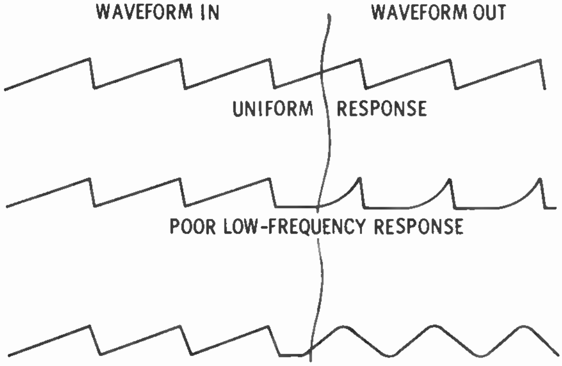


Q32. Sketch how you think a sawtooth wave should be affected by a circuit with a poor low-frequency response. With a poor high-frequency response.

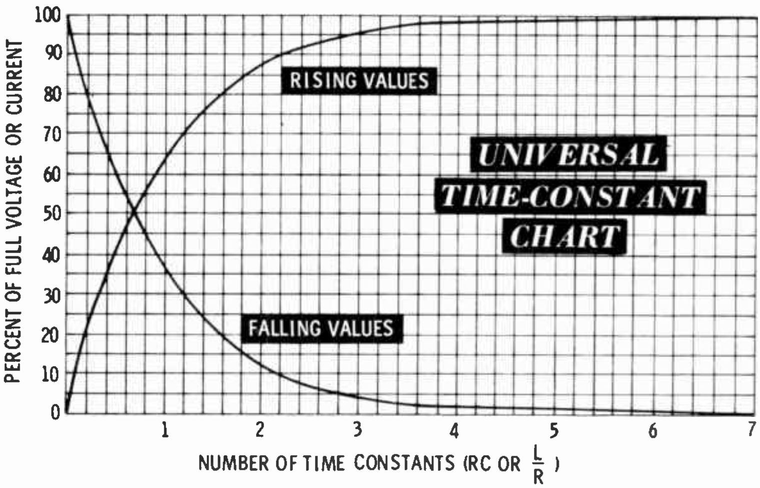
Your Answers Should Be:

A31. The capacitor will tend to **bypass** the **high frequencies** and **emphasize** the **low frequencies** in the output voltage. This will tend to **round off the steep edges** of the waveform.

A32. The response to a sawtooth is very similar to that of the square wave.

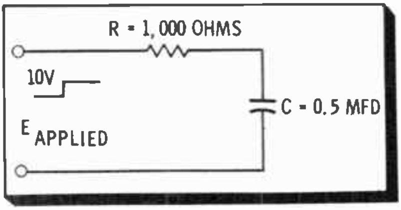


Poor low-frequency response produces a sag in the **sloped portions** of the wave, while poor high-frequency response **rounds off** the **sharp corners** of the wave.



A **universal time-constant chart** can be used to calculate the growth and decay of voltage and currents in any RL or RC circuit to which a sudden step voltage is applied. All you have to know is the final voltage and current, and the time constant of the circuit.

Calculate the voltage across the capacitor and the current in the following circuit:



The time constant is:

$RC = 1{,}000 \times 0.5 \times 10^{-6} = 0.5 \times 10^{-3} = 0.5$ millisecond

When the 10 volts is first applied, the current will be E/R $= \frac{10}{1{,}000} = 0.01$ ampere. Using the time constant and the falling curve in the chart, it can be seen that at the end of one time constant (0.5 millisec), the current is about 37% of its full value ($0.37 \times 0.01 = 0.0037$ ampere). At the end of two time constants (1 millisecond), current will be 13% ($0.13 \times 0.01 = 1.3$ milliamperes). At the end of three time constants, current will be 5% ($0.05 \times 0.01 = 0.5$ milliampere), and so on.

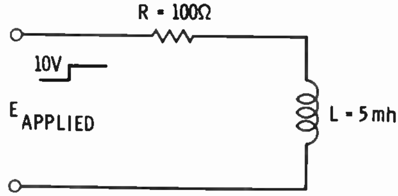
The voltage across the capacitor can be determined in a similar manner. When the switch is first closed, E_C is zero. This voltage gradually increases to the value of the power supply, or 10 volts. At the end of one time constant (0.5 millisec) E_C will be 63% of maximum (6.3 volts). At the end of two time constants (1 millisec) E_C will be 87% of maximum (8.7 volts), etc.

The same chart can be used when the voltage is suddenly removed (the switch is opened). In this case, E_C decays according to the falling curve.

Q33. Use the universal time-constant chart to describe in detail what happens when a step voltage of 10 volts is applied across a 100-ohm resistance in series with a 5-millihenry inductance.

Your Answers Should Be:

A33.



Time constant $= \frac{L}{R} = \frac{0.005}{100} = 50$ microseconds.

(1) Current through R and L is zero to start with, and increases to $\frac{E}{R} = \frac{10}{100} = 0.1$ ampere eventually. Use the rising curve.

(2) Voltage across L is 10 volts initially, and drops to zero eventually. Use the falling curve.

(3) Voltage across R is zero at first, and rises to 10 volts eventually. Use the rising curve.

Time in sec	No. of time constants	I amps	E_L volts	E_R volts
0	0	0	10.0	0
0.25	0.5	0.038	6.2	3.8
0.35	0.7	0.050	5.0	5.0
0.50	1.0	0.063	3.7	6.3
1.00	2.0	0.087	1.3	8.7
1.50	3.0	0.095	0.5	9.5
2.00	4.0	0.098	0.2	9.8
2.50	5.0	0.099	0.1	9.9
3.00	6.0	0.0995	0.05	9.99
		0.100	0	10.00

Remember that a universal time-constant chart can only be used with step voltages or square waves.

WHAT YOU HAVE LEARNED

1. Equal amounts of capacitive and inductive reactance cancel each other when they are combined in series. If inductive reactance is greater than capacitive reactance, the total circuit will behave as though it had only an inductive reactance equal to the difference between the two reactances. If capacitive reactance is greater, the circuit will be capacitive.

2. For any series RLC circuit there is one frequency at which the two reactances are exactly equal. This is called the resonant frequency. This frequency can be found by setting the formulas for inductive and capacitive reactance equal to each other:

$$f_o = \frac{1}{2\pi\sqrt{LC}}$$

3. Maximum current will flow in a series RLC circuit at the resonant frequency, and this current will decrease at higher or lower frequencies.

4. A parallel RLC circuit has maximum impedance at its resonant frequency, and much lower impedance at higher or lower frequencies.

5. The Q of a resonant circuit is the amount of reactance of either kind, divided by the resistance. $Q = \frac{X_L}{R} = \frac{X_C}{R}$. The Q of a resonant circuit determines how quickly current or impedance decreases as the frequency is changed from the resonant frequency. High Q means a very sharp drop, low Q means a slower decrease.

6. Formulas $\frac{L}{CR} = Z_o$, $X_LQ = Z_o$, and $2\pi fLQ = Z_o$ give the impedance of a parallel resonant circuit at its resonant frequency.

7. $P = EI \cos \theta$ is a power formula that can be used to find true power in any kind of RLC circuit. Cos θ is the cosine of the phase angle between the reactive and resistive vectors, and is called the power factor. $I \cos \theta$ represents the resistive portion of the overall current.

8. The straight-line (flat-top) portions of pulses are determined by the low-frequency, sine-wave components and the steep edges are determined by the high-frequency components.
9. RLC circuits that tend to filter out low frequencies cause the straight-line portions of pulse waveforms to sag, while those that filter out high frequencies cause the steep edges to be rounded off.
10. A universal time-constant chart can be used to analyze the response of either an RL or an RC circuit to a step voltage.

14

Transformer Action

What You Will Learn

Your understanding of AC electricity will now be used to show how two common electrical devices work. You will learn how a transformer transfers power from one winding to another. You will learn how to calculate the change in voltage, current, and impedance produced by a transformer with a known turns ratio, and how to select the proper turns ratio to produce a particular change. You will also learn how a magnetic amplifier controls a large AC current with a smaller DC current.

WHAT IS A TRANSFORMER?

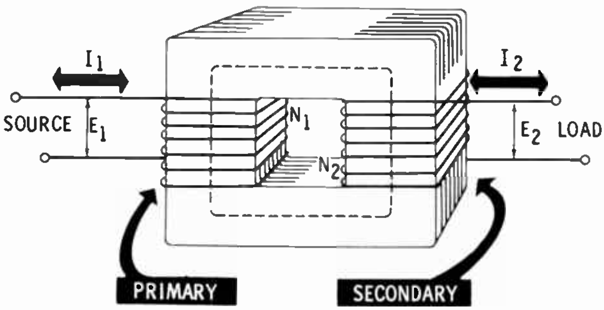
A **transformer** is a device for changing the voltage of AC electricity. Transformers work on the principle of induction. Basically, a transformer has two windings—a primary and a secondary—wound on the same core. This core can be laminated iron, ferrite, or air.

Through the principle of **induction** the alternating current flowing through the primary winding sets up an alternating magnetic field in the core. This magnetic field, in turn, **induces** an alternating voltage in the secondary winding (or windings). In this way, **energy is transferred** from the primary to the secondary.

A transformer that reduces the voltage in a circuit is called a **step-down** transformer. This is true, for example, of a radio-receiver filament transformer, which steps the 120-volt main supply down to 6.3 volts.

A transformer that is used to increase the voltage in the circuit is known as a **step-up** transformer. An example is the high-voltage transformer which produces the several thousand volts needed to operate a television picture tube.

A BASIC TRANSFORMER



The basic transformer has two windings—primary and secondary—wound on a laminated-iron core. The two windings are insulated from each other and from the core.

The primary winding is connected to the energy source, and the secondary winding is connected to the load. As alternating current flows through the primary, a pulsating magnetic field is set up in the core. As the constantly changing magnetic field cuts the turns of the secondary, a voltage is induced in the secondary winding.

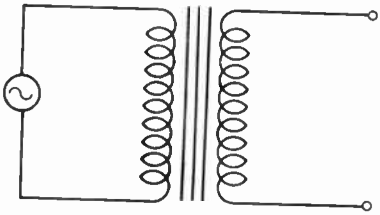
The amount of voltage induced in the secondary winding depends on how many turns of wire the secondary contains compared to the number of turns of wire in the primary winding. So, if the secondary has only half as many turns as the primary winding, the voltage will be stepped down to half its original value. If the secondary has twice as many turns as the primary, the voltage will be stepped up to twice its original value.

The difference in the number of turns is known as the **turns ratio** of the transformer. If the primary winding has N_1 turns and its voltage is E_1, the secondary winding with N_2 turns produces voltage E_2.

$$\frac{E_1}{E_2} = \frac{N_1}{N_2}$$

The power consumed in the secondary circuit of a transformer must be supplied by the primary. Since the voltages are constant in each circuit, the current in the primary circuit must vary to supply the amount of power demanded by the secondary. Current in the primary depends on the current drawn in the secondary circuit.

A TRANSFORMER WITH NO LOAD ACTS LIKE AN INDUCTOR



Q1. If a transformer primary has 1,000 turns and the secondary has 6,500 turns, what is the turns ratio?

Q2. If 85 volts is applied to the primary winding of the transformer in Question 1, what is the voltage at the secondary?

Q3. What would happen if the leads were reversed and 85 volts was applied to the 6,500-turn coil?

Q4. What happens if 130 volts is fed into the 6,500-turn winding of the transformer?

Q5. Can a transformer be used with DC? Why?

Q6. What will be the phase relationship between the voltage across the primary of a transformer and the voltage across the secondary, assuming the coils are wound in the same direction?

Q7. If there is no load between the terminals of the secondary of a transformer, will current flow in the secondary?

Q8. Will there be a magnetic field produced by current in the secondary?

Q9. Will there be a magnetic field produced by current in the primary?

Q10. What effect will this magnetic field have on the impedance of the primary circuit?

Q11. If the magnetic field were weaker, would more or less current flow in the primary circuit?

Your Answers Should Be:

A1.

$$\frac{N_1}{N_2} = \frac{1{,}000}{6{,}500} = \mathbf{1 \text{ to } 6.5}$$

A2.

$$\frac{E_1}{E_2} = \frac{1}{6.5}$$

$$E_2 = E_1 \times 6.5 = 85 \times 6.5 = \mathbf{552.5 \text{ volts}}$$

A3. If you reverse the leads, the turns ratio is:

$$\frac{N_1}{N_2} = \frac{6{,}500}{1{,}000} = \frac{E_2}{E_1}$$

The output would be:

$$E_2 = \frac{1{,}000 \times 85}{6{,}500} = 85 \times 0.153$$

$$= \mathbf{13 \text{ volts (approx.)}}$$

A4. The voltage appearing at the 1,000-turn winding will be $\frac{1{,}000}{6{,}500} \times 130 =$ **20 volts.**

A5. **A transformer cannot be used with direct current.** A direct current in the primary does not produce a pulsating magnetic field.

A6. The voltage across the secondary will be **180° out of phase** with the voltage across the primary.

A7. **No current will flow.**

A8. If no current flows, **no magnetic field** will be produced by the secondary.

A9. **Yes.**

A10. The **stronger the magnetic field,** the **greater will be the impedance** of the primary circuit.

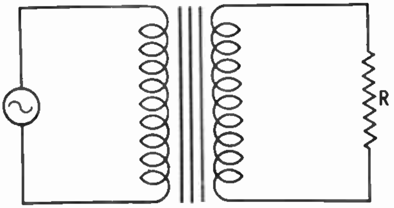
A11. **More** current would flow in the primary.

TRANSFORMER POWER

If the transformer were 100% efficient, all the power from the primary winding would be transferred to the secondary and delivered to the load.

Suppose a transformer has 1,000 turns in the primary and 6,500 turns in the secondary. If 100 volts is applied to the primary, 650 volts will appear at the secondary. Now, suppose the load connected to the secondary is a 65-ohm resistor. It will draw a current of $\frac{650}{65}$, or 10 amperes, and the power consumed will be 650×10, or 6,500 watts. This power must be supplied by the primary winding. Assuming no loss in the transformer, the primary winding must supply 6,500 watts. The primary current, therefore, will be $\frac{6{,}500 \text{ watts}}{100 \text{ volts}}$ = 65 amperes.

A TRANSFORMER WITH A LOAD



In the example above, the current was stepped down in exactly the same proportion as the voltage was stepped up. The power transferred from the primary to the secondary does not change, however, regardless of the turns ratio. This is true providing the rating of the transformer has not been exceeded and assuming 100% efficiency.

Q12. What happens to current in the secondary of a transformer when a load is connected across its terminals?

Q13. Will a magnetic field be produced by the current in the secondary?

Q14. Will the magnetic field add to or oppose the magnetic field produced by the primary? (Remember the coils are wound in the same direction but the currents are in opposite directions.)

Q15. How will the magnetic field produced by current flow in the secondary affect the current drawn by the primary?

Q16. What will happen if the load resistance in the circuit above is increased to 6,500 ohms?

Your Answers Should Be:

A12. There **will be a current** in the secondary when a load is connected across its terminals.

A13. A magnetic field **will be produced** by a current in the secondary.

A14. The secondary magnetic field will **oppose** that of the primary.

A15. The secondary magnetic field will decrease the total magnetic field acting on the primary and, therefore, will decrease the impedance of the primary circuit. The **primary will draw more current.**

A16. Current in the secondary will be $\frac{650 \text{ volts}}{6{,}500 \text{ ohms}} =$ **0.1 ampere.** Power dissipated in the secondary will be 0.1 ampere $\times$ 650 volts $=$ **65 watts.** Therefore, power drawn in the primary must be 65 watts. The current in the primary will then be $\frac{65 \text{ watts}}{100 \text{ volts}}$ $=$ **0.65 ampere.**

TRANSFORMER EFFICIENCY

So far we have assumed that no power is lost in the transfer from the primary winding to the secondary winding. However, no transformer has absolutely 100% efficiency. Some power is lost in heating the core, and some is lost in the resistance of the windings. But, transformers are very efficient; their efficiency often reaches very nearly 100%. Therefore, for rough calculations, it is permissible to assume 100% efficiency.

As with any other device, the efficiency of a transformer is equal to:

$$\frac{\text{output power}}{\text{input power}}$$

Most transformers have an efficiency in the range of 97 to 99%. So even if you neglect the losses, your calculations using 100% as the transformer efficiency will still be accurate within 1 to 3%.

TRANSFORMER LOSSES

The power loss in transformers is due to three factors. The first is simply **resistance** in the windings; no winding is a perfect conductor. The second factor that causes power loss in transformers is **eddy currents.** The iron in the core of a transformer is a conductor. When the changing magnetic field produced by the primary coil cuts through the iron of the core, small currents are generated in the core material. These currents dissipate power as they pass through the resistance of the iron. These currents are called **eddy currents.** This type of loss is held to a minimum by using thin sheets of iron, called **laminations,** in the core. These thin sheets are insulated from each other (often by oxidizing the surface of the sheets) and thus shorten the conducting path for the eddy currents.

The third factor that causes power loss in transformers is **hysteresis.** It takes a certain small amount of power to magnetize a piece of iron. This power must be expended again when the magnetic field is reversed. Since the magnetic field in a transformer is reversed many times each second, these tiny expenditures of power add up to a noticeable loss. Hysteresis loss can be reduced by constructing the core with a type of iron that is very easily magnetized and demagnetized.

Q17. If a transformer supplies 1.9 amperes at 100 volts to a resistive load in the secondary circuit, and if it dissipates 200 watts of power in the primary circuit, what is the efficiency of the transformer?

Q18. This transformer has a relatively (high, low) efficiency.

Q19. If the secondary of a transformer supplies 0.99 watt at 1,000 volts and the transformer has an efficiency of 99%, what power will the primary draw at 120 volts?

Q20. How could you find the amount of power lost due to resistance in a transformer?

Q21. Does an air-core transformer have hysteresis or eddy currents?

Your Answers Should Be:

A17. The power dissipated in the secondary will be 1.9 $\times$ 100 = 190 watts. The efficiency of the transformer will be 190/200 = **95%.**

A18. It has a relatively **low** efficiency. (An efficiency below approximately 97% is considered to be low.)

A19. The voltages have no effect on the problem. The efficiency of the transformer is equal to output power divided by input power.

$$\frac{0.99}{?} = 99\%$$

The input power must be **1 watt.**

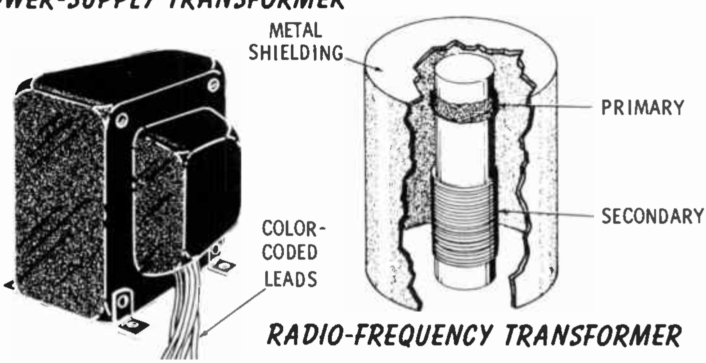
A20. You would have to **measure the resistance** of both windings and then calculate the **power dissipated** due to the current in the windings.

A21. An air-core transformer has neither **eddy-current nor hysteresis losses.**

TYPES OF TRANSFORMERS

There are many varieties of transformers, ranging from huge power-station units to tiny subminiature radio-frequency types.

POWER-SUPPLY TRANSFORMER



RADIO-FREQUENCY TRANSFORMER

Most transformers are designed to transfer power. Others, however, are built to transfer only signal voltages.

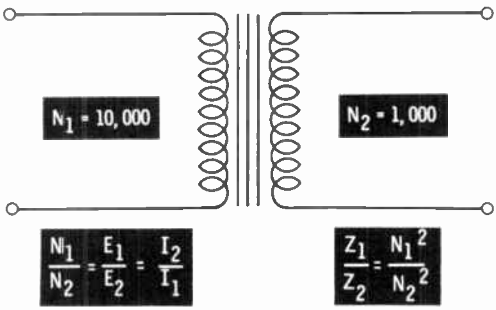
Power-distribution transformers are rated in KVA (kilo-volt-amperes) rather than in kilowatts or other power units. The KVA rating refers to the apparent power carried by the transformer—the real power is smaller by the load power factor.

Special transformers, wound to precision specifications, are used in metering applications to measure the current and voltage passing through large power-transmission lines.

A step-up transformer increases voltage (which increases impedance) and decreases current (resulting from an increased impedance) at the same time. A step-down transformer decreases voltage (which decreases impedance) and increases current (which results from a decreased impedance) at the same time. Therefore, a transformer changes impedance, but the impedance change is more pronounced than the voltage change. In fact, a transformer changes impedance by the square of the turns ratio:

$$\frac{Z_1}{Z_2} = \frac{N_1^2}{N_2^2}$$

AN IMPEDANCE MATCHING TRANSFORMER



Q22. If the primary of a transformer has 10,000 turns and the secondary has 1,000 turns, what is the turns ratio?

Q23. If 100 volts is applied to the primary, what voltage will appear at the secondary?

Q24. If the load impedance of the secondary circuit is 1 ohm, how much current will flow in the primary?

Q25. What is the impedance of the primary?

Your Answers Should Be:

A22. $\frac{10{,}000}{1{,}000} = $ **10-to-1 turns ratio**

A23. $\frac{N_1}{N_2} = \frac{10}{1} = \frac{100}{E_2}$; $E_2 = $ **10 volts**

A24. Current in the secondary is $\frac{10}{1} = 10$ amperes.

$$\frac{N_1}{N_2} = \frac{I_2}{I_1};\ \frac{10}{1} = \frac{10}{I_1}$$

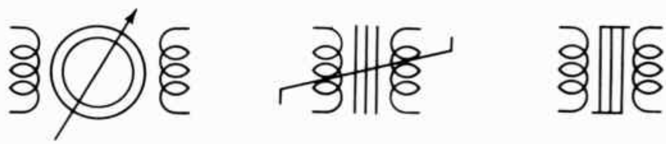
$$I_1 = \mathbf{1\ ampere}$$

A25. The impedance of the primary circuit is:

$$\frac{E_1}{I_1} = \frac{100}{1} = \mathbf{100\ ohms}$$

MAGNETIC AMPLIFIERS

Magnetic amplifiers are special transformer-like devices that use a small amount of power to control larger amounts of power, thus acting as amplifiers. They are simple, rugged, and efficient as compared to other forms of amplification. The following are some of the symbols used to denote magnetic amplifiers.



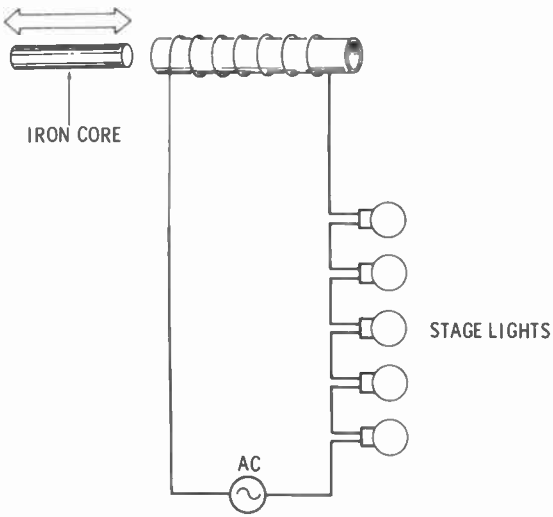
MAGNETIC-AMPLIFIER SYMBOLS

Magnetic amplifiers take advantage of a special property of iron or steel in a strong magnetic field. To explain how a simple magnetic amplifier works, let's first review the basic principles of a coil.

When a current flows in a coil, a magnetic field (flux) is set up inside and around the coil. If the current is AC, the field also alternates. But, in any case, the strength of the magnetic field (the number of lines of flux produced) depends on the material inside the coil as well as how much current is flowing through the coil.

A very simple type of magnetic amplifier is based on the fact that an iron core normally allows greater changes in the magnetic field and, therefore, increases the inductive reactance of a coil at a given frequency.

A MAGNETIC AMPLIFIER USED TO CONTROL STAGE LIGHTS



Q26. A coil with an air core has a (greater, smaller) inductance than a similar coil with an iron core.

Q27. Inductive reactance is the result of a (constant, changing) magnetic field.

Q28. How would you increase the inductive reactance of the device illustrated above?

Q29. What effect would increasing X_L have on the brightness of the lights?

Q30. How should the core be set to obtain maximum brightness of the lights?

Q31. Would this device work with a DC power supply?

Your Answers Should Be:

A26. A coil with an air core has a **smaller** inductance than an iron-core coil.

A27. Inductive reactance is the result of a **changing** magnetic field.

A28. Push the iron core **into the coil.**

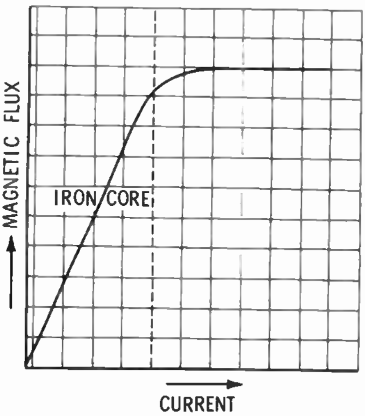
A29. Increasing X_L would **dim** the lights.

A30. The iron core should be **totally removed.**

A31. The device would **not work** with DC.

Magnetic-Amplifier Applications

A more typical magnetic amplifier controls the magnetic properties of the core and the X_L of the coil by electrical means. To more easily understand how this can be done, look at the curve of current versus magnetic flux in iron.



AN IRON CORE BECOMES SATURATED AS CURRENT IS INCREASED

As the current in the coil and the flux in an iron core increase, a point is reached where the curve bends. A further increase in the current produces less and less of a flux increase until, finally, a further increase in current produces no additional flux. At this point the core contains as many lines of flux as it can possibly receive; it is said to be **saturated.**

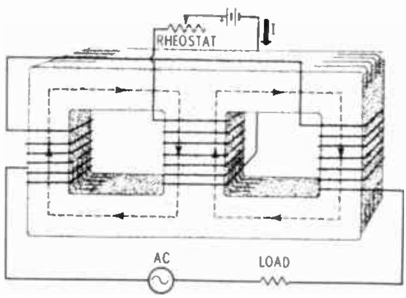
To make a magnetic amplifier, wind two different coils on a core in the same manner as a transformer is constructed.

With no current in the **control winding**, the current flowing through the **load winding** is limited by a strong reactive impedance. The light will shine very dimly, if at all. But if enough DC current is passed through the control winding to saturate the core, then as the saturation point is approached, the impedance of the load winding decreases, and the light will become brighter.

Since the control winding uses less power than the load winding, we have an amplifier—a device in which a small amount of power controls a large amount of power.

As AC current flows through the load winding, an AC voltage is induced back into the control winding. This is a loss of power. The control winding is made immune to the induced voltage by using a **three-legged core.**

AC Current Flow Through the Load Is Controlled by DC Current in a Control Winding



The two parts of the load winding are connected in series in such a way that the AC flux lines they induce in the center leg are equal and opposite, and thus cancel each other. This means there is no AC induced in the control winding, yet the control winding still exerts its influence over the load circuit.

Q32. A coil with an unsaturated iron core has a relatively (large, small) X_L.

Q33. If magnetic flux is added from an outside source (such as a separate coil on the same core) until the core is saturated, will the coil have a higher or lower X_L?

Q34. What type of current is affected by the coil X_L?

Your Answers Should Be:

A32. A coil with an unsaturated iron core has a relatively **large** X_L.

A33. If the core is saturated, X_L will be **lower.**

A34. Only AC is affected by inductive reactance.

WHAT YOU HAVE LEARNED

1. The changing magnetic field produced by the primary winding in a transformer induces a changing voltage in the secondary winding.
2. The ratio of the primary voltage to the secondary voltage is the same as the ratio of the number of turns in the primary winding to the number of turns in the secondary winding.
3. If a transformer steps up voltage, it steps down current, and vice versa. The power drawn by the primary winding is equal to the power dissipated in the secondary circuit.
4. Most transformers have an efficiency of nearly 100%, so very little power is lost in them.
5. Transformers alter the impedance of a load. The change in impedance depends on the square of the turns ratio.
6. Magnetic amplifiers control the inductive reactance of a coil by altering the magnetic property of its core.
7. A very simple magnetic amplifier is basically a coil with a removable iron core. When the core is inserted, X_L increases, and the power supplied to the load decreases.
8. Iron cores can receive only a certain amount of magnetic flux, and when they are saturated, they no longer increase the X_L of a coil.
9. A typical magnetic amplifier uses a DC current through a control winding to control the level of saturation of an iron core and thus the X_L of an AC load winding.

NOTES

NOTES

NOTES

NOTES

BASIC ELECTRICITY/ELECTRONICS

HOW AC & DC CIRCUITS WORK

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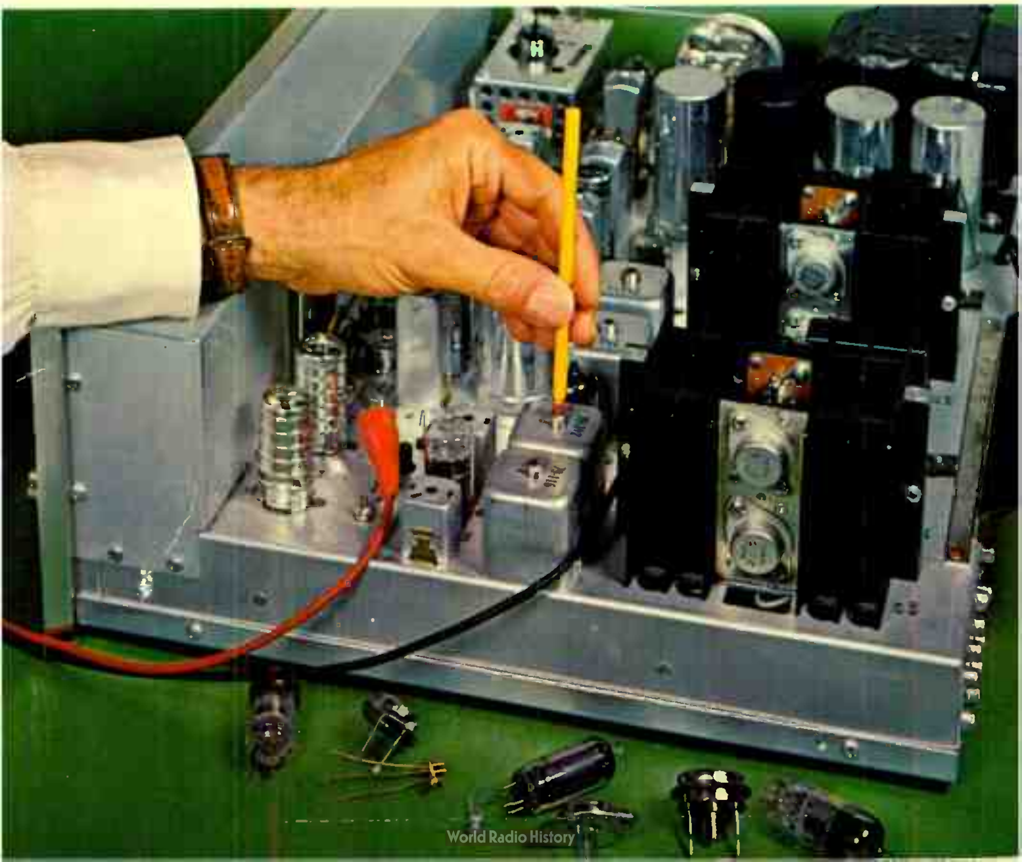

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BASIC
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HOWARD W. SAMS & CO., INC.
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SEYMOUR D. USLAN, *Editor-in-Chief,*
Training & Retraining, Inc.

Introduction

This third volume in the series introduces you to vacuum tubes, transistors, and the ways in which these devices are put to work. Although all of the topics discussed provide background information for further study, many of them also have direct practical applications in circuit design and analysis. After studying this volume, you will have expanded your knowledge of electrical fundamentals to include the basic devices and circuits that make radio, television, radar, computers, and countless other areas of electronics technology possible. With this knowledge you will be better able to understand how electronic equipment works.

WHAT YOU WILL LEARN

Virtually every piece of electronic equipment depends on vacuum tubes and/or semiconductor devices for its operation. In this volume you will learn about both of these groups of components.

Vacuum tubes depend on the behavior of electrons in an electric field for their operation. This subject is discussed along with the ways in which electrons are emitted into the electric field. You will learn about the Edison effect and how the diode (two-element) tube operates. You will see how the addition of more elements to the tube makes it useful in a variety of applications. Tube parameters (numbers that indicate the usefulness of a tube) are explained in detail. The text shows how the operation of vacuum tubes can be described and studied by means of graphs. The meaning of the term amplification is explained, and the most common types of vacuum-tube amplifiers are shown. You will learn about the classification of amplifiers according to the way the vacuum tubes in the amplifiers are operated. Several methods of coupling (connecting) more than one amplifier stage are discussed.

The coverage of semiconductor devices begins with an explanation of what a semiconductor is. You will learn about the PN junction and how the semiconductor diode and the transistor depend on the operation of this junction. As with tubes, the operation of transistors can be described in terms of parameters and graphs. You will learn about these aids and how to work with them. You will be shown how transistors amplify and how they are connected in amplifier circuits. Methods of coupling transistor amplifier stages are explained.

You will learn how power supplies work. Such terms as rectifier, filter, pulsating DC, regulated power supply, and others are explained.

Finally you will learn how pulses are generated and amplified. Some of the applications of pulse circuits are discussed.

WHAT YOU SHOULD KNOW BEFORE YOU START

Before beginning your study of tube and transistor circuits, you should have a good understanding of the basic principles of AC and DC circuit operation. (Such knowledge can be obtained from Volume 2 of this series.) All new terms are carefully defined. Enough math is used to give precise interpretation to important principles, but if you know how to add, subtract, multiply, and divide, the mathematical expressions will give you no trouble.

WHY THE TEXT FORMAT WAS CHOSEN

During the past few years, new concepts of learning have been developed under the common heading of programmed instruction. Although there are arguments for and against each of the several formats or styles of programmed textbooks, the value of programmed instruction itself has been proved to be sound. Most educators now seem to agree that the style of programming should be developed to fit the needs of teaching the particular subject. To help you progress successfully through this volume, a brief explanation of the programmed format follows.

Each chapter is divided into small bits of information presented in a sequence that has proved best for learning purposes. Some of the information bits are very short—a single sentence in some cases. Others may include several paragraphs. The length of each presentation is determined by the nature of the concept being explained and the knowledge the reader has gained up to that point.

The text is designed around two-page segments. Facing pages include information on one or more concepts, complete with illustrations designed to clarify the word descriptions used. Self-testing questions are included in most of these two-page segments. Many of these questions are in the form of statements requiring that you fill in one or more missing words; other questions are either multiple-choice or simple essay types. Answers are given on the succeeding page, so you will have the opportunity to check the accuracy of your response and verify what you have or have not learned before proceeding. When you find that your answer to a question does not agree with that given, you should restudy the information to determine why your answer was incorrect. As you can see, this method of question-answer programming insures that you will advance through the text as quickly as you are able to absorb what has been presented.

The beginning of each chapter features a preview of its contents, and a review of the important points is contained at the end of the chapter. The preview gives you an idea of the purpose of the chapter—what you can expect to learn. This helps to give practical meaning to the information as it is presented. The review at the completion of the chapter summarizes its content so that you can locate and restudy those areas which have escaped your full comprehension. And, just as important, the review is a definite aid to retention and recall of what you have learned.

HOW YOU SHOULD STUDY THIS TEXT

Naturally, good study habits are important. You should set aside a specific time each day to study in an area where you can concentrate without being disturbed. Select a time when you are at your mental peak, a period when you feel most alert.

Here are a few pointers you will find helpful in getting the most out of this volume.

1. Read each sentence carefully and deliberately. There are no unnecessary words or phrases; each sentence presents or supports a thought which is important to your understanding of electricity and electronics.

2. When you are referred to or come to an illustration, stop at the end of the sentence you are reading and study the illustration. Make sure you have a mental picture of its general content. Then continue reading, returning to the illustration each time a detailed examination is required. The drawings were especially planned to reinforce your understanding of the subject.

3. At the bottom of most right-hand pages you will find one or more questions to be answered. Some of these contain "fill-in" blanks. Since more than one word might logically fill a given blank, the number of dashes indicates the number of letters in the desired word. In answering the questions, it is important that you actually do so in writing, either in the book or on a separate sheet of paper. The physical act of writing the answers provides greater retention than merely thinking the answer. Writing will not become a chore since most of the required answers are short.

4. Answer all questions in a section before turning the page to check the accuracy of your responses. Refer to any of the material you have read if you need help. If you don't know the answer even after a quick review of the related text, finish answering any remaining questions. If the answers to any questions you skipped still haven't come to you, turn the page and check the answer section.

5. When you have answered a question incorrectly, return to the appropriate paragraph or page and restudy the material. Knowing the correct answer to a question is less important than understanding why it is correct.

Each section of new material is based on previously presented information. If there is a weak link in this chain, the later material will be more difficult to understand.

6. In some instances, the text describes certain principles in terms of the results of simple experiments. The information is presented so that you will gain knowledge whether you perform the experiments or not. However, you will gain a greater understanding of the subject if you do perform the suggested experiments.
7. Carefully study the review, "What You Have Learned," at the end of each chapter. This review will help you gauge your knowledge of the information in the chapter and actually reinforce your knowledge. When you run across statements you don't completely understand, reread the sections relating to these statements, and recheck the questions and answers before going to the next chapter.

This volume has been carefully planned to make the learning process as easy as possible. Naturally, a certain amount of effort on your part is required if you are to obtain the maximum benefit from the book. However, if you follow the pointers just given, your efforts will be well rewarded, and you will find that your study of electricity and electronics will be a pleasant and interesting experience.

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CHAPTER 1

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1

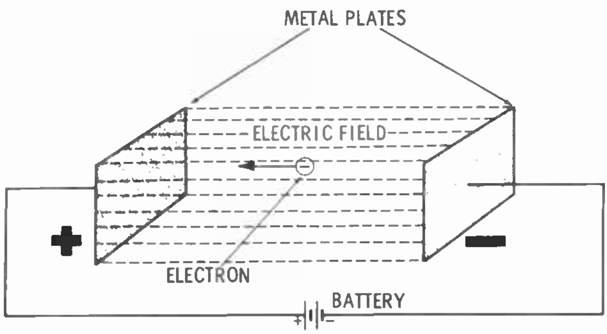
Vacuum Tubes

What You Will Learn

In this chapter you will learn how an electric field influences the motion of electrons. You will be able to name the elements of a diode tube and to explain how the diode operates. You will also learn how graphs are used to show the relationship existing between voltage and current in a diode.

ELECTRONS IN AN ELECTRIC FIELD

The electron is a negatively charged particle. Under the proper conditions, an electron can be moved by placing it under the influence of an electric field. Such a field is formed when a difference of potential exists between two points. If free to move in this field, the electron will move toward the more positive point.



Electron Movement in an Electric Field

Electron Movement in a Vacuum

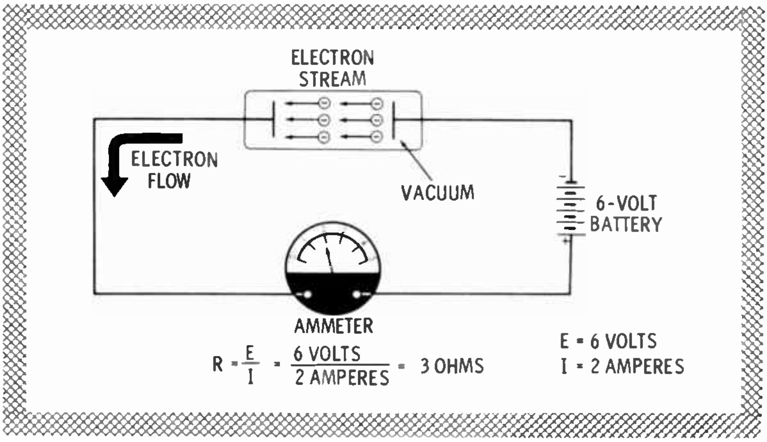
It is difficult for electrons to move through a medium such as air because the electrons collide with the air molecules. For this reason electrons can move more easily in a vacuum.

Many electrons moving in the same direction in an electric field form an electron stream. The number of electrons passing a given point in a given period of time is called **current** (for example, 1,000 electrons per second). The unit of current is the **ampere.** When 6 quintillion, 240 quadrillion electrons pass a point in a circuit each second, a current of 1 ampere is said to be flowing. This number of electrons is called a **coulomb.** Therefore, 1 coulomb per second is 1 ampere.

Resistance Between Two Conducting Plates

Consider two plates placed a specified distance apart in a vacuum, and assume electrons are able to leave one of the plates. A difference of potential between the plates will cause a certain amount of current to flow. If the value of the voltage is known and the current can be measured, the resistance can be calculated by using Ohm's law.

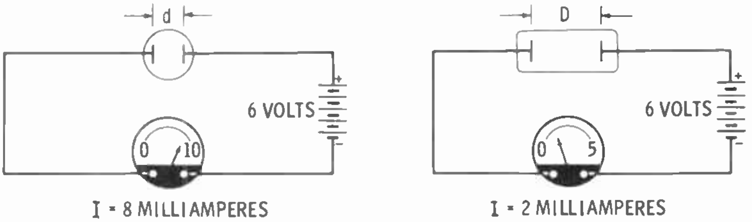
RESISTANCE MEASUREMENT BETWEEN TWO PLATES



One terminal of a 6-volt battery is connected to one of the plates, and the other terminal is connected to the other plate through an ammeter. An electron stream flows through the vacuum between the plates, and the ammeter measures a current of 2 amperes. Using Ohm's law, 6 (volts) divided by 2 (amperes) gives 3 ohms.

Three factors determine the resistance between a set of plates: 1. Distance between the plates. 2. Voltage between the plates. 3. Temperature of the plates.

Variation of Current With Plate Spacing

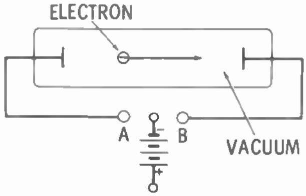


Distance Between the Plates—The figure shows two sets of plates with the same voltage applied between the plates of each set. The plates in one are twice as far apart as the plates in the other. The plates that are **d** distance apart allow four times as much current to flow as the plates **D** distance apart.

Q1. What is the resistance across the d set of plates?

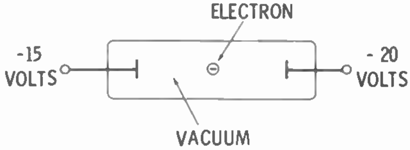
Q2. What is the resistance across the D set of plates?

Q3. Connect the battery so that the electrons move in the direction shown below.



Q4. An electron moves readily in a ______.

Q5. Which way will an electron move in the field shown below?



Your Answers Should Be:

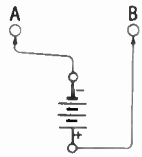
A1. The resistance is **750 ohms.**

$$R = \frac{E}{I} = \frac{6 \text{ volts}}{8 \text{ milliamps}} = 750 \text{ ohms}$$

A2. The resistance is **3,000 ohms.**

$$R = \frac{E}{I} = \frac{6 \text{ volts}}{2 \text{ milliamps}} = 3{,}000 \text{ ohms}$$

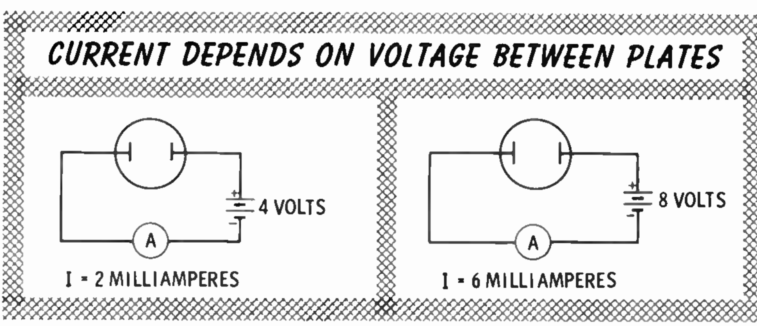
A3. The battery should be connected as shown.



A4. An electron moves readily in a **vacuum.**

A5. The electron must **move** away **from the negative 20-volt terminal and toward the negative 15-volt terminal.**

Voltage Across the Plates—The figure below shows that as the voltage across the plates is increased, the current increases. Note, however, that although the voltage doubles (from 4 volts to 8 volts), the current more than doubles (from 2 amperes to 6 amperes).



The resistance of the 4-volt circuit is 2,000 ohms. The resistance of the 8-volt circuit is 1,333 ohms. It can be seen that as the voltage between the plates increases, the resistance between the plates decreases.

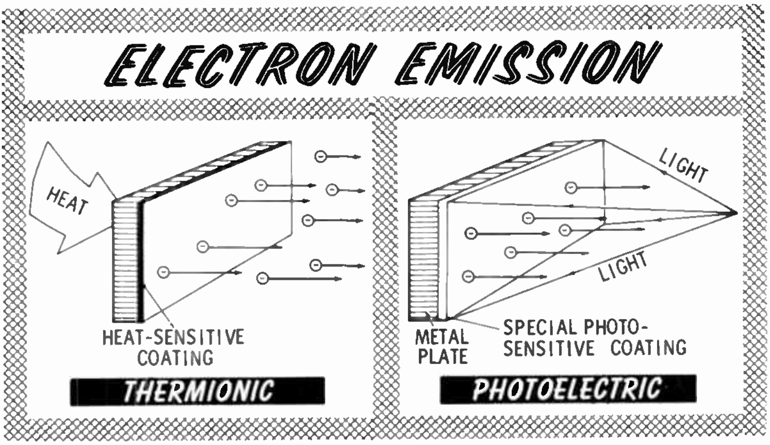
Temperature of the Plates—Electrons are agitated by heat. This agitation causes an increase in electron **velocity** (movement), and the increase in velocity makes it easier for the electrons to leave the plate. Thus, as the plate that emits the electrons is heated, more current flows.

THE CATHODE AND ELECTRON EMISSION

Since they are bound to the nucleus of an atom, electrons are difficult to move. To flow through an electric field, electrons must be freed from their atoms. Such electrons are called **free electrons.**

An electrode from which electrons are emitted is called a **cathode.** One method of generating free electrons is to expose certain materials to light. These materials are called **photosensitive.** If a metal is coated with a photosensitive material and then exposed to light, electrons will be emitted. This type of emission is called **photoelectric emission.**

Certain materials emit electrons readily when heated. This is called **thermionic emission.**



Q6. As the distance between the plates decreases, the resistance between the plates (increases, decreases).

Q7. As the voltage between the plates decreases, the resistance between the plates (increases, decreases).

Q8. As the temperature of the emitting plate is decreased, the resistance between the plates (increases, decreases).

Your Answers Should Be:

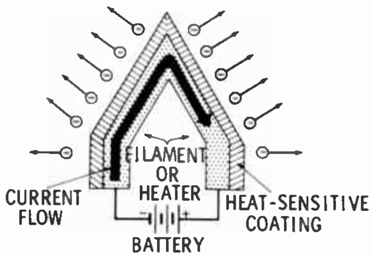
A6. As the distance between the plates decreases, the resistance between the plates **decreases.**

A7. As the voltage between the plates decreases, the resistance between the plates **increases.**

A8. As the temperature of the emitting plate is decreased, the resistance between the plates **increases.**

The Heater

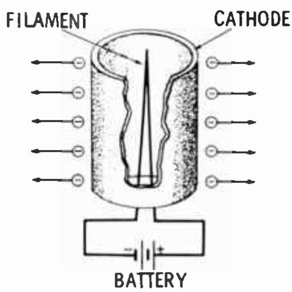
Thermionic emission is the method most commonly used to supply free electrons. The element used to supply the heat for the cathode is called the **heater.** The heater is a very thin filament of wire through which electric current is passed. If coated with a heat-sensitive material, the filament then serves as a cathode and is called a **directly heated cathode.**



DIRECTLY HEATED CATHODE

The **indirectly heated** cathode is made of a good emitting material shaped like a tube open at both ends. A filament is placed inside, but not touching, the cathode. No heater current passes through the cathode.

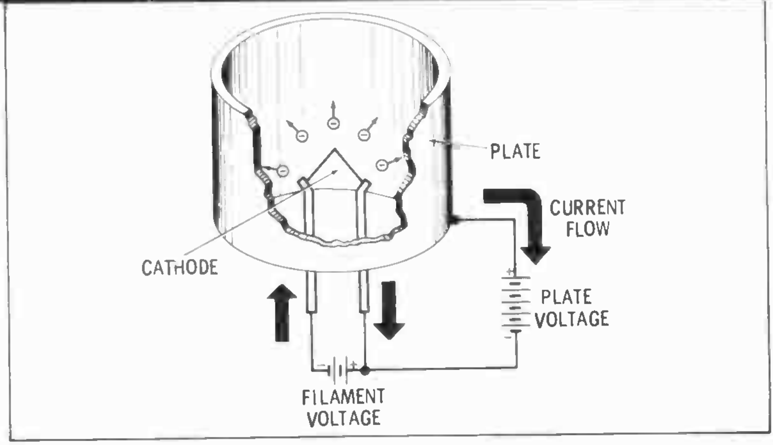
INDIRECTLY HEATED CATHODE



ATTRACTING THE EMITTED ELECTRONS

The free electrons perform useful work if they are moved through an electronic circuit. An element called a **plate** is used to attract the electrons emitted from the cathode. The plate, made of metal, and the cathode are connected to a source of potential which makes the plate positive with respect to the cathode. Therefore, the negative electrons flow to the plate.

Positive Plate Attracts Electrons From Cathode



Q9. An electrode from which electrons are emitted is called a ________.

Q10. Electrons are emitted from a substance that has been exposed to light. This process is called ______________ emission.

Q11. The method most commonly used to generate free electrons is called ___________ emission.

Q12. A heated filament coated with a material that will emit electrons very readily is called a(an) _________ _______ cathode.

Q13. A heated cathode through which no heating current passes is called a(an) ___________ ______ cathode.

Q14. The element that attracts electrons emitted from the cathode is called the _____.

Your Answers Should Be:

A9. An electrode from which electrons are emitted is called a **cathode.**

A10. Electrons are emitted from a substance that has been exposed to light. This process is called **photoelectric** emission.

A11. The method most commonly used to generate free electrons is called **thermionic** emission.

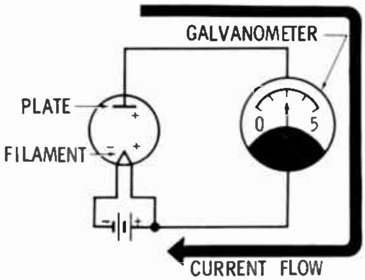
A12. A heated filament coated with a material that will emit electrons very readily is called a **directly heated** cathode.

A13. A heated cathode through which no heating current passes is called an **indirectly heated** cathode.

A14. The element that attracts electrons emitted from the cathode is called the **plate.**

DEVELOPMENT OF THE DIODE

In one of his experiments with the electric lamp, Thomas A. Edison placed a small metal plate inside the evacuated envelope surrounding the filament. This plate was not touching the filament. By placing a galvanometer between the positive side of the filament and the plate, Edison noted a current was flowing through the seemingly open circuit



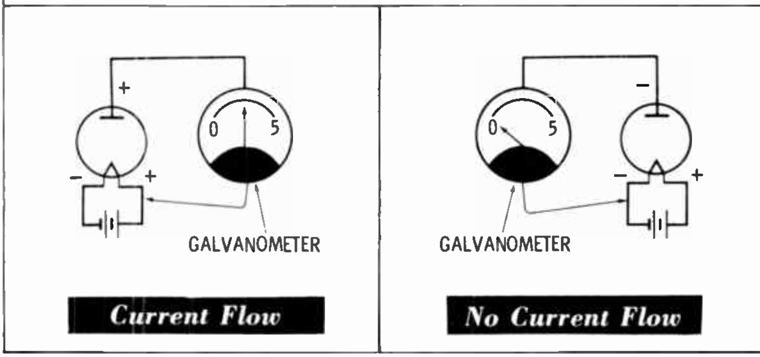
CIRCUIT FOR DEMONSTRATING EDISON EFFECT

between the filament and the metal plate. This action is known as the **Edison effect.**

In 1904 Ambrose Fleming improved the plate by forming it into a tubular shape and using it to completely surround the filament. This two-element tube was called a **diode.**

Fleming's experiments with the diode proved that current flowed through it in only one direction—from cathode to plate. Fleming tried an experiment similar to that shown in the figure below.

Circuit for Demonstrating Unidirectional Conduction of a Diode



In the figure showing Edison's experiment, it can be seen that the side of the filament connected to the galvanometer and to the plate are at the same positive potential (the voltage of the battery). Therefore, there will be no current flow between these two points. However, the side of the filament connected to the negative terminal of the battery is negative with respect to the plate. As a result, electrons emitted from this side of the filament are attracted to the plate and cause a small current through the galvanometer.

In Fleming's experiment, a similar situation existed when the galvanometer was connected to the positive side of the filament. However, when the galvanometer is connected to the negative side of the filament, the plate and that side of the filament are at the same potential. But the plate is more negative than the positive side of the filament. Therefore, no current flows through the galvanometer.

Q15. A two-element tube is called a _____.

Q16. The apparent flow of current between a filament and a plate is called the ______ _______.

Q17. Diode current flows only from _______ to _____.

Your Answers Should Be:

A15. A two-element tube is called a **diode.**

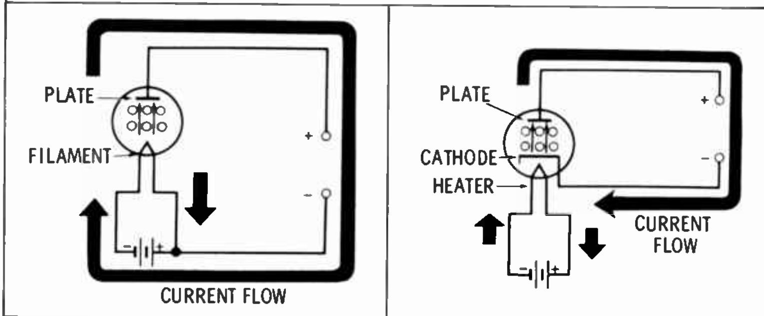
A16. The apparent flow of current between a filament and a plate is called the **Edison effect.**

A17. Diode current flows only from **cathode** to **plate.**

THE CATHODE

The directly heated cathode is a coated filament. The filament is often made of tungsten coated with thorium (this is called thoriated tungsten). The thorium acts as a good emitter of electrons when it is heated. The electrons

TYPES OF CATHODES



Directly Heated — *Indirectly Heated*

emitted by the thorium are replaced by the tungsten. The figure shows how the filament battery sends current through the filament, heating it and causing it to emit electrons.

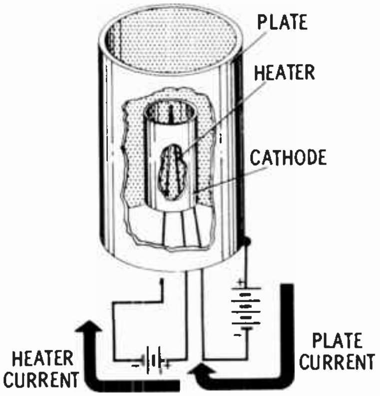
The indirectly heated cathode consists of a metal cylinder heated by a filament placed inside, but not touching it. This type of cathode is usually coated with barium or strontium oxide, which serves as the electron-emitting material.

THE PLATE

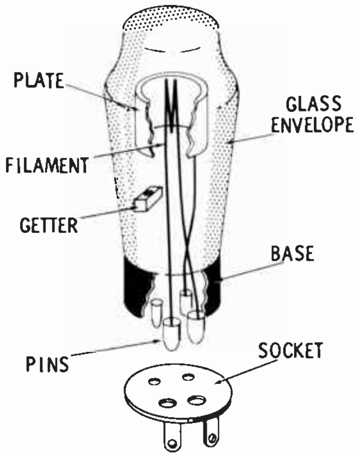
In the diode, the element that collects the electrons is called the plate. This element is usually constructed so that it completely surrounds the cathode.

Below is a pictorial representation of a diode with an indirectly heated cathode. Current flowing through the heater heats the cathode. The cathode emits electrons which flow to the plate and through the battery back to the cath-

DIODE CONSTRUCTION



Indirectly Heated Cathode



Directly Heated Cathode

ode. The figure also shows the actual construction of a diode with a directly heated cathode.

Because of the gases retained in the metal parts, it is very difficult to completely evacuate a vacuum tube. For this reason, a part called the **getter** is provided. The tube elements are brought up to a red heat after the air has been pumped from the tube. This releases the trapped gases, and then the getter is caused to burn quickly by an electromagnetic field surrounding the tube. The getter absorbs the gases released by the heat and, in the process, deposits a silver coating on the inside of the glass envelope.

Q18. In a diode, the element that emits electrons is called a ________.

Q19. A separate filament circuit is used to provide heat for the ___________ heated cathode.

Q20. A ______ is used to remove gases retained in the metal parts of a diode.

Your Answers Should Be:

A18. In a diode the element that emits electrons is called a **cathode.**

A19. A separate filament circuit is used to provide heat for the **indirectly** heated cathode.

A20. A **getter** is used to remove gases retained in the metal parts of a diode.

TUBE CHARACTERISTICS AND EFFECTIVE RESISTANCE

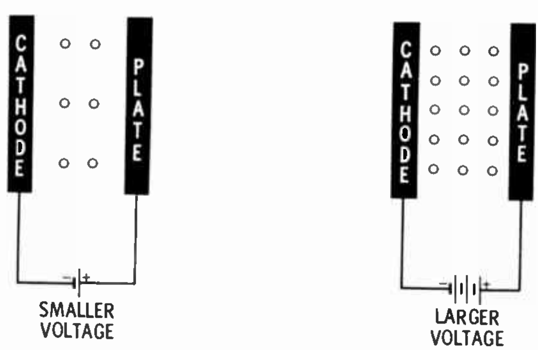
Three factors affect the amount of current passing through a diode. They are the temperature of the cathode, the voltage between the plate and cathode, and the space charge.

Temperature of the Cathode

The hotter the cathode becomes, the more electrons it emits per unit time. There are practical limits to this, however. If the temperature of the cathode is increased too much, the filament will burn out. In addition, there is a limit to the maximum rate at which a cathode can emit electrons.

Plate Voltage

As the positive voltage of the plate becomes greater with respect to the cathode, current flow through the tube increases.

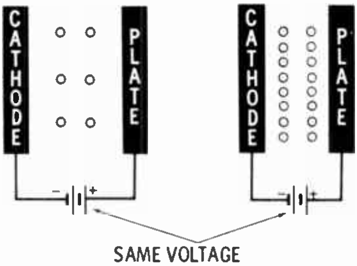


CURRENT FLOW IS AFFECTED BY PLATE VOLTAGE

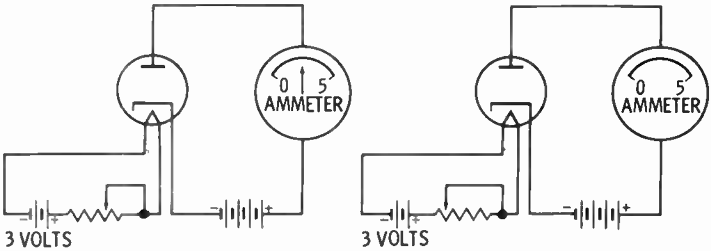
There is also a limit to the tube current that can be obtained by increasing the plate voltage, because the plate cannot attract more electrons than the cathode emits.

Suppose that the voltage on the plate remained the same but the plate was moved closer to the cathode. How would this affect the current through the diode? Under these conditions the current would increase.

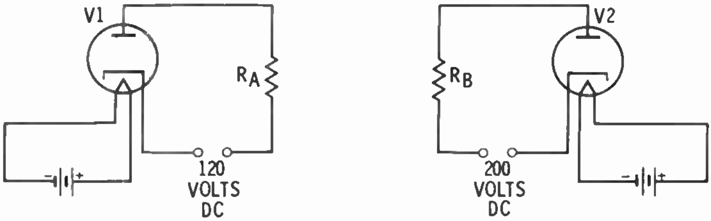
CURRENT FLOW IS AFFECTED BY TUBE-ELEMENT SPACING



Q21. Supply the missing meter pointer (approximate position) in the figure below.



Q22. If resistors R_A and R_B in the two circuits below are identical, which one will have the higher temperature?



Q23. Moving the plate away from the cathode (increases, decreases) the current flow through the diode.

Your Answers Should Be:

A21. The needle should indicate that there is **more current flow in the plate circuit of the diode.** As the arm of the potentiometer in the filament circuit is positioned farther to the left, more current flows in the filament circuit. The filament gets hotter and emits more electrons, and more current then flows in the plate circuit.

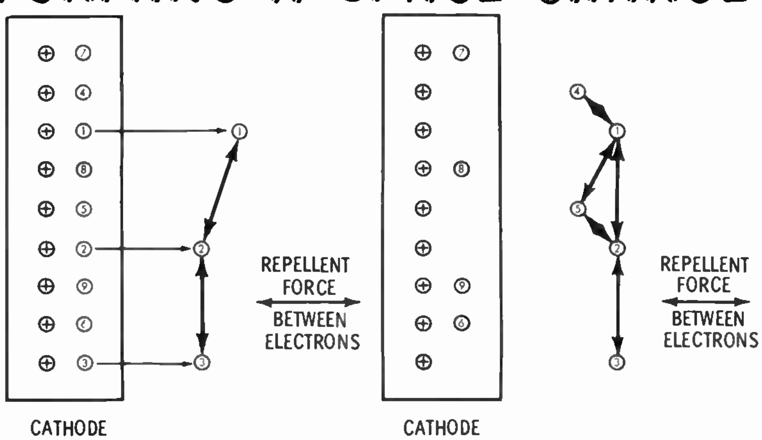
A22. With a higher plate voltage (200 volts), V2 conducts more current than V1, and the current through R_B is more than the current through R_A. Therefore I^2R_B is greater than I^2R_A, and **R_B is hotter than R_A.**

A23. Moving the plate away from the cathode **decreases the current flow through the diode.**

Space Charge

Heat acts as the driving force to push electron number 1 into the space around the cathode. Initially, the electron has much energy. However, most of this energy is expended in

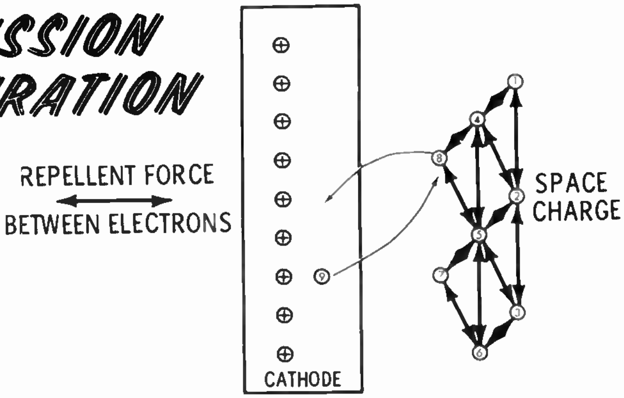
FORMING A SPACE CHARGE



Electrons Begin Leaving Cathode — *More Electrons Leave Cathode* reaking away from the cathode. The electron moves very lowly out into the space around the cathode and soon stops noving. Since the cathode has lost one of its electrons, it now has more positive charges (protons) than electrons.

As a result, the electron is attracted back to the now posi-ive cathode. However, heat is still driving other electrons from the cathode. As electron number 1 heads back toward he cathode, it encounters electrons 2 and 3. Since they are also negative, they repel electron number 1, preventing it from returning to the cathode. The attempt of these elec-trons to return to the cathode is blocked by electrons 4, 5, and 6, and so on. As the electrons move out into space, they form a cloud of negative charges. The larger this cloud becomes, the more opposition it offers to additional electrons eaving the cathode.

EMISSION SATURATION



Finally, a point is reached where, when a sufficient quantity of electrons has been emitted, the cloud has enough negative charge to force newly emitted electrons back to the cathode. From then on, for every electron emitted by the cathode, one will be returned to the cathode. This condition of equilibrium is called **emission saturation**. The cloud of electrons around the cathode is called the **space charge**.

Q24. The cloud of electrons that forms around the cathode is called the _____ ______.

Q25. The condition of equilibrium of the electron cloud around the cathode is called ________ ___________.

Your Answers Should Be:

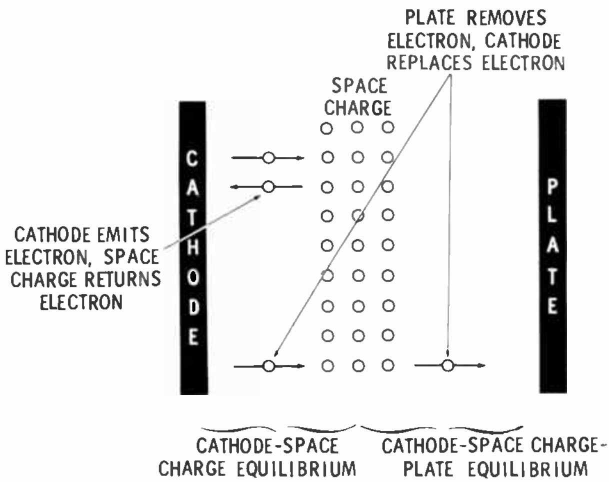
A24. The cloud of electrons that forms around the cathode is called the **space charge.**

A25. The condition of equilibrium of the electron cloud around the cathode is called **emission saturation.**

HOW THE SPACE CHARGE AFFECTS CURRENT FLOW

When a plate is placed in a vacuum tube, it does not receive electrons directly from the cathode. Instead, it takes them from the side of the space charge nearest the plate.

TWO EQUILIBRIUM CONDITIONS IN A DIODE

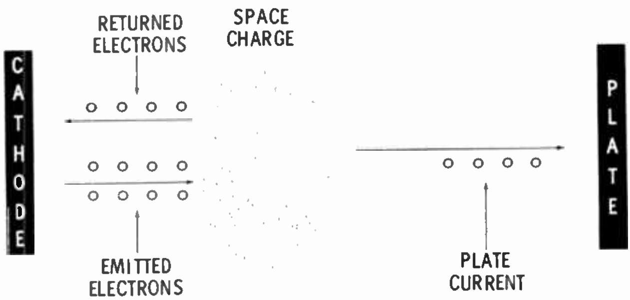


Each time the plate removes one electron from the space charge, the overall negative charge is decreased. Another electron must then be placed in the space charge to take its place. Thus, equilibrium (state of balance) in the space charge is maintained. Note there are now two conditions of equilibrium being maintained. One is when the electrons are emitted by the cathode into the space charge and are then returned to the cathode. The other condition of equilibrium is when the plate removes an electron from the space charge and the cathode replaces this electron.

Space-Charge Equilibrium

A state of equilibrium is set up between the plate, the cathode, and the space charge. This is shown in the figure below. Electrons are emitted from the cathode into the space charge from which the plate draws some electrons

EQUILIBRIUM IN A DIODE



(plate current). The remaining or surplus electrons not required by the plate are returned to the cathode. The quantity returned is the difference between the amount of electrons originally emitted by the cathode and the amount going to make up the plate current. The result of all this is that the space charge is maintained at a constant size. In other words, it reaches and stays in a state of equilibrium.

This cloud of electrons making up the space charge provides a ready source of electrons for the plate current. This reservoir permits short periods of greater plate current flow than could be supplied directly from the cathode.

Q26. The space charge is a substantial (negative, positive) charge between cathode and plate.

Q27. The field that repels the electrons emitted by the cathode lies between the _______ and the _____ ______.

Q28. The field that removes electrons from the space charge lies between the _____ ______ and the _____.

Q29. The plate exerts its force directly on the _____ ______.

Your Answers Should Be:

A26. The space charge is a substantial **negative** charge between the cathode and the plate.

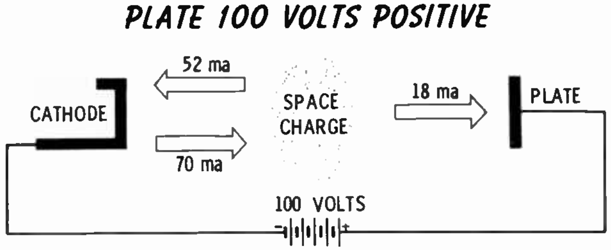
A27. The field that repels the electrons emitted by the cathode lies between the **cathode** and the **space charge.**

A28. The field that removes electrons from the space charge lies between the **space charge** and the **plate.**

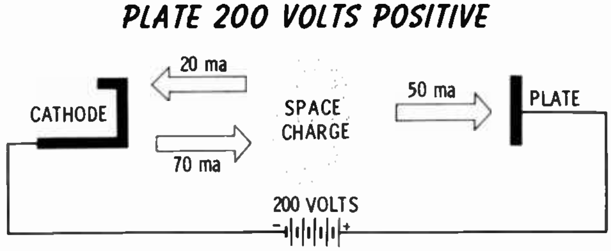
A29. The plate exerts its force directly on the **space charge.**

Current-Flow Control

In the figure below, the applied plate voltage is 100 volts. This results in a plate current of 18 ma. The cathode emits enough electrons to produce a current of 70 ma, but the



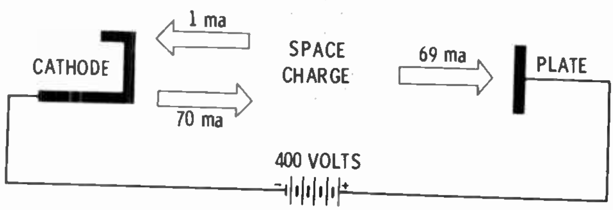
space charge prevents some of them from reaching the plate. The 52-ma surplus is returned to the cathode.



If the plate voltage is increased to 200 volts, the plate current becomes 50 ma, and the current returned is 20 ma.

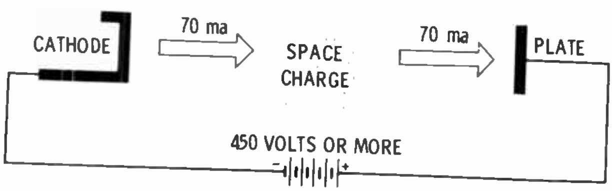
In the figure below, the plate voltage has been increased to 400 volts, and the plate current becomes 69 ma. Note that in each of these cases the sum of the plate current and the current returned to the cathode is equal to the current emitted by the cathode.

PLATE 400 VOLTS POSITIVE



When the plate voltage is increased to 450 volts, the plate current equals the cathode emission. This is illustrated in the figure below.

PLATE 450 VOLTS OR MORE POSITIVE



Any further increase in the plate voltage will result in reducing the space charge. Then the voltage on the plate acts directly on the cathode and forces the cathode to emit more electrons than it is designed to emit. This results in rapid destruction of the emitting material and reduced life of the tube.

Q30. Draw a diagram showing the conditions of equilibrium in a diode.

Q31. The number of electrons returned to the cathode plus the _____ _______ equals the number of electrons emitted by the cathode.

Q32. If the emitted electrons produce a current of 90 ma and the returned electrons produce a current of 30 ma, the plate current is ____ ma.

Your Answers Should Be:

A30. Your diagram should be similar to the one on page 32.

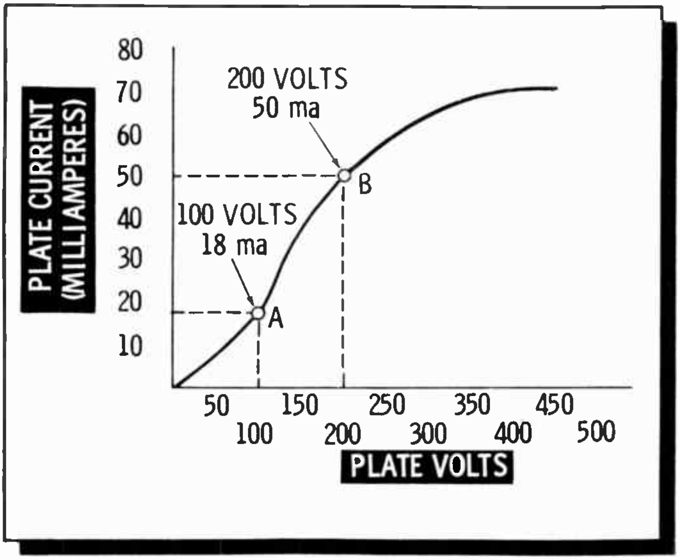
A31. The number of electrons returned to the cathode plus the **plate current** equals the number of electrons emitted by the cathode.

A32. If the emitted electrons produce a current of 90 ma and the returned electrons produce a current of 30 ma, the plate current is **60** ma.

GRAPH OF PLATE VOLTAGE VERSUS PLATE CURRENT

The most important fact to remember about a diode is how much current it will pass with a given amount of plate voltage. This type of information is summarized by a graph of plate voltage versus plate current.

GRAPH OF PLATE VOLTAGE VERSUS PLATE CURRENT



Each point on the graph represents a plate current for a particular plate voltage. For instance, the current for a plate voltage of 100 volts is found by drawing a vertical line from the 100-volt point on the horizontal axis to the curve. This locates point A. A horizontal line through point A passes through the 18-ma point on the vertical axis. Thus the graph shows that a current of 18 ma flows through the diode when the plate voltage is 100 volts. The current corresponding to any value of plate voltage can be found in the same way.

The graph can also be used to determine the plate voltage necessary to cause a certain amount of current to flow. Assume that you wish to know the value of plate voltage required to cause a current of 50 ma. First find the 50-ma point on the vertical axis. A horizontal line through this point intersects the curve at point B. A vertical line through point B passes through the 200-volt point on the horizontal axis. Therefore, a plate voltage of 200 volts is required to produce a current flow of 50 ma.

A graph similar to the one shown here can be prepared for any type of diode tube. Of course, a graph for one type of tube usually cannot be used to find voltage and current values for another type of tube.

Notice the **knee** of the curve at around 400 volts. Increasing the voltage in this area changes the plate current very little. Therefore this must be the point where all of the emitted electrons are being attracted to the plate.

You have just seen how to use a graph of plate voltage versus plate current. The figure on the next page shows a circuit that can be used to obtain data for such a graph.

Q33. In a graph of plate current versus plate voltage, the voltage is shown along the ---------- axis.

Q34. In a graph of plate current versus plate voltage, the current is shown along the --------- axis.

Q35. The part of the curve where all of the emitted electrons are attracted to the plate is called the ---- of the curve.

Q36. A graph for one type of tube usually (can, cannot) be used for another type of tube.

Your Answers Should Be:

A33. In a graph of plate current versus plate voltage, the voltage is shown along the **horizontal** axis.

A34. In a graph of plate current versus plate voltage, the current is shown along the **vertical** axis.

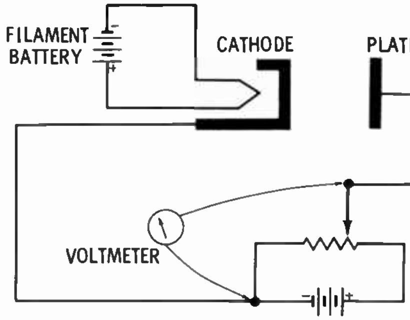
A35. The part of the curve where all of the emitted electrons are attracted to the plate is called the **knee** of the curve.

A36. A graph for one type of tube usually **cannot** be used for another type of tube.

PLOTTING A PLATE-VOLTAGE, PLATE-CURRENT CURVE

To plot a plate-voltage, plate-current curve, the arrangement below can be used. Each time the position of the

Circuit to Obtain Data for Graph



arm of the variable resistor is changed, read the voltage and the current. After recording several of these readings, plot a graph similar to the one on page 36.

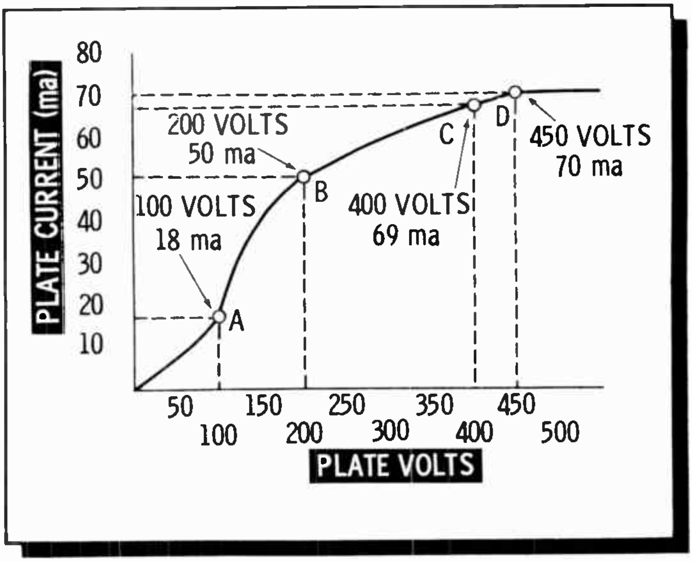
EFFECT OF PLATE VOLTAGE ON EFFECTIVE RESISTANCE

Remember the effective resistance between conducting plates in a vacuum? This same opposition exists between the cathode and plate of a vacuum tube and is called **DC plate resistance, R_p.**

Calculating DC Plate Resistance

Assume that the graph shown below has been obtained by taking voltage and current readings on a diode tube.

POINTS FOR CALCULATING DC PLATE RESISTANCE



To see how the DC plate resistance varies with plate voltage, calculate R_p at each of the points marked on the graph. The calculations yield the following results:

Point A: $\frac{100 \text{ volts}}{18 \text{ ma}} = 5{,}500 \text{ ohms}$

Point B: $\frac{200 \text{ volts}}{50 \text{ ma}} = 4{,}000 \text{ ohms}$

Point C: $\frac{400 \text{ volts}}{69 \text{ ma}} = 5{,}800 \text{ ohms}$

Point D: $\frac{450 \text{ volts}}{70 \text{ ma}} = 6{,}400 \text{ ohms}$

Q37. To obtain data for a graph of plate current versus plate voltage, _______ readings are taken as the _______ is varied.

Your Answer Should Be:

A37. To obtain data for a graph of plate current versus plate voltage, **current** readings are taken as the **voltage** is varied.

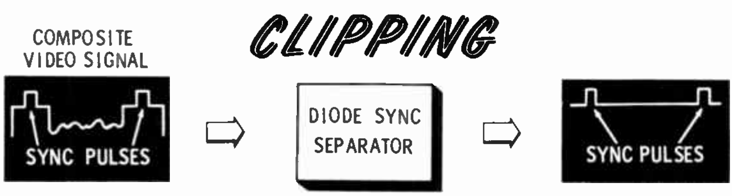
Variations of DC Plate Resistance

In going from point A to point B (see the preceding page), the plate voltage increases and the DC plate resistance decreases. However, in going from point B to point C, the resistance increases as the voltage increases. This happens because points C and D are on the knee of the curve. The portion of the curve between points A and B is almost (but not quite) a straight line. It is often called the **linear** part of the curve. Normally, in the linear part of the curve, R_p decreases when the plate voltage is increased.

APPLICATIONS

Because of the unidirectional characteristic of the diode, it can perform many valuable functions.

In the figure above, the diode is used as a **detector.** A typical TV picture signal is shown. It is passed through a diode detector which selects only the positive half of the signal.



A diode can also eliminate undesired portions of a signal. This is called **limiting,** or **clipping.** In the figure above, another type of TV signal is shown; it is the composite video signal. For certain applications, only the two sync pulses are needed. The signal is sent through a diode sync separator which clips the sync pulses off the composite video signal.

CLAMPING

Another use for a diode is to maintain a special voltage level for a signal—this is called **clamping,** or **DC restoration.** The figure above shows a composite video signal whose pedestal is riding at positive 20 volts. The diode clamp causes this pedestal to ride at negative 50 volts.

RECTIFICATION

In the figure above, an AC signal is shown entering a diode rectifier and leaving as pulsating DC. This first step in changing AC to DC is called **rectification.** It is the basis for all electronic power supplies.

GATING

In gate-circuit action, several signals must be present at the same time for an output to be obtained. In the figure you see one signal which opens the gate at regular intervals. However, the only time there is an output is when two signals are present at the same time.

Q38. A diode circuit used to pass one half of a signal is a _________.

Q39. A diode circuit used as a sync separator is a ________.

Q40. A ___________ changes AC to pulsating DC.

Your Answers Should Be:

A38. A diode circuit used to pass one half of a signal is a **detector.**

A39. A diode circuit used as a sync separator is a **clipper.**

A40. A **rectifier** changes AC to pulsating DC.

WHAT YOU HAVE LEARNED

1. Electrons move most easily in a vacuum.
2. Electrons move from negative to positive in an electric field.
3. Electrons are emitted from the cathode of a diode tube and are attracted to the plate.
4. Some cathodes emit electrons due to the action of light and others due to the action of heat.
5. Cathodes may be either directly or indirectly heated.
6. A space charge consisting of a cloud of electrons exists between the cathode and the plate.
7. Equilibrium normally exists in a diode between the cathode and the space charge and between the cathode, space charge, and plate.
8. The relationship of plate voltage and plate current in a diode can be shown by a graph.

2

Multielement Tubes

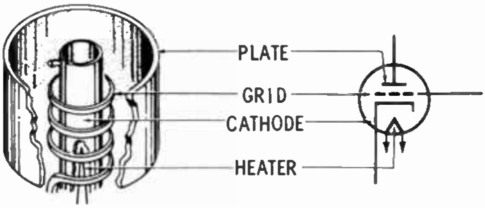
What You Will Learn

You will learn about triodes, tetrodes, and pentodes. You will be shown schematic symbols for these tubes and the shorthand notations used to identify the various voltages and currents associated with amplifiers. You will learn about the three tube parameters (amplification factor, AC plate resistance, and transconductance) and about bias. You will also learn how to use a tube manual to obtain information about vacuum tubes.

THE TRIODE

In 1907 Lee De Forest took out a patent on a Fleming valve containing a third element. Because of its gridiron-like construction, this element was called a **grid.** This three-element vacuum tube is called a **triode.**

TYPICAL TRIODE

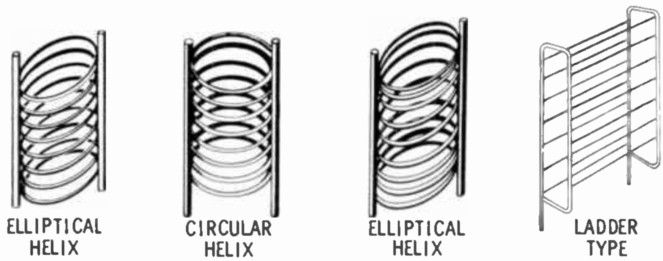


De Forest's experiments proved that the triode could do something that had never been done before—it could make small signals larger. The process of making strong signals out of weak signals is called **amplification.** The triode is often used as an amplifier.

THE GRID

Through the years, grids have been constructed in many different ways. Some of these are improvements on the basic design, and others are for new applications. All of the grids have one thing in common—they are always placed between the cathode and the plate.

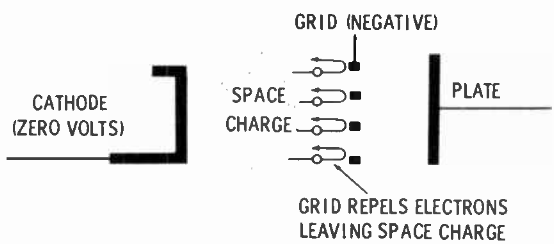
TYPICAL GRIDS



The Grid Introduces a Third Electric Field

Adding a grid between the cathode and the plate introduces another electric field in the triode. The effect of this additional electric field is shown in the figure below.

Effect of the Grid in a Triode

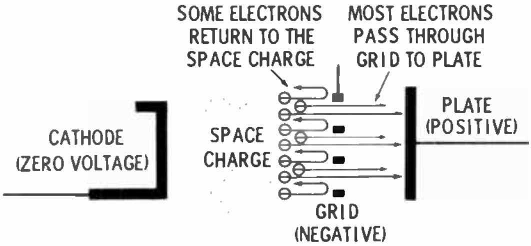


The direction of this field is determined by the polarity of the voltage applied to the grid. For reasons which will become evident later, the grid is operated with a small negative voltage (relative to the cathode) applied to it. The effect of this voltage is to repel electrons which would otherwise leave the space charge and flow to the plate.

Plate Voltage Accelerates Electrons

As plate voltage is applied to the triode, electrons leave the space charge and head for the plate. As they travel toward the plate, they gain momentum. As they approach the grid, the negative voltage on this element slows them down. Some, in fact, are even turned back to the space charge. However, due to the mesh-like construction of the grid, many of the electrons pass between the wires and on to the plate.

ELECTRON MOVEMENT IN A TRIODE



Distance Between the Grid and Cathode

This factor of triode construction affects the electron flow in the following manner. The slower the electrons move, the easier it is to stop them and return them to the space charge. Therefore a grid placed near the space charge (before the electrons have gained much momentum) is better able to stop the electrons than one placed farther away (where the electrons have had a chance to gain momentum). In other words, the **closer the grid** is to the cathode, the more control it will have on electron flow to the plate.

Effect of Cathode-Grid Distance on Plate Current

Q1. A three-element tube is called a ______.

Q2. What are the names of the elements of a triode?

Q3. The process of making small signals larger is called ______________.

Q4. The negative grid tends to _______ electrons from reaching the plate.

Your Answers Should Be:

A1. A three-element tube is called a **triode.**

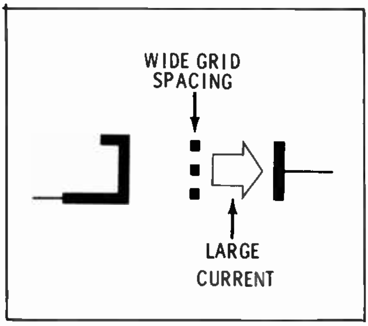
A2. The names of the three elements of a triode are the **plate,** the **grid,** and the **cathode.**

A3. The process of making small signals larger is called **amplification.**

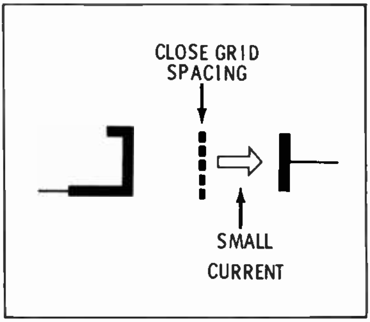
A4. The negative grid tends to **prevent** electrons from reaching the plate.

Spacing Between the Grid Wires

This factor of construction affects the flow of plate current in a rather obvious manner. Closely spaced grid wires tend to concentrate the electric field. Therefore, the grid is better able to turn back the electrons when the grid wires are closely spaced. That is, the electrons have less chance of passing through the grid wires.



EFFECT OF WIDE GRID SPACING ON PLATE CURRENT

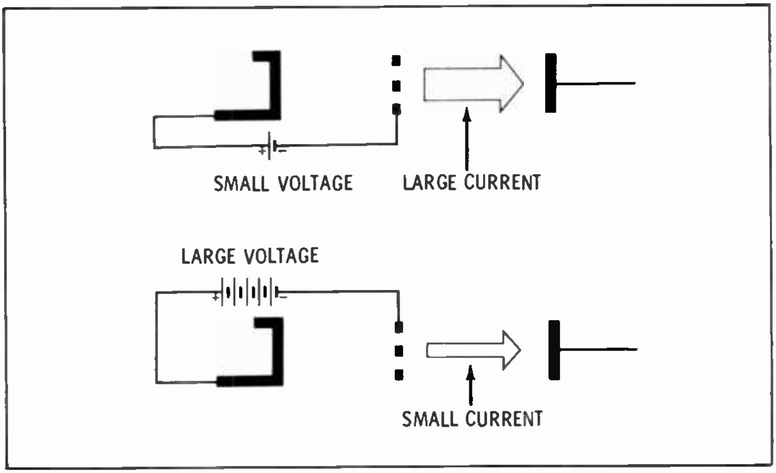


EFFECT OF CLOSE GRID SPACING ON PLATE CURRENT

Negative Voltage Applied to the Grid

As the grid is made more negative with respect to the cathode, its repelling effect becomes greater. Therefore, the more negative the grid, the less the plate current will be.

EFFECT OF GRID VOLTAGE ON PLATE CURRENT

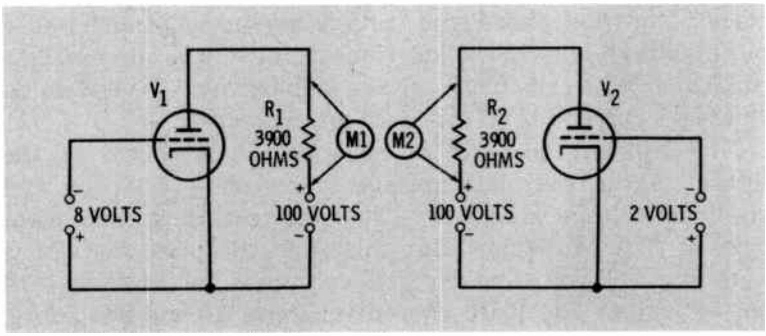


Q5. The grid is operated (negative, positive) with respect to the cathode.

Q6. The farther the grid is from the cathode, the (more, less) the plate current is.

Q7. The wider the spacing between the grid wires, the (more, less) the plate current is.

Q8. Which meter measures more voltage?



Your Answers Should Be:

A5. The grid is operated **negative** with respect to the cathode.

A6. The farther the grid is from the cathode, the **more** the plate current is.

A7. The wider the spacing between the grid wires, the **more** the plate current is.

A8. **M_2 measures more voltage.** The plate voltage (V_1 and V_2) is the same. The grid voltage of V_2 is less negative than that of V_1. Therefore, V_2 conducts more, causing a larger voltage drop across R_2 than across R_1. Meter M_2 thus measures more voltage than M_1.

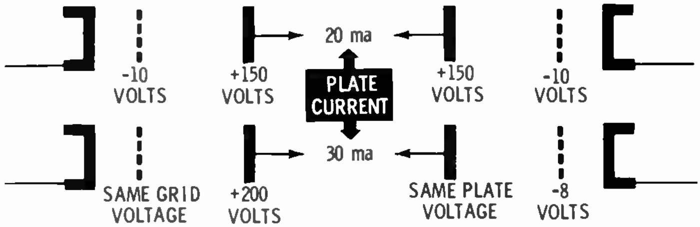
EFFECT OF THE GRID ON TRIODE PLATE CURRENT

The plate and cathode in a triode are essentially the same as those used in a diode. You know that increasing the voltage on the plate increases the plate current. The grid can also be used to increase plate current. However, since the voltage on the grid is a small negative voltage as opposed to the large positive voltage on the plate, the grid is made **less negative** to increase the plate current. **Making the grid less negative is the same as making it more positive.** Thus, there are two ways of varying the plate current. However, one of these ways provides more efficient control than the other. Since the grid is nearer to the cathode, its effect on the electrons is much greater than that of the plate.

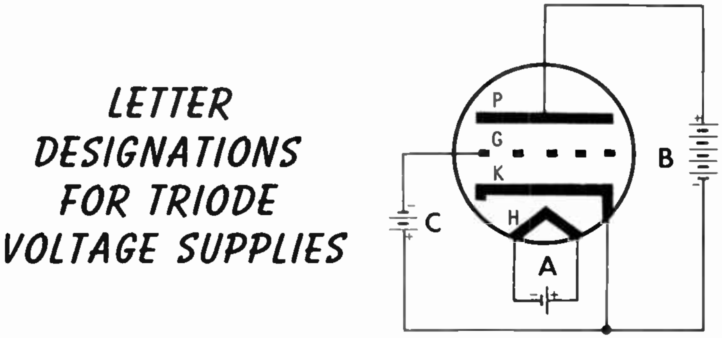
Look at the figure on the next page. In the upper left corner is a tube whose grid voltage is —10 volts and whose plate voltage is +150 volts. This results in a current flow of 20 ma. When the plate voltage is increased to +200 volts, the plate current is 30 ma, a 10-ma increase.

Now look at the tube in the upper right corner of the figure. Again the plate voltage starts at +150 volts and the grid voltage starts at —10 volts, resulting in a plate current flow of 20 ma. But this time the plate voltage is kept at +150 volts and the grid voltage is varied from —10 to —8 volts. The plate current changes 10 ma as before, from 20 ma to 30 ma. Thus, to change the plate current 10 ma, either the plate voltage can be changed 50 volts or the grid voltage changed 2 volts (for the tube in this example). In most cases, this is done by varying the grid voltage.

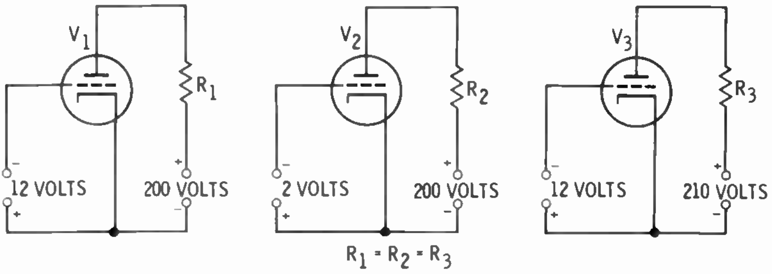
RELATIVE EFFECTS OF CHANGES IN GRID AND PLATE VOLTAGE



The constant use of the terms plate voltage, grid voltage, and filament voltage has led to the use of some simple shorthand notations, as shown in the figure below.



Q9. List the following resistors in order of decreasing wattage rating.



Your Answer Should Be:

A9. R_2, R_3, R_1. Since all of the resistors have the same resistance, the one through which the most current flows requires the highest wattage rating. All that is necessary is to determine which tube has the highest plate current. V_1 and V_2 both have plate voltages of 200 volts, but V_2 has a grid voltage that is less negative than V_1 by 10 volts. Therefore V_2 conducts more heavily than V_1. The grid voltages of V_1 and V_3 are the same, but the plate voltage of V_3 is 10 volts higher than the plate voltage of V_1. For this reason, V_3 also conducts more heavily than V_1. Thus, V_1 has the least plate current; its resistor needs the lowest wattage rating. Note that both V_2 and V_3 have had a change of 10 volts (with respect to V_1)—V_2 +10 volts to the grid and V_3 +10 volts to the plate. Since the grid has more effect on the plate current and since the voltage changes were the same, V_2 must conduct more heavily than V_3. Thus R_2 requires a higher wattage rating than R_3.

TUBE CHARACTERISTICS

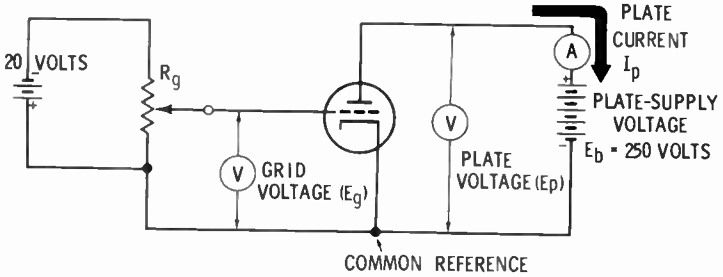
You have already learned that three factors affect the amount of current passing through a diode. These are the temperature of the cathode, the voltage on the plate (with respect to the cathode), and the space charge. The plate current of a triode is also affected by all of these factors and, in addition, one more—the voltage on the grid with respect to the cathode.

Remember the diode characteristic called DC plate resistance (R_p): **Increases** in **plate voltage** cause **decreases** in R_p (in the linear part of the curve). Do changes in grid voltage affect the R_p of a triode in a similar fashion? To find out, plot a curve of grid voltage versus plate current. The circuit shown in the figure on the next page can be used to obtain the information for this curve. The method used to obtain this information is also explained in the paragraphs that accompany the illustration.

Grid-Voltage, Plate-Current Characteristic

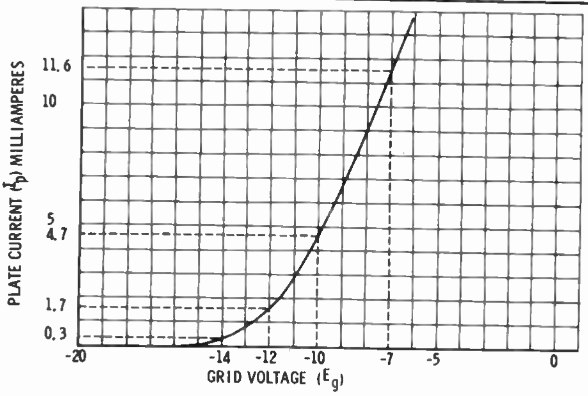
Note that the filament voltage is not shown in the figure, but it must be supplied. The plate-supply voltage (E_b) is

CIRCUIT TO OBTAIN DATA FOR TRIODE CHARACTERISTIC CURVE



250 volts, but any voltage may be used as long as it is correct for the tube you have selected (you may determine this voltage from a tube manual). The plate-supply voltage will be held constant throughout this test. Adjust R_g until some plate-current flow is indicated on ammeter A. Read the value of this current and the grid voltage and record these values. Continue to change the grid voltage and read the two meters until you have obtained about five pairs of readings. Plot the data on a graph. You should obtain a graph similar to that shown in the figure below.

TRIODE PLATE CURRENT VERSUS GRID VOLTAGE



Q10. Determine R_p for each of the points on the graph.

Your Answers Should Be:

A10. For each of the selected grid voltages, **R_p should be:**

e_g	R_p
—7	21.4K
—10	53.2K
—12	147K
—14	833K

Sample Calculation:

$$R_p = \frac{E_b}{I_p} = \frac{250V}{4.7\ ma}$$

$$R_p = 53.2K$$

First find the point at which a vertical line through the desired grid voltage intersects the curve. Next, observe where a horizontal line through this point on the curve passes through the vertical axis. Read the plate current at this point. Use this value along with the value of E_b to calculate R_p.

Shorthand Notations

Below is a list of some of the shorthand notations used to represent the various voltages and currents associated with a triode.

E_b = the plate-supply voltage.
e_b = the instantaneous total plate voltage.
I_b = the average total plate current.
E_c = the control-grid supply voltage.
e_g = the instantaneous total grid voltage.

Note that capital letters are used to indicate source or average values and small letters are used to indicate instantaneous values.

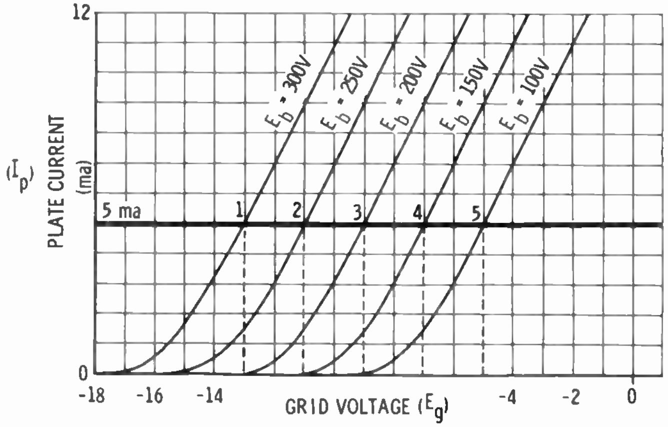
FAMILIES OF CURVES

When discussing the characteristics of a diode, it was only necessary to plot one curve to completely describe the behavior of the tube. However, with the addition of a grid, another variable must be added to cover the operating conditions. In plotting the curve of grid voltage versus plate current, one of the tube voltages must be maintained constant or the result will be meaningless. In plotting the grid-voltage, plate-current curve, the plate voltage was maintained constant at 250 volts. Plot the curve again for plate voltages of 200 and 300 volts. These curves make up a **family of curves** to describe the operation of the triode almost as thoroughly as the one curve described the operation of the diode. To improve on the coverage given by these curves, just add additional curves at other plate voltages. This group of curves is called the **grid family of characteristic curves.**

Grid Family of Curves

The figure below shows a grid family of characteristic curves. Three of the curves were determined previously—the ones for E_b equal to 300, 250, and 200 volts. Note the points at which the plate current is zero. The grid voltage that is sufficiently negative to stop the flow of plate current is called the **cutoff voltage.** Note that the higher the value of E_b, the more negative the cutoff voltage is.

GRID FAMILY OF CHARACTERISTIC CURVES



Q11. A group of curves that describes the operation of a tube is called a ______ of ______________ curves.

Q12. _______ letters are used to indicate source or average values; _____ letters are used to indicate instantaneous values.

Q13. The _____ voltage is held constant for each curve in a grid family of characteristic curves.

Your Answers Should Be:

A11. A group of curves that describes the operation of a tube is called a **family of characteristic** curves.

A12. **Capital** letters are used to indicate source or average values; **small** letters are used to indicate instantaneous values.

A13. The **plate** voltage is held constant for each curve in a grid family of characteristic curves.

Interpreting the Curves

Suppose that R_p was calculated for the points shown in the figure on the previous page. When e_p is 300 volts, R_p is 60K; when e_p is 100 volts, R_p is 20K. These results seem to show that as the plate voltage decreases, R_p decreases. Why was this wrong conclusion reached? The plate voltage was changed at the same time the grid voltage was changed. Note, however, that the plate current remains the same. You will soon see that even though this method of collecting information does not give the correct information about how the R_p of a tube varies with plate voltage, it does offer very useful information. This information is one of three measures of the usefulness of a tube known as **tube parameters.**

TUBE PARAMETERS

In referring to vacuum tubes, the term parameter is defined as a **measure.** It is usually a combination of more than one measure (often a ratio). A parameter is normally fairly constant for the item it describes.

Suppose you wish to describe a bar of steel. You might say that it is 6 feet long, but this can change (you might cut some of it off). Its weight may be 30 pounds; this would also change if the bar were cut. Length and weight are not parameters because they do not remain constant. How about the density of the steel (its weight per cubic foot)? This does not change as you change the dimensions of the steel. Therefore, density is a parameter of the steel.

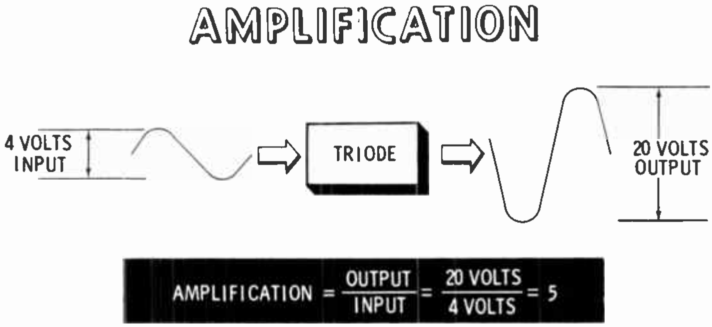
Suppose you were told that two cars made a trip of 80 miles. It is easy to see that these trips were entirely different in nature if one was made in an hour and the other was made in six days. In the same fashion, what if two cars traveled for four hours? What does this mean? Nothing until it is specified that one car traveled 80 miles and the other traveled 320 miles. The best way to compare the speeds of the two cars is to specify their speeds in miles per hour (this is a parameter).

R_p is not a parameter because it changes as the plate voltage and grid voltage change. The parameters used to describe vacuum tubes are often called **tube constants.** They are **amplification factor,** AC **plate resistance,** and **transconductance.**

Amplification Factor

Amplification factor is the tube parameter that indicates the maximum amplification of which the tube is capable. (In actual circuits this maximum is never reached.) The symbol for amplification factor is the Greek letter μ (also written mu).

You know that a triode is an amplifier. Just how much can it amplify a signal applied to it? The amplification is the ratio of the amplitude of the output signal to the amplitude of the input signal.



In the above figure, the amplification is 20 volts divided by 4 volts, or 5.

Q14. The symbol for amplification factor is __.

Q15. The ratio of the ______ voltage over the _____ voltage in a triode is called amplification.

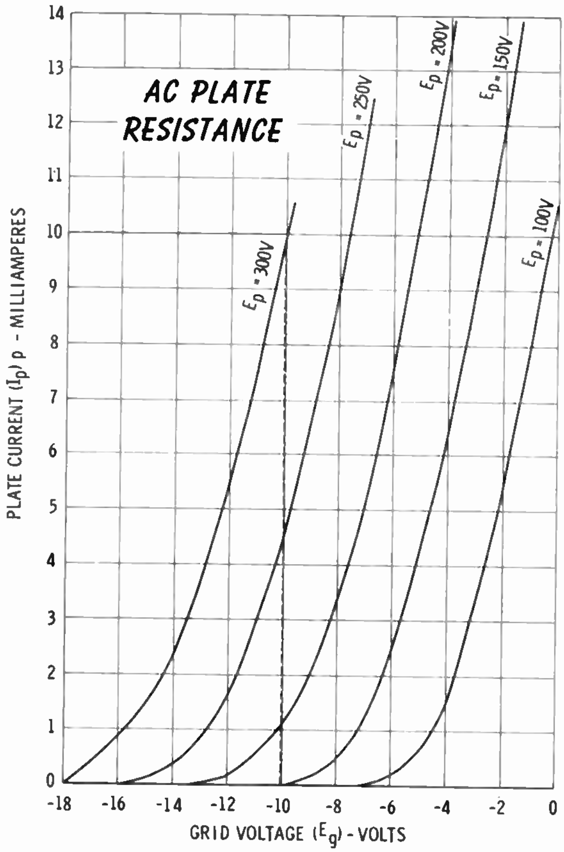
Your Answers Should Be:

A14. The symbol for amplification factor is μ.

A15. The ratio of the **output** voltage over the **input** voltage in a triode is called amplification.

Calculating the Amplification Factor

Imagine that you have just designed a new triode. In order to check its characteristics you have collected a grid family of curves, such as the one that was illustrated on page 53. Returning to the erroneous conclusion about the relationship between the plate voltage and the DC plate re-



sistance, select points 1 and 2 on the graph. In going from point 1 to point 2 the plate voltage decreases 50 volts. But the plate current remains the same (5 ma). Picture this in steps. Lower the plate voltage 50 volts and cause a decrease in plate current. Now raise the plate current back to its original value (5 ma in this example) by making the grid voltage less negative (from —13 to —11 volts). It takes a 50-volt change of plate voltage to change the plate current a certain amount, but a grid-voltage change of only 2 volts is required to return the plate current to normal. The ratio of these two voltage changes is the amplification factor of the triode. In this case:

$$\mu = \frac{\text{Change in Plate Voltage}}{\text{Change in Grid Voltage}} = \frac{50V}{2V} = 25$$

AC Plate Resistance

You have seen how DC plate resistance varies for a triode. The resistance that a triode offers to changing voltages, such as sine waves, is called **AC plate resistance,** r_p. Unlike R_p, r_p remains fairly constant for a particular triode; it is a parameter.

In the figure on the facing page, the line for a grid voltage of —10 volts intersects the curve for $e_p = 300$ volts at a plate current of 10 ma. It also intersects the curve for $e_p = 250$ volts at a plate current of 4.6 ma. To simplify what is to follow, a new symbol is introduced. The symbol is Δ, the Greek letter delta. This symbol means a "change in" or the "difference between" two successive values of something. For example, the change in e_p from 300 volts to 250 volts may be written $\Delta e_p = 50$ volts. AC plate resistance is the ratio between Δe_p and its corresponding change in plate current (Δi_p) with the grid voltage held constant. In this case,

$$r_p = \frac{\Delta e_p}{\Delta i_p} = \frac{300 - 250 \text{ volts}}{10 - 4.6 \text{ ma}} = \frac{50 \text{ volts}}{5.4 \text{ ma}} = 9{,}280 \text{ ohms}$$

Use the figure on the facing page to calculate r_p at —6 volts and —8 volts. Work right on the figure.

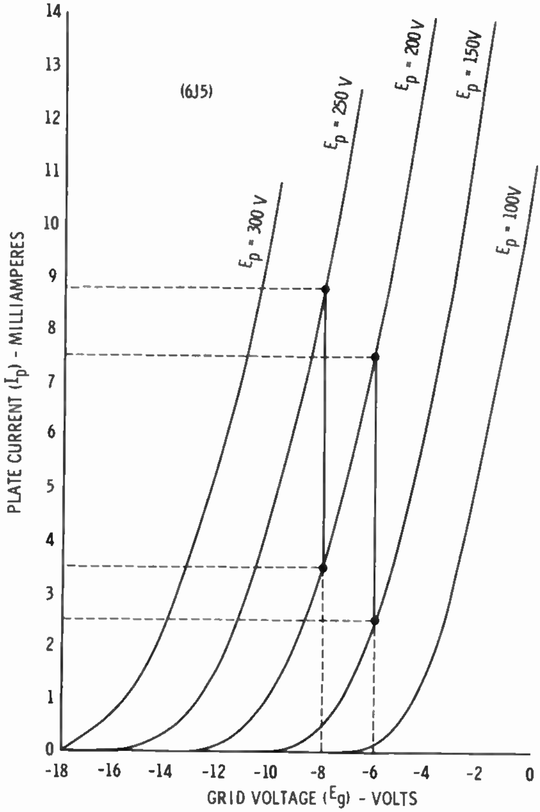
Q16. For $e_g = -6$ volts, $r_p =$ ________ ohms.

Q17. For $e_g = -8$ volts, $r_p =$ ________ ohms.

Your Answers Should Be:

A16. $r_p = \frac{200 - 150 \text{ volts}}{7.5 - 2.5 \text{ ma}} = \frac{50 \text{ volts}}{5 \text{ ma}} = $ **10,000 ohms**

A17. $r_p = \frac{250 - 200 \text{ volts}}{9.0 - 3.5 \text{ ma}} = \frac{50 \text{ volts}}{5.5 \text{ ma}} = $ **9,090 ohms**



Note that these values (9,280, 10,000, and 9,090 ohms) are all fairly close to each other. When compared to the changes in R_p (from thousands of ohms to hundreds of thousands of ohms), the AC plate resistance (r_p) may be considered almost a constant for a particular triode.

Linear Portion of the Curve

In considering r_p to be a constant, the points used to calculate this parameter must be selected with care. For example, suppose the —8-volt point is selected again, but this time the plate-voltage curves for 200 and 150 volts are used. The resultant calculation gives:

$$r_p = \frac{200 - 150 \text{ volts}}{3.5 - 0.5 \text{ ma}} = \frac{50 \text{ volts}}{3 \text{ ma}} = 16{,}700 \text{ ohms}$$

What makes this value so much different from the others? This is due to the selection of the point on the 150-volt curve. What's different here? Refer to the curve on the opposite page. Notice how it starts out as a gentle curve but soon straightens out. Place a straightedge against it and notice that this portion of the curve is practically a straight line. This straight-line portion is called the **linear** portion of the curve. When points are selected on the linear portion of the curve, the result is a fairly constant r_p. Those selected on the curved portion result in quite different values of r_p (see the previous page). This linear portion of the curve plays a great part in preventing distortion of signals.

Tubes Are Like Highways

It may be helpful to think of vacuum tubes as being like highways with electrons for cars. The electrons try to go from cathode to plate just as cars try to reach their destination. A highway also has a property that can be thought of as resistance. Which offers more resistance to cars, a dirt road or a paved road? Think of other factors that affect the "resistance" of a highway (curves, hills, intersections, etc.).

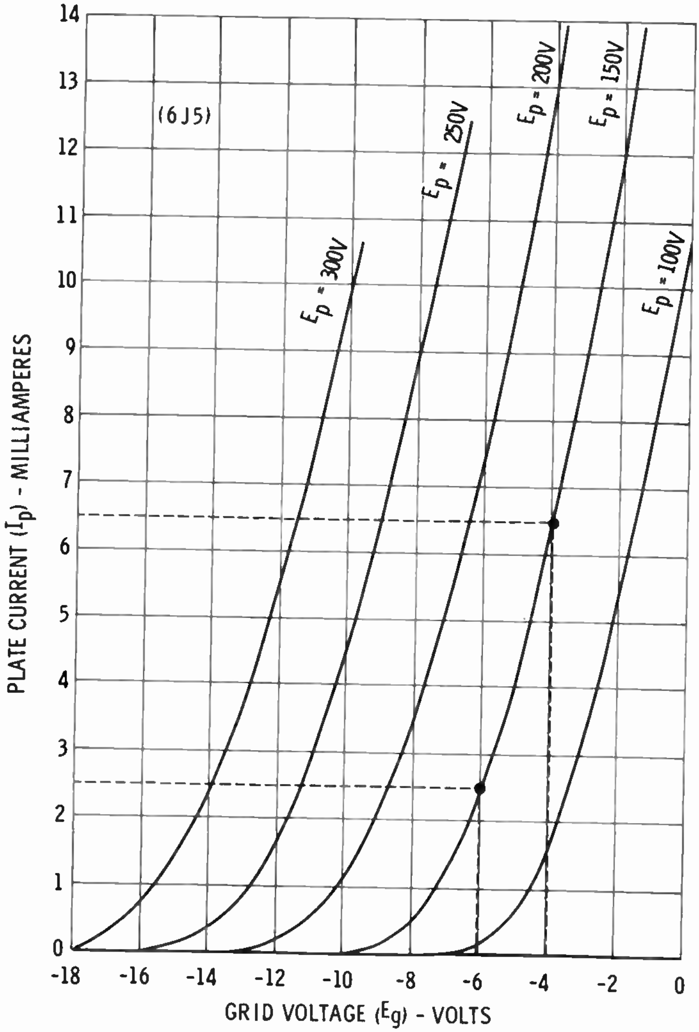
Many kinds of signs give the driver an idea of the "resistance" of the road. As a result they caution him to change his speed. But how slow should he go? There are signs that tell the exact "resistance" of the highway. A lot of resistance calls for a slower speed—a small resistance allows a higher speed. In other words, the speed-limit signs tell the driver the amount of opposition the highway offers.

Q18. The value of r_p is (nearly, not) constant when it is calculated from points on the linear parts of the curves.

Your Answer Should Be:

A18. The value of r_p is **nearly** constant when it is calculated from points on the linear parts of the curves.

TRANSCONDUCTANCE



Transconductance

The speed limit is based on an estimated safe traveling speed for a particular road. In this sense, it is a parameter. Notice something about it. Instead of a number increasing as resistance increases, the number expressing "resistance" of a highway decreases as the "resistance" of the highway increases.

There is a tube constant that describes a tube in much the same fashion as a speed limit describes highways. This constant is called **transconductance.** Transconductance is a measure of the effect that changes in grid voltage have on plate current. The symbol for transconductance is g_m.

You can find g_m from the grid family of curves in the following manner. Inspect the curve for a plate voltage of 150 volts. Record the current at grid voltages of —6 and —4 volts. Then divide the change in plate current by the change in grid voltage to find g_m.

$$g_m = \frac{\Delta i_p}{\Delta e_g} = \frac{6.5 - 2.5 \text{ ma}}{(-4) - (-6) \text{ volts}} = \frac{4 \text{ ma}}{2 \text{ volts}} = 2$$

The result is in milliamps over volts. Volts over milliamps results in resistance in thousands of ohms (kilohms). The inverse of the ohm is called the **mho** (ohm spelled backward). Just as most of the currents in vacuum tubes are in the order of thousandths of an ampere (milliamps), so the units of transconductance are usually in the order of millionths of a mho (micromhos) or thousands of a mho (millimhos). Micromho is often written as μmho. Returning to the answer in the previous calculation, it should be 2 millimhos, or 2,000 μmhos. Transconductance is usually measured in micromhos.

Q19. The transconductance at e_p = 200 volts is ___________. (Use the graph on the facing page.)

Q20. The transconductance at e_p = 300 volts is ___________.

Q21. Write the equations for each of the three tube constants.

Q22. Transconductance is usually measured in units called __________.

Your Answers Should Be:

A19. At $e_p = 200$ volts:

$$g_m = \frac{\Delta i_p}{\Delta e_g} = \frac{7.5 - 3.4 \text{ ma}}{(-6) - (-8)\text{ V}}$$
$$= \frac{4.1 \text{ ma}}{2 \text{ volts}} = \mathbf{2{,}050\ \mu mhos}$$

A20. At $e_p = 300$ volts:

$$g_m = \frac{\Delta i_p}{\Delta e_g} = \frac{10 - 5.5 \text{ ma}}{(-10) - (-12)\text{ V}}$$
$$= \frac{4.5 \text{ ma}}{2 \text{ volts}} = \mathbf{2{,}250\ \mu mhos}$$

A21. $\mu = \frac{\Delta e_p}{\Delta e_g}$ (i_p constant)

$r_p = \frac{\Delta e_p}{\Delta i_p}$ (e_g constant)

$g_m = \frac{\Delta i_p}{\Delta e_g}$ (e_p constant)

A22. Transconductance is usually measured in units called **micromhos.**

Significance of Transconductance

Transconductance is the parameter most used to describe the characteristics of a vacuum tube. For example, a tube with a transconductance of 2,000 μmhos would give more amplification (at the same plate voltage) than a tube with a transconductance of 1,500 μmhos. Note from answers A19 and A20 above that the g_m for a particular triode remains fairly constant over the entire grid family of curves, except in the nonlinear portions.

Tube-Constant Relationships

All of the parameters (μ, g_m, and r_p) are obtained from the same family of curves. It would appear there must be a relationship existing between the parameters. That relationship is:

$$\mu = g_m \times r_p = \frac{\text{ma}}{\text{volts}} \times \frac{\text{volts}}{\text{ma}}$$

Note how the volts and milliamps cancel. As a result, the amplification factor has no units.

To show this relationship, take the values of r_p found around the 200- and 150-volt curves (10,000 ohms) and the g_m found on the 150-volt curve (2,000 μmhos). These values of transconductance and AC plate resistance can be substituted in the equation, and the value of the amplification factor can be calculated.

$$\mu = 10{,}000 \text{ ohms} \times 2{,}000\ \mu\text{mhos} = 20$$

Note how the ohms cancel out the mhos. This is the same value calculated earlier for the μ of the tube.

The equations for μ, g_m, and r_p can be used to prove the equation for the relationship of the parameters. Start with the equation for μ:

$$\mu = \frac{\Delta e_p}{\Delta e_g} \qquad (1)$$

Take the equation $r_p = \frac{\Delta e_p}{\Delta i_p}$, and solve for Δe_p:

$$e_p = \Delta i_p r_p \qquad (2)$$

Take the equation $g_m = \frac{\Delta i_p}{\Delta e_g}$, and solve for Δe_g:

$$e_g = \frac{\Delta i_p}{g_m} \qquad (3)$$

Substitute equations (2) and (3) in equation (1).

$$\mu = \frac{\Delta e_p}{\Delta e_g} = \frac{\Delta i_p r_p}{\frac{\Delta i_p}{g_m}} = g_m r_p.$$

TUBE MANUALS

Up until now you have been supplied with data on how tubes behave under various conditions. You have also seen how to generate this information experimentally. However, where can you obtain this information on a particular tube? Nearly all manufacturers of vacuum tubes publish manuals containing tube data.

Q23. $r_p = 7.5K$; $\mu = 15$; $g_m = ?$

Q24. $\mu = 45$; $g_m = 9$ millimhos; $r_p = ?$

Your Answers Should Be:

A23. $g_m = \frac{\mu}{r_p} = \frac{15}{7{,}500 \text{ ohms}} = 2{,}000\ \mu\text{mhos}$

A24. $r_p = \frac{\mu}{g_m} = \frac{45}{0.009 \text{ mho}} = 5{,}000 \text{ ohms}$

General Contents of a Tube Manual

Most tube manufacturers publish a new manual each year, but there are those who publish only one manual every three or four years and keep it up to date by mailing data sheets to subscribers. The manual published by one leading tube manufacturer contains the following sections.

Electrons, Electrodes, and Electron Tubes—This section contains the basic theory of vacuum tubes from the electron to the cathode-ray tube. It is a very condensed version and is intended as a refresher rather than as a textbook presentation.

Electron-Tube Characteristics—This section contains a brief review of the tube characteristics, parameters, and curves already covered in this chapter.

Electron-Tube Applications—In this section you will find brief descriptions of many vacuum-tube applications. In this particular manual these are divided into the following nine categories: amplification, rectification, detection, automatic volume or gain control, tuning indication with electron-ray tubes, oscillation, deflection circuits, frequency conversion, and automatic frequency control.

Electron-Tube Installation—Under this heading you will find various suggestions and precautions to be followed when installing electron tubes.

Interpretation of Tube Data—This section lists the information necessary to interpret the data provided in the Tube Types section of the tube manual.

Receiving-Tube Classification Chart—This section provides a chart summarizing all of the tubes in the manual. It groups them according to tube types and characteristics, as well as to physical configuration.

Tube Types–Technical Data—This section comprises the bulk of the manual. It lists all of the tubes in alpha-numeric order. A tube is identified by a combination of numbers and letters. The first grouping in the identification code is usually numeric and may contain as many as three digits. This grouping is usually an indication of the filament voltage necessary to operate the tube. For example, a 1A3 uses a heater voltage of 1.4 volts, a 5U4 uses a heater voltage of 5.0 volts, and a 117Z3 uses a heater voltage of 117 volts. (For picture tubes, the initial digits do not give the heater voltage.) This section of the manual is discussed in more detail later.

Picture-Tube Characteristics Chart—This chart summarizes the physical and electrical characteristics of television picture tubes in much the same fashion as the receiving-tube classification chart.

Electron-Tube Testing—This section gives information and circuits that describe and illustrate practical tube-tester considerations.

Resistance-Coupled Amplifiers—This section describes the use of the resistance-coupled amplifier and provides charts showing the voltages and components necessary to operate over 50 different type tubes as resistance-coupled amplifiers.

Circuits—Here you will find a number of representative circuits complete with component values. Some of the circuits included are AM, FM, and auto receivers; microphone and phonograph amplifiers; a code practice oscillator; and an electronic volt-ohmmeter.

Outlines—This section gives the physical dimensions of every tube in the manual. There are only a few pages because many of the tubes have the same external physical construction.

Index—The index for this manual is in a standard alphabetical form as used in most publications.

Q25. The first digits in a tube-type number usually represent the ______ _______ of the tube.

Q26. Tube manuals usually list tubes in _____ _______ order in the technical-data section.

Q27. (A few, nearly all) tube manufacturers publish manuals giving data on the tubes they manufacture.

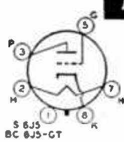
Your Answers Should Be:

A25. The first digits in a tube type number usually represent the **heater voltage** of the tube.

A26. Tube manuals usually list tubes in **alpha-numeric** order in the technical-data section.

A27. **Nearly all** tube manufacturers publish manuals giving data on the tubes they manufacture.

Page From a Typical Tube Manual



MEDIUM-MU TRIODE

6J5
6J5GT
Related type: 12J5GT

Metal type 6J5 and glass octal type 6J5-GT used as detectors, amplifiers, or oscillators in radio equipment. These types feature high transconductance together with comparatively high amplification factor. Outlines 2 and 14C, respectively, OUTLINES SECTION. Tubes require octal socket and may be mounted in any position. For typical operation as resistance-coupled amplifiers, refer to RESISTANCE-COUPLED AMPLIFIER SECTION. Type 6J5-GT is used principally for renewal purposes.

HEATER VOLTAGE (AC/DC)		6.3	volts
HEATER CURRENT		0.3	ampere
DIRECT INTERELECTRODE CAPACITANCES (Approx.):	*6J5**	*6J5-GT***	
Grid to Plate	3.4	38	pf
Grid to Cathode and Heater	3.4	4.2	pf
Plate to Cathode and Heater	3.6	5.0	pf

* Shell connected to cathode. ** Base sleeve and external shield connected to cathode.

CLASS A_1 AMPLIFIER

Maximum Ratings, *Design-Center Values:*

PLATE VOLTAGE	300 *max*	volts
GRID VOLTAGE, Positive-bias value	0 *max*	volts
PLATE DISSIPATION	2.5 *max*	watts
CATHODE CURRENT	20 *max*	ma
PEAK HEATER-CATHODE VOLTAGE:		
Heater negative with respect to cathode	90 *max*	volts
Heater positive with respect to cathode	90 *max*	volts

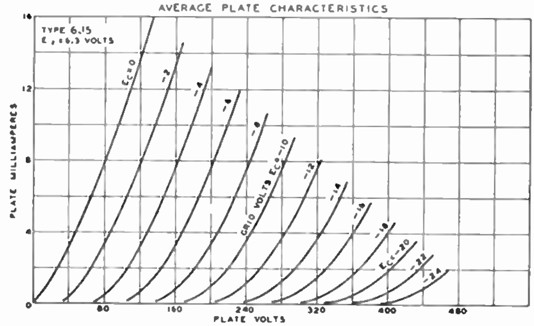
Characteristics:

Plate Voltage	90	250	volts
Grid Voltage	0	−8	volts
Amplification Factor	20	20	
Plate Resistance (Approx.)	6700	7700	ohms
Transconductance	3000	2600	µmhos
Grid Voltage (Approx.) for plate current of 10 µa	−7	−18	volts
Plate Current	10	9	ma

Maximum Circuit Value:

Grid-Circuit Resistance	1.0 *max*	megohm

AVERAGE PLATE CHARACTERISTICS



Courtesy Radio Corporation of America

Technical Data

A typical technical-data page is shown at the left. These data are for a type 6J5 vacuum tube, the type that has been used for all the examples concerning tube characteristics and parameters. On the right side of the data sheet is a diagram showing how each of the elements is connected to the tube pins. These connections (pins) are numbered in a clockwise direction as you look down on the top of the tube. In addition, there are letters next to these pins that identify the elements to which they are connected. These letters are identified in the diagram below.

KEY TO SOCKET CONNECTION DIAGRAMS

Bottom Views

• = Gas-Type Tube	F_M = Filament Mid-Tap	IS = Internal Shield
BC = Base Sleeve	G = Grid	K = Cathode
BS = Base Shell	H = Heater	NC = No Connection
C = External Conductive Coating	H_L = Heater Tap for Panel Lamp	P = Plate or Anode
CL = Collector	H_M = Heater Mid-Tap	RC = Ray-Control Electrode
DJ = Deflecting Electrode	IC = Internal Connection — Do Not Use	S = Shell
ES = External Shield		TA = Target
F = Filament		

Courtesy Radio Corporation of America

Alphabetical subscripts B, D, HP, HX, P, and T indicate, respectively, beam unit, diode unit, heptode unit, hexode unit, pentode unit, and triode unit in multi-unit types.

At the top of the sample page is a short paragraph describing the important features of and suggested uses for the tube. References are made to other portions of the manual where additional information about this tube can be found. Below this paragraph is a tabular presentation of significant tube characteristics.

Use the sample page to obtain the following information:

Q28. The amplification factor of the 6J5 is _____.

Q29. The 6J5 may be used as a _ _ _ _ _ _ _ _ _, _ _ _ _ _ _ _ _ _ _, or _ _ _ _ _ _ _ _ _ _ _.

Q30. With a plate voltage of 90 and a grid voltage of 0, the g_m is ______ _ _ _ _ _.

Q31. With a grid voltage of −8 and a plate voltage of 250, the r_p is ______ _ _ _ _.

Your Answers Should Be:

A28. The amplification factor of the 6J5 is 20.

A29. The 6J5 may be used as a **detector, amplifier,** or **oscillator.**

A30. With a plate voltage of 90 and a grid voltage of 0, the g_m is **3,000 μmhos.**

A31. With a grid voltage of —8 and a plate voltage of 250, the r_p is **7,700 ohms.**

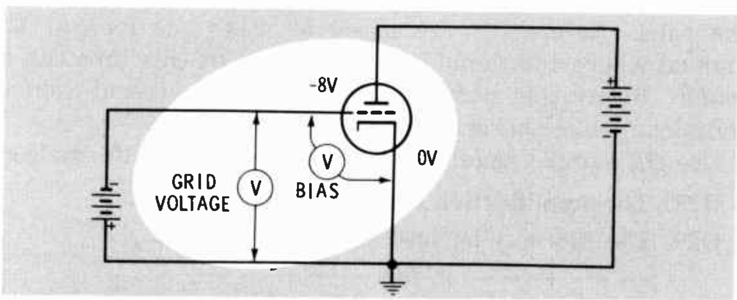
Characteristic Curves

At the bottom of the sample page is a family of curves. This is not the grid family that you have been using up until now. The grid family of curves (also referred to as the **transfer-characteristic curves**) was obtained by varying e_g while observing i_p with several fixed values of e_p. The curve in the tube manual is called the **plate characteristic curve** (also called the **plate family of curves**) and is obtained by observing i_p as e_p is varied with e_g held constant.

BIASING

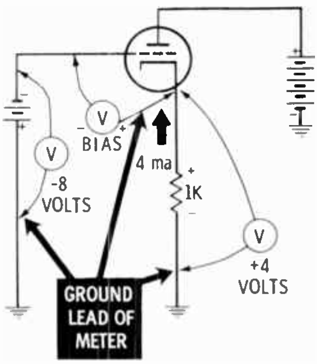
Grid bias is the difference in DC potential between the grid and the cathode. Bias determines the operating point of the tube. Consider the tube in the figure.

GRID VOLTAGE AND BIAS



The bias on the tube above is equal to the difference between the grid voltage (—8 volts in the figure) and the cathode voltage (0 volts in the figure). Therefore the bias in this case is equal to —8 volts.

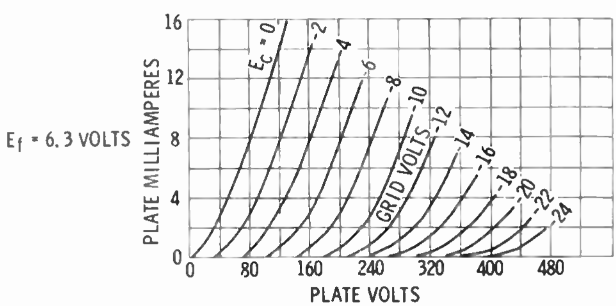
One way to measure the bias on a tube is to measure the voltage on the grid and then the voltage on the cathode (always with respect to the same common point, or ground). Add these voltages as if you were going from the grid to the cathode, and observe the polarities of the voltages. For example, in the figure you will measure —8 volts from grid to ground. The cathode voltage measured will be +4 volts (4 ma × 1K). However, in going from grid to cathode, you pass through the battery from negative to positive and then through the cathode resistor from negative to positive. Thus you pass through a total of —12 volts of bias.



MEASURING BIAS VOLTAGE

Q32. Use the graph below to find μ at a plate current of 8 ma.

Q33. Use the graph to find g_m at an E_p of 120 volts.

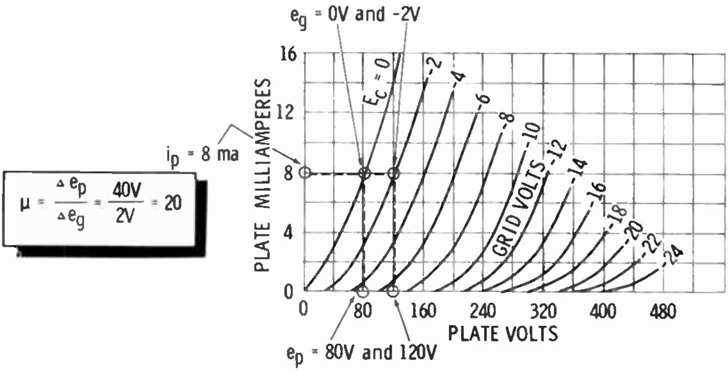


Q34. Grid bias is the difference in DC potential between the ____ and the ________.

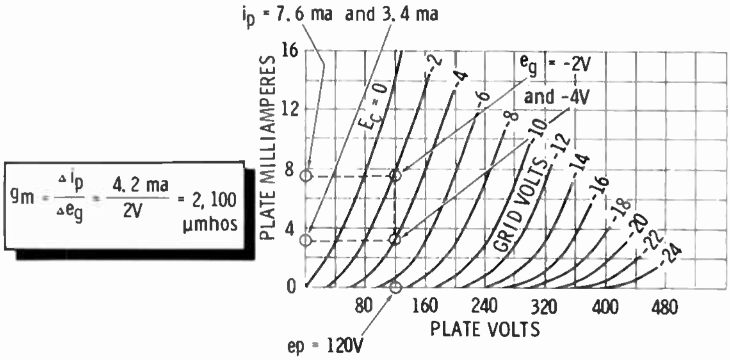
Q35. Bias voltage equals grid voltage if the _______ voltage is zero.

Your Answers Should Be:

A32.



A33.



A34. Grid bias is the difference in potential between the **grid** and the **cathode** (not cathode to grid).

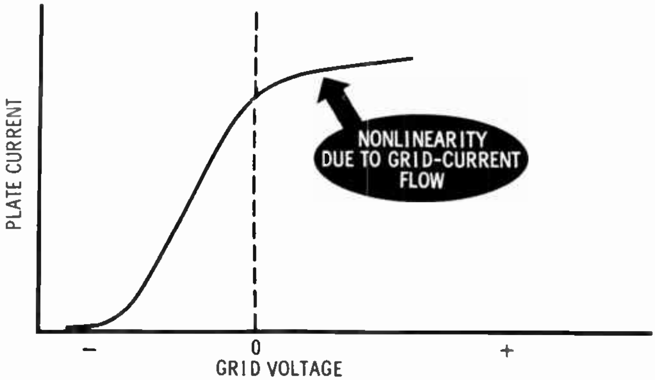
A35. Bias voltage equals grid voltage if the **cathode** voltage is zero.

Biasing Methods

There are several methods of supplying bias. The fundamental method is the application of a steady DC voltage to the grid of the tube. Other methods will be discussed in the chapter on vacuum-tube amplifiers.

The bias determines the operating point of the tube. That is, with no signal applied to the tube a certain plate current will flow. This current is the **static** plate current and is controlled by the bias. The bias is nearly always negative. The figure shows what happens when the bias is positive.

EFFECT OF POSITIVE GRID VOLTAGE

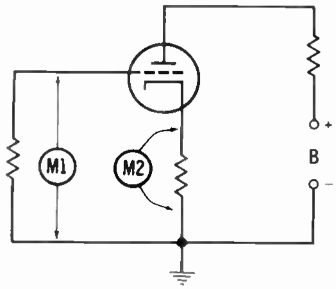


When the grid voltage is positive, it can remove electrons from the electron stream. These are electrons that would normally be part of the plate current. Thus, increasing the grid voltage in the positive region would increase the number of electrons taken from the space charge and would also draw more and more electrons from the plate current. This would result in a nonlinearity at the top of the e_g-i_p curve, as shown in the figure above. This is just as objectionable as the nonlinearity at the bottom of the curve.

Q36. Bias determines the ---------- ----- of the tube.

Q37. When the meters measure the voltages shown below, what is the bias?

M1	M2	BIAS
0	+6	
—3	+3	
—6	0	



Your Answers Should Be:

A36. Bias determines the **operating point** of the tube.

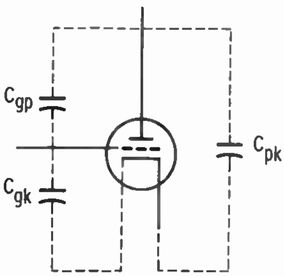
A37. **All of your answers should have been —6 volts.** In each case, as you look from the grid to the cathode, you are looking through 6 volts of potential. Thus, the grid must be 6 volts negative with respect to the cathode.

MULTIGRID TUBES

As electronics advanced and became more complex, the design of the electron tube also progressed. Many of these advancements have resulted in a need for new kinds of diodes and triodes. Others have made it necessary to add other elements to the triode.

Feedback in the Triode

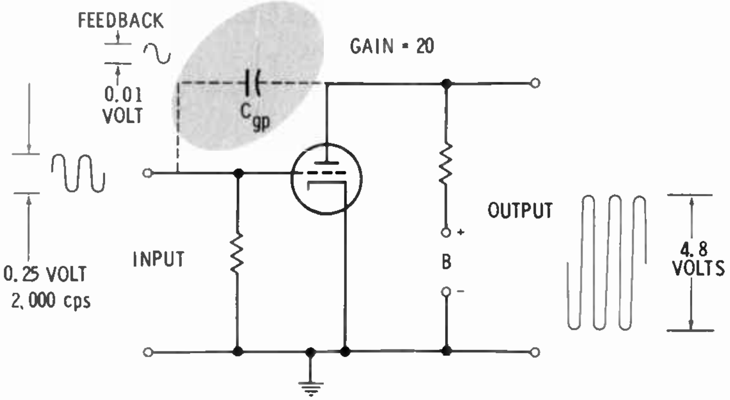
The elements of a triode act like capacitors. This effect is called **interelectrode capacitance.** The capacitances are very small, but at high frequencies they become quite objectionable. This is especially true of the capacitance between the grid and plate (C_{gp}).



TRIODE INTERELECTRODE CAPACITANCES

In the circuit on the next page, some of the output signal from the triode plate is returned (fed back) to the input grid circuit through C_{gp}. The nature of this **feedback voltage** is such that it tends to reduce the input signal on the grid (this is called **negative feedback**). The reasons for this negative feedback are demonstrated in the chapter on vacuum-tube amplifiers. At present it is enough to say that as the signal goes from grid to plate, it undergoes a phase shift of 180°. Thus, the signal fed back from the plate will be going negative when the grid signal is going positive. The effect of this is to decrease the signal on the grid.

EFFECTS OF GRID-PLATE CAPACITANCE



Above you see a typical triode amplifier circuit. Later you will learn exactly how it operates, but for now observe the following. The input signal (0.25 volt peak-to-peak) is applied to the grid. Since the gain of the amplifier is 20, the output should be multiplied by that amount (0.25×20), resulting in an output of 5.0 volts at the plate. However, at a frequency of 2,000 cps the capacitive reactance of C_{gp} is such that there is a feedback voltage of 0.01 volt. Since this is a negative feedback, it results in a reduction of the input signal ($0.25 - 0.01 = 0.24$). This signal is then multiplied by the amplification (0.24×20), resulting in an output voltage of 4.8. Thus the gain of the amplifier is 4.8 volts $\div$ 0.25, or 19.2 instead of 20. (Of course, reducing the output voltage also reduces the feedback voltage slightly.) If the frequency of the input signal is increased to 20,000 cps, would the gain of the triode increase or decrease?

Q38. The capacitance between elements of a tube is called ________________ ______________.

Q39. The most objectionable capacitance in a triode is the ____ __ _____ capacitance.

Q40. Negative feedback ________ the gain of an amplifier.

Your Answers Should Be:

A38. The capacitance between elements of a tube is called **interelectrode capacitance.**

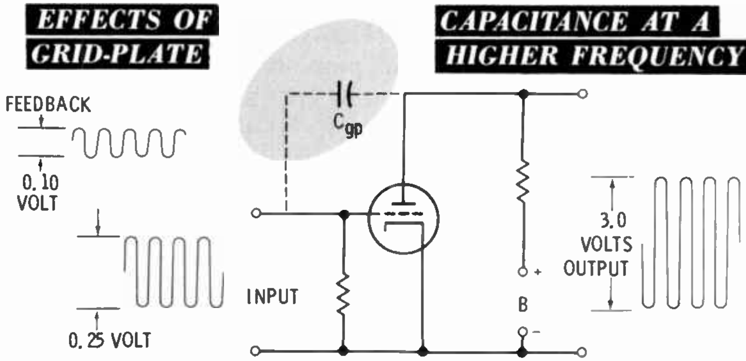
A39. The most objectionable capacitance in a triode is the **grid-to-plate** capacitance.

A40. Negative feedback **reduces** the gain of an amplifier.

Feedback at Higher Frequencies

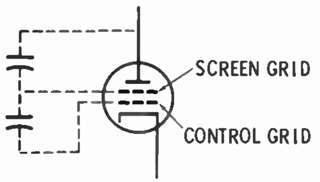
The figure below shows the same circuit as before, but the input signal is at a higher frequency. Since the capacitive reactance of C_{gp} decreases with the change in frequency, there is a greater feedback voltage. In this case it is 0.10 volt. Subtracting 0.10 from 0.25 leaves an input signal of 0.15 volt. Multiplying 0.15 volt by 20 gives an output signal of 3.0 volts. The gain is thus 3.0 ÷ 0.25, or 12.

EFFECTS OF GRID-PLATE CAPACITANCE AT A HIGHER FREQUENCY



Tetrodes

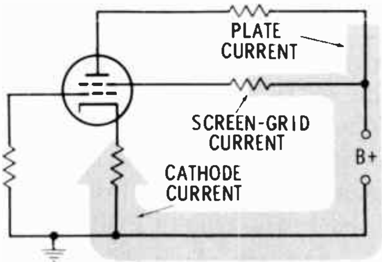
To prevent or reduce feedback, the grid-to-plate capacitance must be decreased. To do this, another element is added between the grid and the plate.



GRID-PLATE CAPACITANCES IN A TETRODE

This element, called a **screen grid**, is similar in construction to the control grid. The screen grid introduces two capacitances in series—a capacitance between the plate and the screen grid and the capacitance between the screen grid and the control grid. As a result, the capacitance between the plate and the control grid is considerably reduced. The screen grid of the **tetrode** (so-called because of the addition of the fourth element) is wound with a very thin wire. The screen grid usually operates with a high positive voltage on it. This voltage is never higher than that on the plate.

CURRENT FLOW IN A TETRODE CIRCUIT



The voltage on the screen grid helps to pull electrons out of the space charge. Because of the thin, widely spaced wires, most of the electrons are not collected by the screen grid but pass through to the plate. Some of the electrons will be attracted to the screen grid, but its current is usually small compared to the plate current. The result of this new construction is a tube with high AC plate resistance. A high r_p means that changes in plate voltage have little effect on the plate current. As a result, the tetrode has a high μ (in the order of 200 or 300 as opposed to 20 to 50 for a triode). In addition, the interelectrode capacitance is very low, and the tube is more suitable for high-frequency applications than a triode.

Q41. The effects of grid-to-plate capacitance (increase, decrease) as frequency increases.

Q42. When capacitors are connected in series, the total capacitance is (greater, less) than that of the smaller capacitor.

Q43. The element added to the triode to make a tetrode is the ------ ----.

Your Answers Should Be:

A41. The effects of grid-to-plate capacitance **increase** as frequency increases.

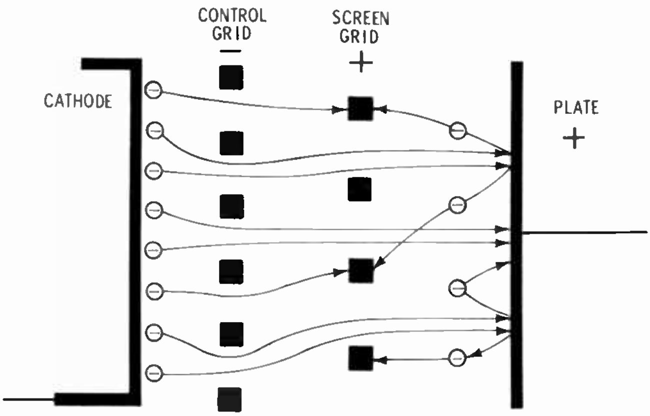
A42. When capacitors are connected in series, the total capacitance is **less** than that of the smaller capacitor.

A43. The element added to the triode to make the tetrode is the **screen grid.**

Pentodes

The tetrode is a high-mu tube that can operate at high frequencies. But this type of tube presents another problem. Due to the extra grid operating at a high positive voltage, electron speed is increased. Some move so fast that they dislodge other electrons when they strike the plate. This is called **secondary emission.** Some of these extra electrons are attracted to the screen grid.

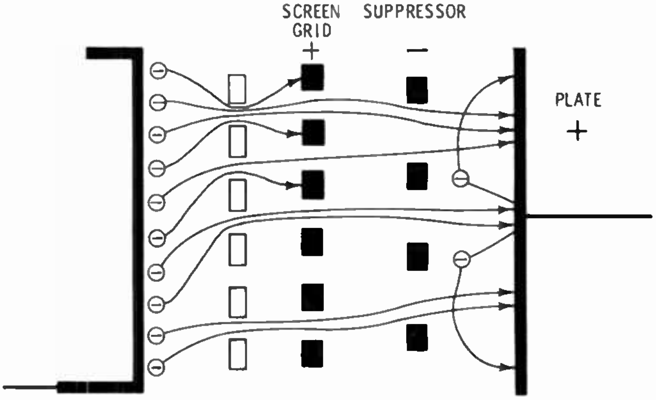
SECONDARY EMISSION



When the screen-grid voltage is equal to or greater than the plate voltage, the amount of current drawn by the screen grid is enough to disturb the operation of the tube. This problem was solved by the development of the **pentode.**

To prevent the screen grid from drawing too much current due to secondary emission, another element, also grid-like in construction, was added to the tetrode. Physically, this extra element is placed between the screen grid and the plate; electrically, it is connected to either the cathode or to ground. As far as the plate is concerned, this element is negative. Electrons leaving the plate due to secondary emission are forced back to the plate by this negative element. Since this element helps suppress secondary emission, it is called the **suppressor grid.**

ACTION OF A SUPPRESSOR GRID



The addition of the suppressor grid between the plate and screen grid also serves to reduce the interelectrode capacitance between the plate and control grid still further. This results in a tube with even better high-frequency performance than the tetrode. Pentode amplification factors are in the order of 1,200 to 1,500 (as opposed to 200 or 300 for a tetrode).

Q44. The release of electrons from the plate when it is struck by electrons from the cathode is called ________ ________.

Q45. A _______ tube results when a third grid is added to a tetrode.

Q46. The third grid in a pentode is called a __________ grid.

Q47. The amplification factor of a pentode is (higher, lower) than that of a triode or a tetrode.

Q48. The suppressor grid of the pentode reduces ________ ________.

Your Answers Should Be:

A44. The release of electrons from the plate when it is struck by electrons from the cathode is called **secondary emission.**

A45. A **pentode** tube results when a third grid is added to a tetrode.

A46. The third grid in a pentode is called a **suppressor** grid.

A47. The amplification factor of a pentode is **higher** than that of a triode or a tetrode.

A48. The suppressor grid of the pentode reduces **secondary emission.**

WHAT YOU HAVE LEARNED

1. A tube containing a cathode, control grid, and plate is a triode.
2. The voltage on the control grid of a triode has a greater effect on plate current than does the plate voltage.
3. A triode can be used to amplify signals.
4. The control grid is usually operated negative with respect to the cathode.
5. There are three tube constants—amplification factor (μ), AC plate resistance (r_p), and transconductance (g_m).
6. Tube-constant values can be determined from graphs called tube characteristics.
7. Tube manuals contain information about tubes.
8. Bias is the difference of potential between the grid and cathode. It determines the operating point of the tube.
9. The screen grid in a tetrode tube reduces undesirable grid-to-plate capacitance.
10. μ and r_p are higher for a tetrode than for a triode.
11. The suppressor grid in a pentode reduces the effects of secondary emission.
12. The amplification factor for a pentode is very high.

3

Semiconductor Devices

What You Will Learn

In this chapter the difference between N- and P-type semiconductor material is discussed. A semiconductor diode will be compared with a vacuum-tube diode. You will learn the difference between forward and reverse bias. You will also learn about the elements of a transistor, and how transistors are used as amplifiers. Transistor characteristic curves are also introduced.

WHAT IS A SEMICONDUCTOR?

Materials can be classed in three groups, according to their electrical properties—conductors, semiconductors, and insulators. Metals such as silver, copper, and aluminum have many free electrons. This makes it easy for current to flow through them. For this reason these metals are called **conductors**.

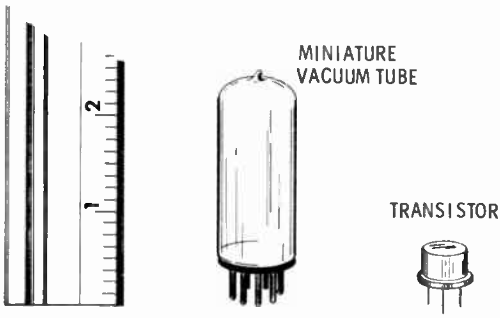
Materials such as glass, rubber, and many plastics have practically no free electrons. This makes it very difficult for current to flow through them. These materials are known as **insulators** and are used in a variety of applications ranging from the covering on conductors to the dielectric in capacitors.

Materials such as selenium, silicon, and germanium have some free electrons—more than an insulator but fewer than a conductor. These materials are generally referred to as **semiconductors**.

WHY SEMICONDUCTOR MATERIALS ARE IMPORTANT

A diode made of semiconductor material is called a **solid-state** diode. Semiconductor materials are also the basic ingredients of transistors. Solid-state diodes can replace vacuum-tube diodes, and transistors can replace vacuum-tube triodes. Why is this important? Solid-state diodes and transistors are smaller, weigh less, and use less power than their vacuum-tube counterparts. They are also more rugged and last longer than vacuum tubes. In addition, they do not require a filament-supply voltage.

TRANSISTORS ARE SMALLER THAN VACUUM TUBES



How do solid-state diodes and transistors work? How can a solid substance maintain unidirectional current flow in the same manner as a vacuum-tube diode? How can a solid substance amplify like the triode? To answer these questions we must first go back and examine the basic building blocks of matter—atoms.

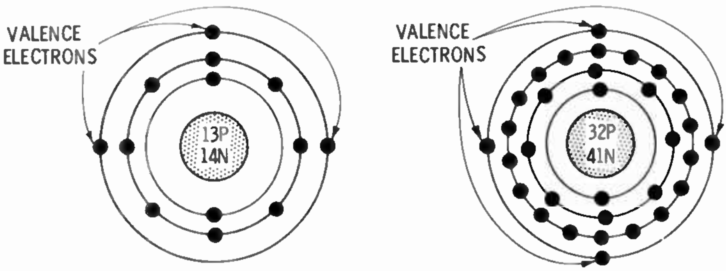
MATTER, ELEMENTS, AND ATOMS

Matter is defined as anything that has mass and occupies space. Air, water, books, and people are examples. Matter consists of one or more materials called **elements.** Elements are substances that cannot be divided into other substances. Copper, aluminum, silicon, and germanium are examples of elements. The smallest particle of an element is an atom, which has all the properties of the element and can take part in chemical reactions.

The Aluminum Atom

The aluminum atom has thirteen electrons circling in orbits around a nucleus of thirteen protons and fourteen neutrons. The negative charges on the thirteen electrons are exactly balanced by the positive charges on the thirteen protons. The three **valence** electrons in the outer shell, or ring, are loosely bound to the atom and are easily dislodged. These three loosely bound electrons are the reason why aluminum is a conductor. Aluminum has a valence of minus 3. This means that aluminum easily gives up the three electrons in its outer ring.

DIAGRAMS OF ATOMS



ALUMINUM *GERMANIUM*

The Germanium Atom

The nucleus of the germanium atom is larger than the aluminum nucleus. It has thirty-two protons and forty-one neutrons. There are thirty-two orbiting electrons, of which four are in the outer ring. These four electrons make germanium a semiconductor. The germanium atom can either give up these electrons or take on four more to complete its outer ring.

Q1. Copper is a(n) __________.

Q2. Glass is a(n) __________.

Q3. A conductor has many ____ __________.

Q4. Silicon is a(n) ______________.

Q5. A substance that cannot be subdivided into other substances is called a(n) ________.

Q6. The electrons in the outer shell of an atom are known as ________ electrons.

Your Answers Should Be:

A1. Copper is a **conductor.**

A2. Glass is an **insulator.**

A3. A conductor has many **free electrons.**

A4. Silicon is a **semiconductor.**

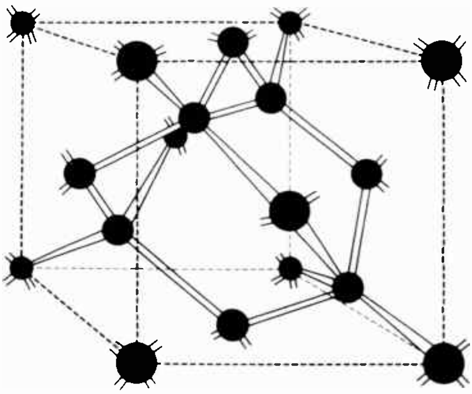
A5. A substance that cannot be subdivided into other substances is called an **element.**

A6. The electrons in the outer shell of an atom are known as **valence** electrons.

GERMANIUM CRYSTALS

The illustration below shows a typical arrangement of germanium atoms. Each germanium atom shares its four outer electrons with four of its neighbors. This sharing of electrons causes a bond which tends to keep the atoms

GERMANIUM CRYSTAL LATTICE



together. This electron-pair bond, called a **covalent bond,** is formed because each atom of germanium attempts to complete a full count of eight electrons in its outer ring. Whenever several cubic structures combine, the lattice-like effect becomes evident. A visible crystal of germanium is composed of many millions of these basic crystal lattices. This crystalline germanium is electrically neutral.

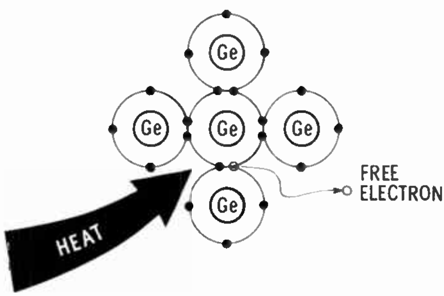
INTRINSIC GERMANIUM

The crystal just examined is an ideal crystal. It probably never exists in nature as such. Because of its purity, this crystal is called **intrinsic**—intrinsic germanium is free from impurities. Manufacturing intrinsic germanium is the first step in the production of solid-state diodes and transistors.

Conduction in Intrinsic Germanium

How do electrons flow in semiconductors? The outer shells of the germanium atoms form covalent bonds, so these shared electrons are not easily dislodged to provide electric current. This is true of all semiconductors. The reason for current flow in semiconductors is the addition of energy to the material. This energy may be in the form of heat, light, or the application of an electric field, such as that due to a voltage. Notice that these properties differ for different semiconductors. When crystals of germanium are heated, for example, the energy level of one of the electrons in a covalent bond is raised. The electron frees itself from the bond and can wander through the crystal lattice. Such free electrons are then available for conduction when an electric field is applied.

COVALENT BOND BROKEN BY HEAT



Q7. Germanium that is free from impurities is called __________ germanium.

Q8. Germanium atoms are held together in a crystal by _________ _____.

Q9. Conduction is produced in intrinsic germanium by the addition of _______.

Your Answers Should Be:

A7. Germanium that is free from impurities is called **intrinsic** germanium.

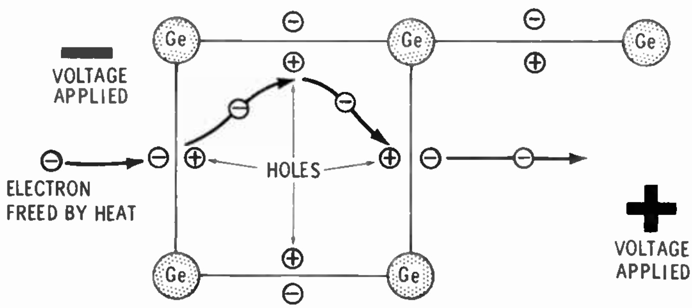
A8. Germanium atoms are held together in a crystal by **covalent bonds.**

A9. Conduction is produced in intrinsic germanium by the addition of **energy.**

Electron Flow Through Intrinsic Germanium

In the figure below you see a few covalent bonds of intrinsic germanium after the material has been heated. Electrons have been liberated from each of the bonds shown. A positive voltage is applied to the germanium. Since an electron is missing from each of the bonds, there is, in effect, a positive charge at each covalent bond. This positive charge is called a **hole.** A free electron drifting in the direction of the applied positive voltage drifts from hole to hole until it finally reaches the positive voltage.

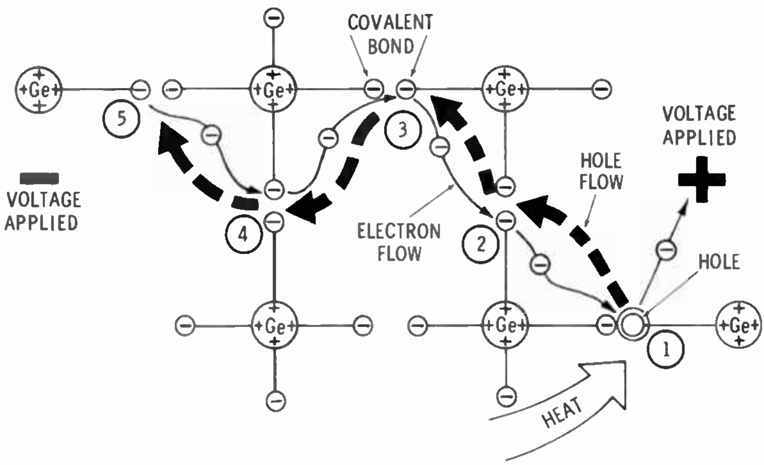
ELECTRON FLOW THROUGH INTRINSIC GERMANIUM



Hole Flow Through Intrinsic Germanium

Examine the figure on the next page. For each of the four electrons in the outer ring of each atom, there is a corresponding proton in the nucleus. When heat is applied (1), an electron is liberated and starts drifting toward the positive voltage. The electron leaves a hole which may be considered to be positive. This hole attracts an electron from the next covalent bond (2), thus leaving a hole at that point. The effect of this is that the hole has moved from point 1 to point 2. In a similar fashion the hole will move to points 3, 4, and 5, and will eventually be filled by an electron from the applied-voltage source. As long as heat continues to liberate electrons at point 1, this action will continue.

HOLE FLOW IN INTRINSIC GERMANIUM



Doping Intrinsic Germanium

You have seen how electrons and holes flow through germanium. This was done by adding heat to liberate electrons and create holes. An electric field was set up to control the direction of hole and electron flow (also called drift). However, for transistors and solid-state diodes, intrinsic germanium is of little value. There is a more efficient way of causing conduction in germanium (or any semiconductor)—by adding impurities to the intrinsic material. This process is called **doping.** The type of impurity must be carefully selected and the amount accurately controlled. Accuracies up to one part in ten million are often required.

Q10. The addition of controlled amounts of impurities to a semiconductor is called ______.

Q11. Current flow in a semiconductor consists of the movement of __________ and _____.

Your Answers Should Be:

A10. The addition of controlled amounts of impurities to a semiconductor is called **doping.**

A11. Current flow in a semiconductor consists of the movement of **electrons** and **holes.**

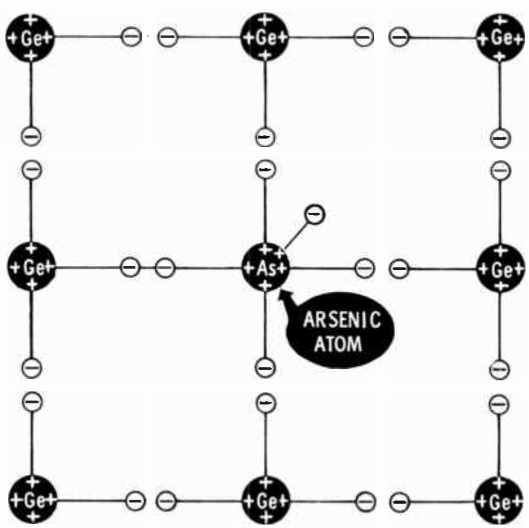
Types of Impurities

Two types of impurities can be added to germanium. One type produces free electrons, and the other type produces holes. The electron-producing type of impurity is known as **N-type** (negative type) and the hole-producing type is known as **P-type** (positive type).

N-TYPE GERMANIUM

Examine the germanium in the figure below. Notice that the crystal is no longer intrinsic. An N-type impurity atom (arsenic) has replaced a germanium atom. Arsenic has five

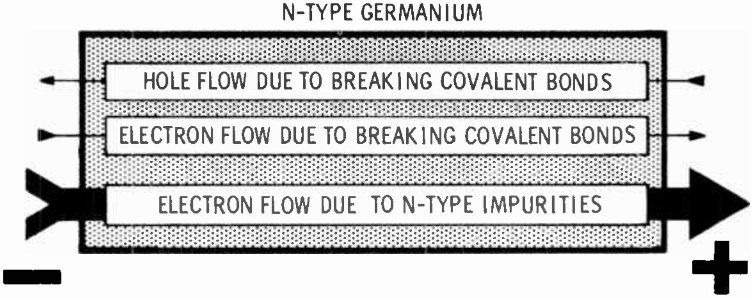
GERMANIUM DOPED WITH ARSENIC



electrons in its outer ring. Therefore it can combine with four electrons from an adjacent germanium atom. When this covalent bond is established, an extra electron is left unpaired. This electron is loosely attached to the arsenic nucleus because the arsenic atom now has eight electrons in its outer ring. In order for this electron to free itself, it requires only one-seventieth of the energy needed to free an electron from a covalent bond. Because the arsenic has donated an electron to the crystal, it is called a **donor** atom. The crystal is called N-type germanium because of the presence of loosely bound negative electrons. The number of extra electrons or current carriers controls the resistance of a semiconductor material. Obviously, the more heavily doped materials contain more donor atoms and more extra electrons for conduction, and thus have a lower electrical resistance.

When an electric field is applied to an N-type crystal, most of the electron flow is due to donor atoms. Some additional current flows due to the breaking of covalent bonds, but this is very minor. The amount of electron flow and hole flow due to breaking of covalent bonds will be equal. Since

ELECTRONS AS MAJORITY CARRIERS



most of the flow is due to donor electrons, they are called the **majority carriers.** The holes are called the **minority carriers.**

Q12. The type of germanium containing an impurity that produces free electrons is called _____ germanium.

Q13. The free electrons in N-type germanium are called _________ carriers.

Q14. Does hole flow equal electron flow in N-type germanium? Why?

Your Answers Should Be:

A12. The type of germanium containing an impurity that produces free electrons is called **N-type** germanium.

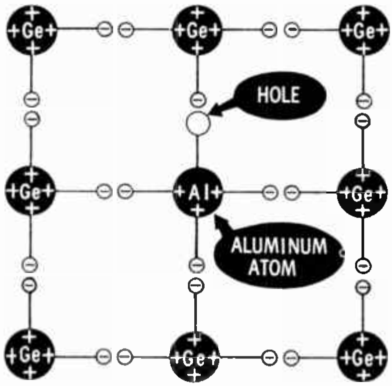
A13. The free electrons in N-type germanium are called **majority** carriers.

A14. **No.** N-type germanium is made by adding an N-type donor atom, such as arsenic (some others are antimony and boron), to the crystal. Most of the current flow in a crystal is due to loosely bound electrons from the donor atoms.

P-TYPE GERMANIUM

Suppose an aluminum atom replaced a germanium atom in a germanium crystal. Aluminum has three electrons in its outer ring. In the crystal, the aluminum atom combines with four germanium atoms. The aluminum atom estab-

GERMANIUM DOPED WITH ALUMINUM

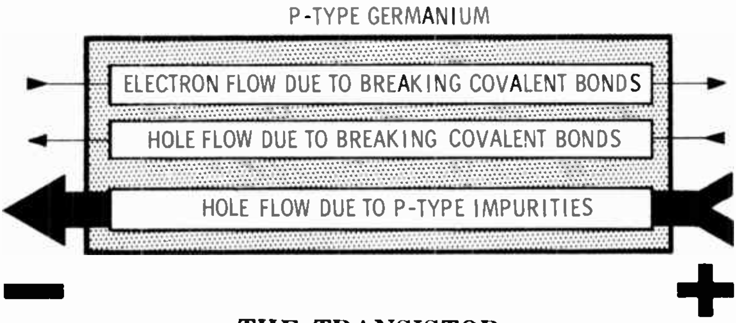


lishes a covalent bond with three of its neighbors. In place of the fourth covalent bond there is a combination of an electron and a hole. This hole acts as a strong positive charge and tends to attract electrons from nearby covalent bonds. When an electron leaves a neighboring bond, it leaves a hole which is then filled by an electron from another covalent bond. Thus, holes wander through P-type germanium just as electrons wander through N-type germanium.

Because the aluminum atom is capable of accepting an electron, it is called an **acceptor** atom. The crystal is known as P-type germanium because of the presence of positive holes. When an electric field is applied to the crystal, aluminum acceptor atoms accept more electrons to fill holes than are allowed to flow freely. Therefore the majority current carriers are holes, and the minority carriers are electrons.

To sum up, N-type semiconductor material has extra electrons donated by the impurity (donor) atom, while P-type semiconductor material has excess holes contributed by acceptor impurities. The more heavily the material is doped, the lower its electrical resistance will be.

HOLES AS MAJORITY CARRIERS



THE TRANSISTOR

In a sense, a transistor is a valve. It controls the flow of majority carriers through the semiconductor crystal of which it is made. The transistor can be compared to a triode. In fact, it is convenient to think of the transistor as a solid-state triode.

Q15. The hole left by an electron has a ________ charge.

Q16. An electric field causes electrons to flow to the _________ terminal while holes flow to the _________ terminal.

Q17. The majority carriers in P-type germanium are the ______.

Q18. P-type atoms are also called _________ atoms.

Q19. The transistor can be compared to a ______ vacuum tube.

Your Answers Should Be:

A15. The hole left by an electron has a **positive** charge.

A16. An electric field causes electrons to flow to the **positive** terminal while holes flow to the **negative** terminal.

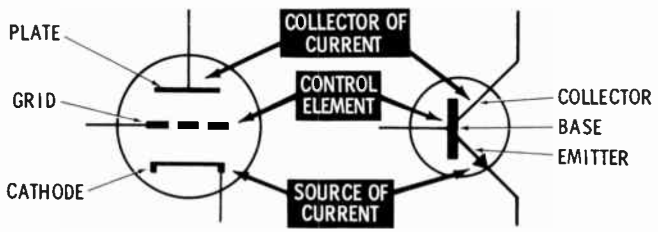
A17. The majority carriers in P-type germanium are the **holes.**

A18. P-type atoms are also called **acceptor** atoms.

A19. The transistor can be compared to a **triode** vacuum tube.

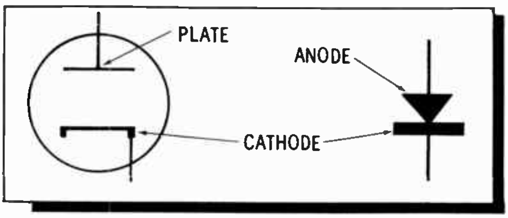
The symbols for the triode and the transistor can be compared in the figure below. Each has three elements, one of which acts as a source of current. In the triode, this element is called the cathode; in the transistor, this element is called an **emitter.** (The arrow in the symbol points in the direction of hole movement.) Both the transistor and triode vacuum tube have a control element. In the triode, it is called the grid, and in the transistor it is called the **base.** The tube and transistor each have a current collector, called the plate in the triode and the **collector** in the transistor.

COMPARISON OF TRANSISTOR AND TRIODE TUBE



In a similar fashion, a solid-state diode may be compared to a vacuum-tube diode. Here there are only two elements.

COMPARISON OF DIODES

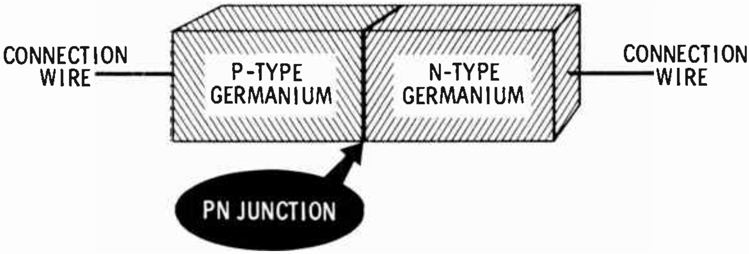


SEMICONDUCTOR DIODES

Early radios used crystal diodes to detect radio signals. These diodes allowed current to flow in one direction but not in the other. This **unidirectional** current capability is the distinguishing feature of the diode.

A solid-state diode consists of a section of P-type semiconductor material joined to an N-type section. The activity

DIAGRAM OF A SOLID-STATE DIODE



occurring at the junction of the materials is responsible for the unidirectional property of the diode. The contacting surface is called the PN **junction.**

PN JUNCTION

Although N-type germanium has an excess of free electrons, it is electrically neutral. This is because each donor atom becomes positively charged when it gives up an electron. Thus, for every freed electron in the crystal there is a positively charged donor atom. Therefore the crystal is only negative in the sense that the freed electrons are the most mobile particles.

Q20. The ability of a diode to conduct current in only one direction is called a ______________ capability.

Q21. N-type germanium crystals are electrically ________.

Q22. When P- and N-type germanium are joined together, the contacting surface is called the __________.

Your Answers Should Be:

A20. The ability of a diode to conduct current in only one direction is called a **unidirectional** capability.

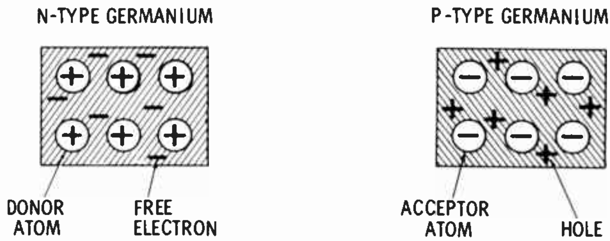
A21. N-type germanium crystals are electrically **neutral.**

A22. When P- and N-type germanium are joined together the contacting surface is called the PN **junction.**

Joining P- and N-Type Germanium

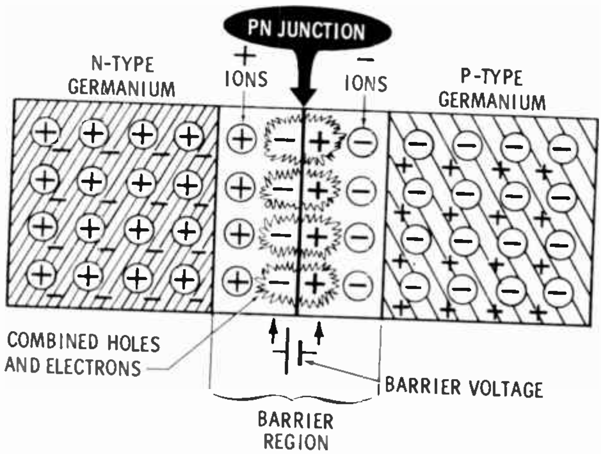
Like N-type germanium, P-type germanium is also electrically neutral.

DOPED GERMANIUM IS ELECTRICALLY NEUTRAL



When N-type germanium and P-type germanium are joined, some electrons and holes combine at the junction. In the region of the junction, N-type germanium loses some of its electrons. Thus, it is no longer neutral in this area; it now has a positive charge. The electrons it loses combine with holes from the P-type germanium at the junction. Thus the P-type germanium becomes negative. The majority carriers have combined at the junction, leaving charged atoms (ions) in the area near the junction. A potential difference (in the order of several tenths of a volt) exists between the N- and P-type germanium ions. If more electrons try to move from the N-type to the P-type, they are stopped by the negatively charged ions in the P-type germanium near the junction. In a similar fashion, holes from the P-type are prevented from crossing the junction by the buildup of positively charged ions in the N-type germanium near the junction. The net effect of this action is to set up a **barrier voltage** that prevents further combination of electrons and holes. The area in which this voltage exists is called the **barrier region.**

ACTION IN A PN JUNCTION



Reverse Bias

You know that a diode passes current more readily in one direction than in the other. Let's consider the effect of the barrier region on current flow through a semiconductor diode. Suppose that the positive terminal of a battery is connected to the N-type germanium of a diode and the negative terminal to the P-type germanium.

The positive terminal of the battery attracts electrons from the PN junction, and the negative terminal of the battery attracts holes from the PN junction. This results in more positive ions (donor atoms that have lost their free electrons) in the N-type germanium in the vicinity of the PN junction and more negative ions (acceptor atoms that

Q23. The area at the junction is called the ------- -------.

Q24. At the junction, N-type germanium is ---------- charged.

Q25. The ------- ------- prevents complete combination of all of the holes and electrons.

Q26. The barrier voltage is in the order of ------ -- - ----.

Your Answers Should Be:

A23. The area at the junction is called the **barrier region.**

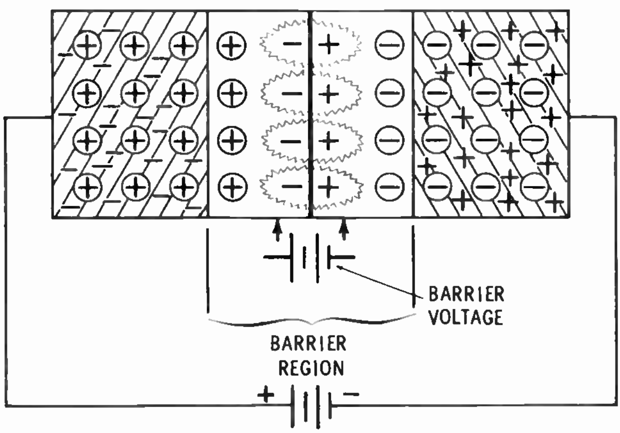
A24. At the junction, N-type germanium is **positively** charged.

A25. The **barrier voltage** prevents complete combination of all the holes and electrons.

A26. The barrier voltage is in the order of **tenths of a volt.**

have lost their holes) in the P-type germanium in the same area. This action creates a wider barrier region and results

REVERSE-BIASED DIODE

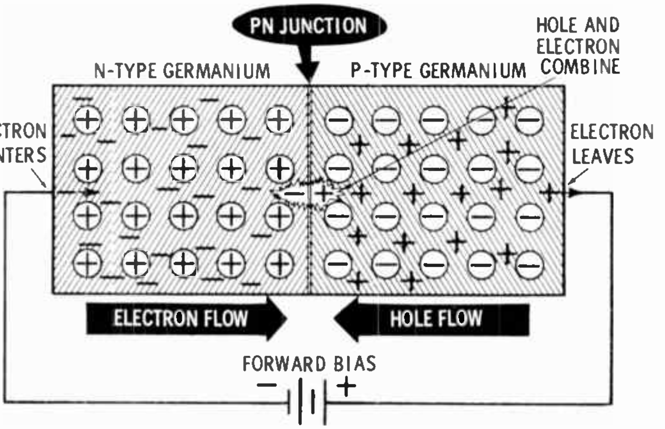


in a larger barrier voltage. The action continues until the barrier voltage equals the reverse bias (battery voltage). No current flows because these voltages are equal and opposite. This condition is called equilibrium.

Forward Bias

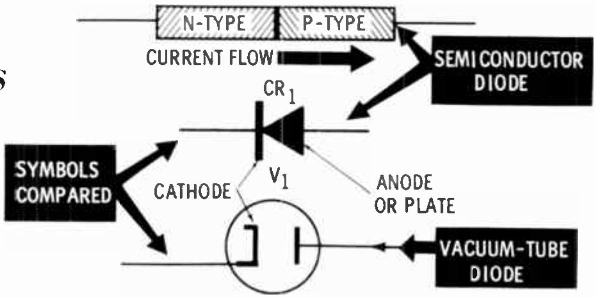
Now suppose the battery leads are reversed. Instantly, electrons are attracted to the positive terminal of the battery. An electron flow is set up in the N-type germanium and moves toward the PN junction. When an electron reaches the junction, it combines with a hole. The N-type germanium is now positive and may accept an electron from the negative battery terminal. Similarly, the P-type be-

FORWARD-BIASED DIODE



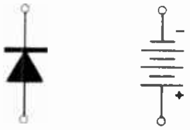
comes negative when a hole combines with an electron at the barrier. Thus, it gives up an electron to the positive battery terminal. A solid-state diode symbol is shown below.

DIODE SYMBOLS



Q27. Equilibrium due to reverse bias occurs when the _______ voltage equals _______ voltage.

Q28. Connect the diode to the battery so the diode is reverse-biased.

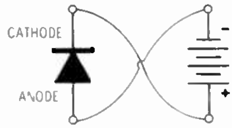


Q29. Conduction is due to ____ flow in P-type germanium and _________ flow in N-type germanium.

Your Answers Should Be:

A27. Equilibrium due to reverse bias occurs when the **barrier** voltage equals **battery** voltage.

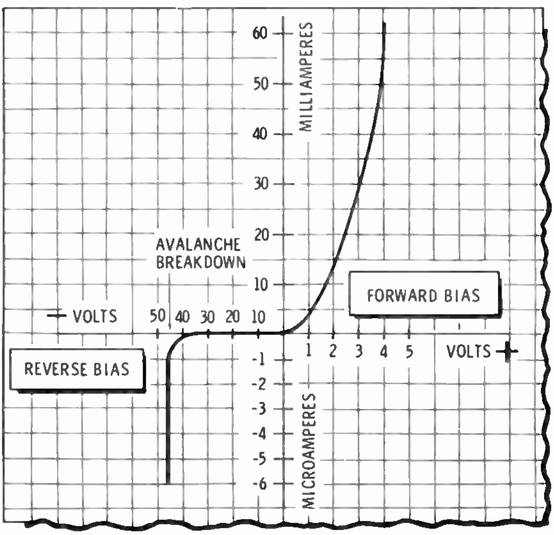
A28. For the diode to be reverse-biased, the **positive terminal** of the battery must be connected to the **cathode**, and the **negative terminal** of the battery must be connected to the **anode.**



A29. Conduction is due to **hole** flow in P-type germanium and **electron** flow in N-type germanium.

DIODE CHARACTERISTICS

You have learned how a solid-state diode operates. Now some of its important characteristics will be examined. These are the current-voltage, resistance, temperature, and capacitance characteristics.



CURRENT-VOLTAGE CHARACTERISTIC CURVE

urrent-Voltage Relationships

The graph on the opposite page shows the amount of cur-ent that will flow through a typical diode when various oltages are applied. The positive-voltage region is the area ı which the diode is forward-biased. The reverse-bias egion is to the left of the origin. Remember that the diode ill not conduct in the reverse direction. This is true on he graph up to almost 40 volts of reverse bias. Above this alue, small currents in the order of a few microamps start ɔ flow. This current flow is due to the minority carriers. Vhen the reverse bias reaches about 45 volts there is a harp increase in reverse current. This is called **avalanche reakdown.**

esistance

The resistance of solid-state diodes varies with the ap-lied voltage. Resistance is high for low forward-bias volt-ges and is low for high forward-bias voltages. For reverse iases, the resistance is very high until avalanche break-own occurs.

'emperature

Solid-state diodes have a negative temperature coefficient. 'his means that as the temperature increases, the resist-nce of the diode decreases. Within certain limits the effects f resistance changes due to temperature change are not etrimental to the operation of the diode. However, when a ery high temperature is reached, the resistance of the iode decreases so much that the current through the diode nay be high enough to permanently damage the crystalline tructure. This action is called **thermal runaway** and pre-ents a serious problem in circuit design.

Q30. The condition in which the current through a reverse-biased, solid-state diode sharply increases is called __________ __________.

Q31. The resistance of a solid-state diode varies with the _______ ________.

Q32. Solid-state diodes have a _________ temperature coefficient.

Your Answers Should Be:

A30. The condition in which the current through a reverse-biased, solid-state diode sharply increases is called **avalanche breakdown.**

A31. The resistance of a solid-state diode varies with the **applied voltage.**

A32. Solid-state diodes have a **negative** temperature coefficient.

Capacitance

Two conductors separated by a dielectric constitute a capacitor. Thus, a solid-state diode is a capacitor in which the barrier region serves as the dielectric. At low frequencies the effects of this capacitance need not be considered. At high frequencies, however, this capacitance (in the order of about 3 to 5 micromicrofarads) becomes an important factor.

SEMICONDUCTOR-DIODE DATA

Most electronic parts catalogs have several pages devoted to semiconductor diodes. An example of some of the data you will see in such a catalog is shown in the table below. Notice that diodes are designated 1N34, 1N58, etc. Just as with vacuum tubes, manufacturers have agreed to call diodes having the same characteristics by the same type number.

SEMICONDUCTOR DIODE CHARACTERISTICS					
TYPE	Peak Inverse Volts	Ambient Temperature Range—°C	Forward Peak ma	CURRENT AVERAGE ma	CAPACITANCE $\mu\mu f$
1N34A	60	—50 to +75	150	50	1.0
1N58A	100	—50 to +75	150	50	1.0

The table shows some of the characteristics for the 1N34A and 1N58A. Peak inverse voltage (PIV) is the reverse bias at which avalanche breakdown occurs. The ambient temperature range is that range of temperatures over which the diode will operate and still maintain its basic characteristics. Forward current values are given for both the average current (that current at which the diode is usually operated) and the peak current (that current which, if exceeded, will damage the diode). The only difference between these two diodes is in the peak inverse voltage. Therefore the 1N34A could be substituted for the 1N58A in applications involving signals of less than 60 volts peak-to-peak.

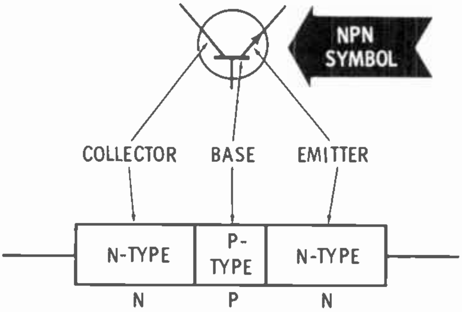
TRANSISTORS

Understanding how the semiconductor PN junction operates was the first step in understanding how a transistor operates. As you will see, a transistor is a semiconductor device with two PN junctions. The two junctions are in the form of a sandwich made up of two types of material (N and P). This sandwich can form either an NPN or PNP transistor.

NPN Transistors

By sandwiching a very thin piece of P-type germanium between two slices of N-type germanium, an NPN transistor is formed. A transistor made in this way is called a **junction transistor.** The symbol for this type of transistor showing the three elements (emitter, base, and collector) is given below. The three elements correspond to the cathode, grid, and plate, respectively, of a vacuum-tube triode.

NPN TRANSISTOR SYMBOL



Q33. The capacitance of a solid-state diode must be considered at ____ frequencies.

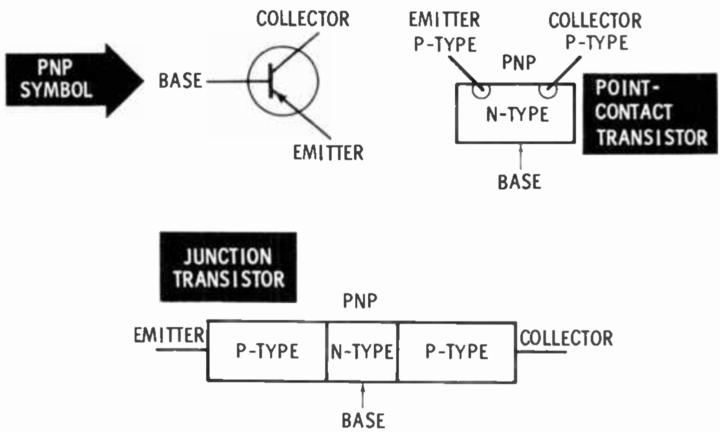
Q34. The three elements of a transistor are the ________, ____, and __________.

> **Your Answers Should Be:**
>
> A33. The capacitance of a solid-state diode must be considered at **high** frequencies.
>
> A34. The three elements of a transistor are the **emitter, base,** and **collector.**

PNP Transistors

By placing N-type germanium between two slices of P-type germanium, a PNP junction transistor is formed. A PNP **point-contact** transistor can be made by fusing two "catwhiskers" to a large N-type base.

PNP TRANSISTORS



The symbol for the PNP transistor is almost identical to that of the NPN transistor. The only difference is the direction of the emitter arrow. In the NPN transistor it points away from the base, and in the PNP it points toward the base. **Electrons always flow against the direction of the arrow.** Electron flow is from N-type to P-type germanium. If the arrow points toward the base, the electron flow is in the opposite direction—from base to emitter. Thus, the emitter must be P-type germanium and the transistor is PNP. The reverse is true for NPN transistors.

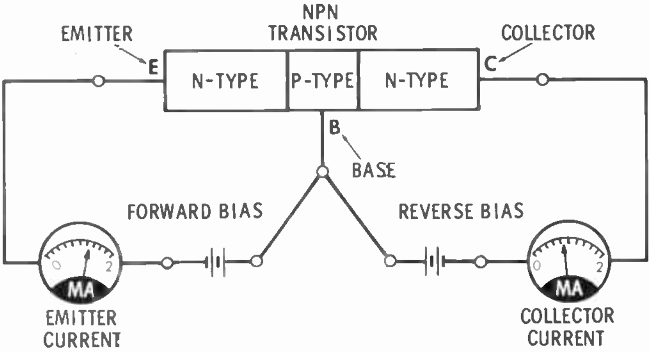
TRANSISTOR OPERATION

Several questions have probably come to mind by now How can a solid-state material amplify? Is there a difference between a junction and point-contact transistor or between a PNP and an NPN transistor? One of these questions can be answered immediately. Junction and point-contact transistors are almost identical in operation. Therefore, all discussion will be directed to junction transistors but it is understood that it applies to both types.

Biasing

The PN junction establishes a barrier voltage in solid state diodes. In the junction transistor, two such PN junctions are established, each with its own barrier voltage. If these PN junctions are properly biased, the transistor can be made to operate as an amplifier. The proper method for biasing an NPN transistor is discussed next.

BIAS FOR NPN TRANSISTOR AMPLIFIER



The figure shows an NPN transistor biased properly to operate as an amplifier. Addition of certain resistors (which you will see later) would complete the picture.

Q35. A transistor is a single semiconductor crystal with ___ PN junctions.

Q36. A transistor can perform the same function as a ______ ____ ______.

Q37. P-type semiconductor material sandwiched between two pieces of N-type material forms an ___ transistor.

Your Answers Should Be:

A35. A transistor is a single semiconductor crystal with **two** PN junctions.

A36. A transistor may perform the same function as a **vacuum-tube triode.**

A37. P-type semiconductor material sandwiched between two pieces of N-type material forms an **NPN** transistor.

In the arrangement on the preceding page, a forward bias is applied between the base and the emitter. This results in emitter current. A reverse bias is applied between the collector and the base. This results in a flow of collector current that is nearly equal to the emitter current. The reason for this seeming contradiction is that the base is very thin—less than one-thousandth of an inch.

Before continuing, it is time to learn a few more shorthand notations used when referring to transistors:

B—Base
E—Emitter
C—Collector
I_b—Base current
I_e—Emitter current
I_c—Collector current
V_{eb}—Voltage from emitter to base
V_{cb}—Voltage from collector to base

Note: these are all average values

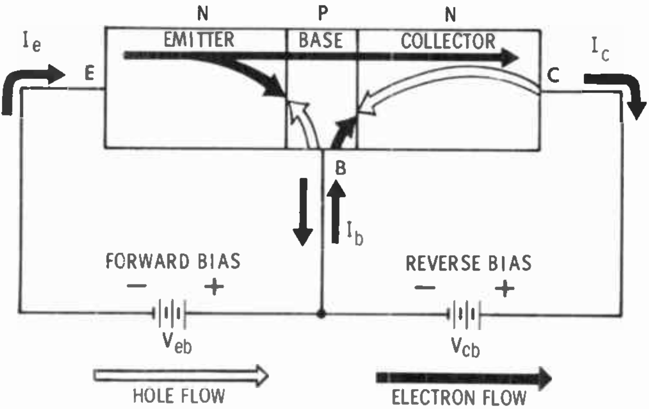
Current Flow in a Biased Transistor

The figure on the next page shows the electron and hole flow in a biased NPN transistor. With the emitter-base junction forward biased, electrons in the emitter drift into the base to combine with the holes in the base. For each combination an electron enters the emitter from V_{eb}. At the same time, an electron leaves the base (creating another hole) and returns to V_{eb}. Thus there is electron flow in the emitter and hole flow in the base.

Since the base-collector junction is reverse-biased, very little current will flow through it. This current is produced by minority carriers—hole flow in the N-type collector and electron flow in the P-type base—due to V_{cb}.

Why is I_c almost equal to I_e? Since the base is very thin there is not a sufficient number of holes in the base region to combine with the large number of electrons coming from the emitter. These excess electrons pass through the base and on to the collector due to the presence of V_{cb}. The reason why these electrons are not stopped by the collector-base barrier voltage is that there is a strong positive voltage attracting them. This voltage is due to the series combina-

CURRENT IN A BIASED NPN TRANSISTOR



tion of V_{eb} and V_{cb}. The major portion of I_c is due to the electron flow from emitter to collector. Notice that current flow in the base is due to both electron and hole flow. Thus there are current flows indicated in both directions. I_b is the difference between these two currents.

Q38. The emitter-base junction of a transistor amplifier must be ________ biased and the collector-base junction must be ________ biased.

Q39. Under these conditions collector current is (equal to, slightly less than, more than) emitter current.

Q40. This is explained by the fact that not enough ______ exist in the base to combine with all the __________ coming from the ________.

Q41. Identify the following shorthand notations: I_b, I_c, I_e, V_{eb}, and V_{cb}.

Your Answers Should Be:

A38. The emitter-base junction must be **forward**-biased and the collector-base junction **reverse**-biased.

A39. Under these conditions collector current is **slightly less than** emitter current.

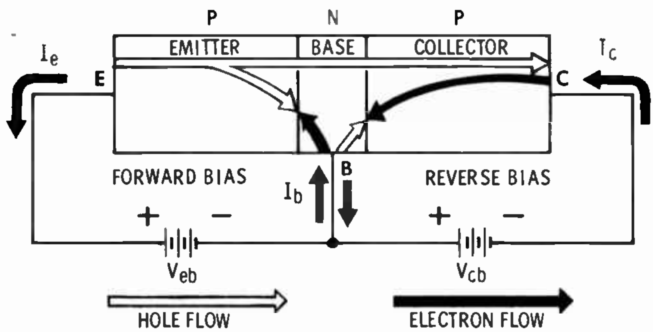
A40. This is explained by the fact that not enough **holes** exist in the base to combine with all the **electrons** coming from the **emitter.**

A41. I_b—**Base current**
I_c—**Collector current**
I_e—**Emitter current**
V_{eb}—**Voltage from emitter to base**
V_{cb}—**Voltage from collector to base**
(All average values)

Biasing PNP Transistors

The difference in operation between PNP and NPN transistors is that holes are the majority carriers in the PNP transistor. Proper bias for a PNP unit is achieved by using "negative" voltage polarities—just the opposite of those used for an NPN transistor. However, the bias between emitter and base is still forward bias and the bias between collector and base is still reverse bias. Since the emitter is P-type and the base is N-type germanium, a battery with its positive terminal connected to the emitter will forward-bias

CURRENT IN A BIASED PNP TRANSISTOR



the emitter-base junction. In a similar fashion, a battery whose negative terminal is connected to the P-type collector will reverse-bias the collector-base junction.

When so biased, the transistor conducts. The emitter, being a P-type semiconductor, releases holes to combine with electrons in the base. For each combination an electron in the emitter enters the positive terminal of the bias battery. This leaves a hole to migrate toward the base. At the same time, an electron from the negative terminal of the battery enters the base. Notice that electrons, and not holes, flow in the external circuit.

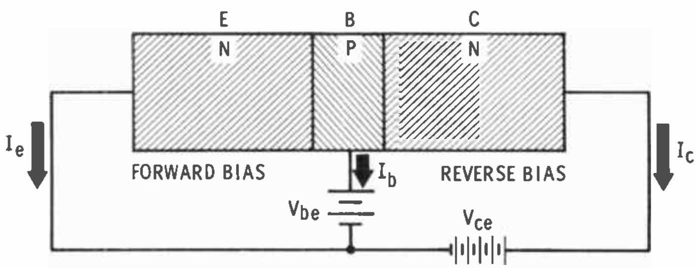
Because the base is thin, many more emitter holes exist than base electrons. The excess holes are drawn to the negative battery terminal connected to the collector.

HOW A TRANSISTOR AMPLIFIES

Recall how the control grid in a vacuum-tube triode has a much greater control of plate current than the plate. A transistor is capable of amplification because of a similar arrangement. The base in the transistor acts to control current through the transistor in much the same fashion as the grid controls current in the triode.

Consider another arrangement of the transistor. This arrangement is similar to the one showing a properly biased NPN transistor. The only difference is that the

GROUNDED-EMITTER CIRCUIT



reverse bias between collector and base is provided by V_{ce} in series with but opposing V_{be}, and V_{ce} is large compared to V_{be}. Thus, V_{ce} replaces V_{cb} in series with V_{be}. This is called a **grounded-emitter** circuit.

Q42. Bias polarities for a PNP transistor are the _________ of those for an NPN transistor.

Q43. The base in a transistor has an action similar to the _____ in a triode.

Your Answers Should Be:

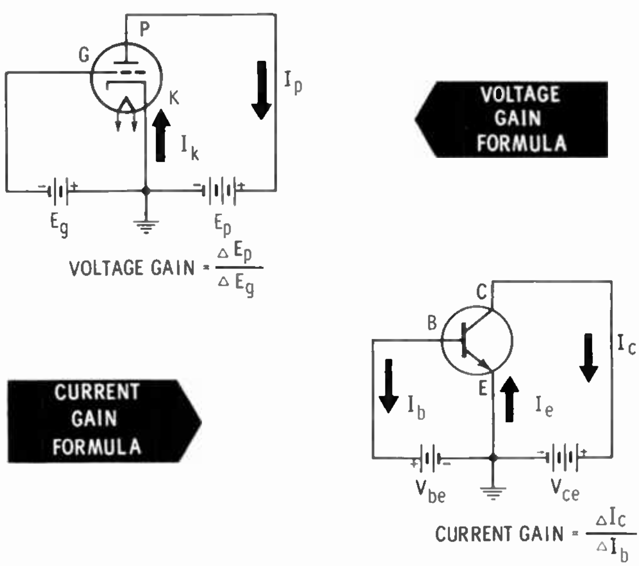
A42. Bias polarities for a PNP transistor are the **opposite** of those for an NPN transistor.

A43. The base in a transistor has an action similar to the **grid** in a triode.

Triode Amplifier Versus Transistor Amplifier

The grounded-emitter circuit mentioned on the previous page is the most common arrangement for a transistor amplifier. Let's compare it with the most common triode circuit, the grounded-cathode amplifier. You can see from the figure where this amplifier gets its name.

BASIC AMPLIFIERS



Compare the two circuits shown in the figure. The triode is composed of a cathode (K) that emits electrons; a plate, or anode, (P) that collects the electrons; and a grid (G) that controls the flow of electrons to the plate. The transistor is composed of an emitter (E) that supplies electrons, collector (C) that collects the electrons, and a base (B) hat controls the flow of electrons. The transistor base is ery thin, and the vacuum-tube grid has a fine-wire con-truction. Each of these elements, therefore, allows accel-rated electrons to pass through. However, each has great ontrol over the number of electrons that actually reach the ollector of electrons (the plate or collector).

The gain of a triode is determined as follows. The change 1 plate voltage necessary to produce a change in plate cur-ent is compared with the change in grid voltage that pro-uces the same change in plate current. In the transistor he forward bias (V_{be}) serves the same function as the egative bias in the triode. Instead of a voltage gain, how-ver, a current gain will be measured. The symbol for cur-ent gain is the Greek letter β. To obtain this current gain, . and I_b are recorded for a particular V_{be}. V_{be} is changed nd the new I_c and I_b recorded (V_{ce} is held constant). Cur-ent gain is then calculated by dividing the change in I_c by he change in I_b. β is often called h_{fe}.

Another parameter of the transistor (beta is a parameter ke mu in the triode tube) is alpha (α). Alpha is the ratio f the change in collector current to the corresponding hange in emitter current, when the collector voltage is onstant. Another symbol for α is h_{fb}. It has been shown hat under most biasing methods the collector current is lightly less than the emitter current (due to the base draw-ng some of the current from the emitter). Therefore the atio of ΔI_c and ΔI_e must be less than one. For example, if he collector current changes 4.8 ma and the emitter cur-ent changes 5 ma, then the base current must change 0.2 na. Calculate alpha as follows:

$$\alpha = \frac{\Delta I_c}{\Delta I_e} = \frac{4.8\ \text{ma}}{5.0\ \text{ma}} = 0.96$$

Q44. A ________ _______ transistor config-uration corresponds to a grounded-cathode triode amplifier.

Q45. The numerical value of alpha is ____ ____ ___.

Q46. If I_b is 100 μa when I_c is 1.0 ma, and I_b is 50 μa when I_c is 0.5 ma, what is β?

Your Answers Should Be:

A44. A **grounded-emitter** transistor configuration corresponds to a grounded-cathode triode amplifier.

A45. The numerical value of alpha is **less than one.**

A46.

$$\beta = \frac{\Delta I_c}{\Delta I_b} = \frac{1.0 \text{ ma} - 0.5 \text{ ma}}{100\mu a - 50\mu a} = \frac{0.5 \text{ ma}}{50\mu a} = 10$$

Transistor Amplification

How can a current gain of less than one result in amplification? The answer is that a power gain is realized. The reason for this can be found in the values of the input and output impedances (resistances) of the transistor. The input resistance of the forward-biased, emitter-base junction is low. The output impedance of the reverse-biased, collector-base junction is very high. Consider the formula for power:

$$P = I^2R$$

If you compare the input and output circuits of the transistor in terms of their power consumption, you will see that there is a power gain. Consider a transistor with an emitter-base resistance of 100 ohms and a collector-base resistance of about 1 megohm. Since the collector and emitter currents are very nearly the same, the difference in the power produced by each will depend largely on the resistance. Thus, the power in the collector circuit will be much larger than that in the emitter circuit. The transistor is capable of matching low-resistance circuits to high-resistance circuits and providing a power gain. It is this transfer of resistance that gives the transistor its name. Contracting **transfer** and **resistor** gives **transistor.**

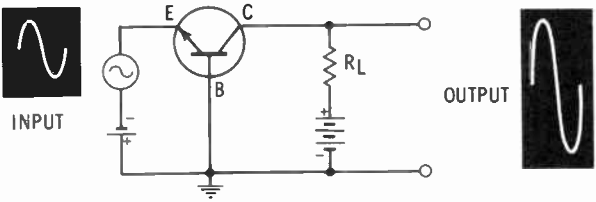
BASIC TRANSISTOR AMPLIFIERS

NPN or PNP transistors can also be used as grounded-collector and grounded-base amplifiers. The three basic transistor amplifiers can be compared with the three basic vacuum-tube amplifiers—the grounded-cathode, grounded-grid, and grounded-plate.

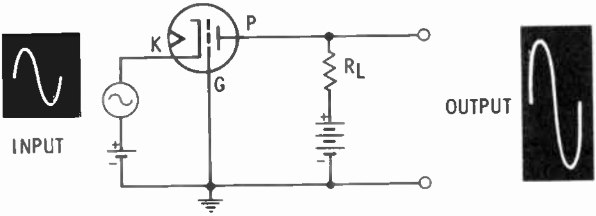
Common-, or Grounded-, Base Amplifier

Shown below are an NPN, **common-base amplifier** and its vacuum-tube equivalent, the **grounded-grid amplifier.** The base and grid are grounded. The input signal is applied to

COMPARISON OF AMPLIFIERS



GROUNDED BASE



GROUNDED GRID

the emitter in the common-base circuit, and to the cathode in the grounded-grid circuit. The output signal is taken from the collector and the plate. The input and output signals of these amplifiers have the same polarity; that is, they are in phase. The common-base circuit is used mostly as a voltage amplifier. It has these characteristics:

1. The input impedance is low, about 60 to 100 ohms.
2. The output impedance is high, about 0.5 to 1.0 megohm.
3. Current gain is less than one.
4. Voltage gain is medium, about 150.
5. Power gain is medium, about 450.
6. No phase reversal occurs.

Q47. Phase shift in a grounded-base amplifier is _____.

Q48. The voltage gain in a grounded-base amplifier is _______.

Q49. In a grounded-base amplifier, the input impedance is ___, and the output impedance is _____.

Your Answers Should Be:

A47. Phase shift in a grounded-base amplifier is **zero.**

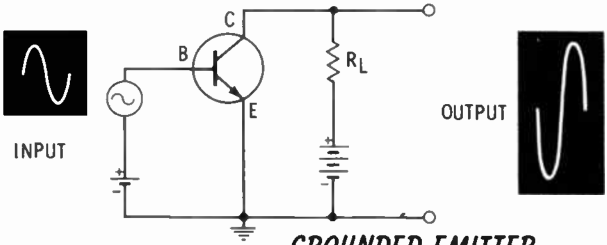
A48. The voltage gain in a grounded-base amplifier is **medium.**

A49. In a grounded-base amplifier, the input impedance is low, and the output impedance is **high.**

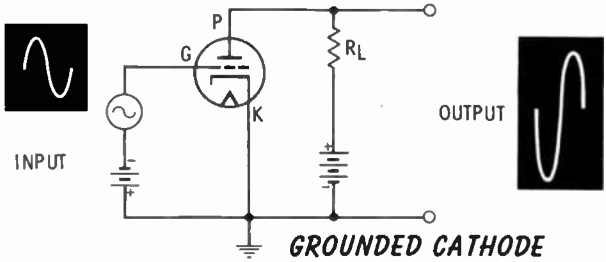
Common-, or Grounded-, Emitter Amplifier

The figure below shows a **common-emitter amplifier** and its vacuum-tube equivalent, **the grounded-cathode amplifier.** The emitter and cathode are grounded. The input signal is applied to the base and the grid, respectively, and the amplified output is taken from the collector and the plate, respectively.

COMPARISON OF AMPLIFIERS



GROUNDED EMITTER



GROUNDED CATHODE

A phase reversal of 180° occurs between the input and the output. This phase reversal will be explained in the chapter on triode amplifiers. The common-emitter amplifier has these characteristics:

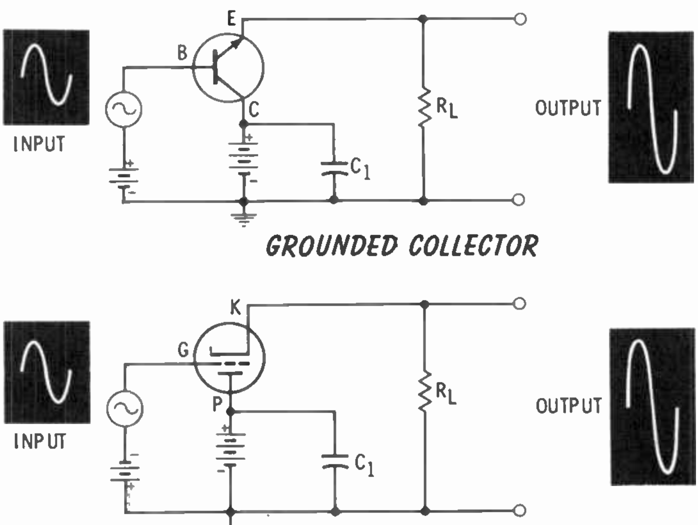
1. Input impedance is low, about 700 to 1,000 ohms.
2. Output impedance is high, about 50,000 ohms.

3. Current gain is about 50.
4. Voltage gain is high, about 500.
5. Power gain is very high, about 800.
6. Phase reversal occurs.

Common-, or Grounded-, Collector Amplifier

The figure shows a **common-collector amplifier** and its vacuum-tube equivalent, the **grounded-plate amplifier.** Notice that the collector and plate are not at DC ground, but at AC ground, due to the large capacitor bypassing the battery. The input signal is applied to the base and grid, respectively.

COMPARISON OF AMPLIFIERS



GROUNDED PLATE

The output signal is taken from the emitter and cathode, respectively. This circuit is also called an **emitter follower,** and its equivalent is called a **cathode follower.** The characteristics of the emitter-follower amplifier are summarized on the next page.

Q50. A common-emitter amplifier produces a phase shift of ____.

Q51. The voltage gain of a common-emitter amplifier is ____.

Your Answers Should Be:

A50. A common-emitter amplifier produces a phase shift of 180°.

A51. The voltage gain of a common-emitter amplifier is **high.**

Emitter-Follower Characteristics

The gain of an emitter-follower and a cathode-follower circuit is always less than one. These circuits are usually used to match impedances between two circuits. The common-collector amplifier has these characteristics:

1. Input impedance is very high, about 300K to 600K.
2. Output impedance is low, about 100 ohms.
3. Current gain is about 50.
4. Voltage gain is less than 1.
5. Power gain is low, about —250. (The negative sign means that power is consumed by R_L.)
6. No phase reversal occurs.

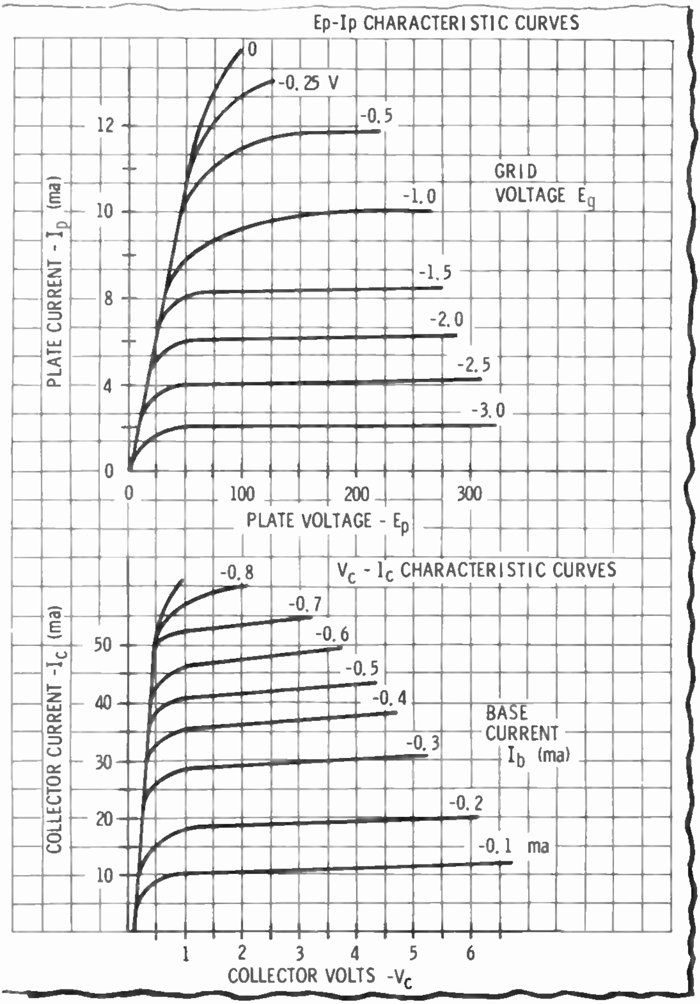
TRANSISTOR CHARACTERISTICS

The performance of transistors, like solid-state diodes, is affected by temperature. A change in temperature varies the junction resistance. From the study of diodes you learned that the PN junction has a negative temperature coefficient. This changes the junction bias and the current flow across the junction and therefore affects transistor performance. For this reason, manufacturers list operating temperatures for their transistors.

TRANSISTOR CHARACTERISTIC CURVES

Do you remember how to obtain information from the family of curves associated with the vacuum-tube amplifier? Transistors have similar curves. The figure shows the family of curves for both a pentode amplifier and an NPN-type transistor connected as a common-emitter amplifier. Notice the correspondence between I_p and I_c, E_p and V_c, and E_g and I_b.

CHARACTERISTIC CURVES



52. The emitter follower is best used for what purpose?

53. The common-base circuit is most used as a _______ __________.

54. The ______ _______ circuit may best be used as a power amplifier.

55. Use the V_c-I_c curves to obtain beta.

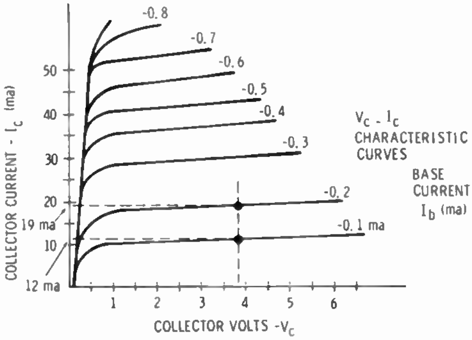
Your Answers Should Be:

A52. The emitter follower is best used to **match high-impedance circuits to low-impedance circuits.**

A53. The common-base circuit is most used as a **voltage amplifier.**

A54. The **common-emitter** circuit may be used as a power amplifier.

A55.



$$\beta = \frac{\Delta I_c}{\Delta I_b} = \frac{19 - 12 \text{ ma}}{0.2 - 0.1 \text{ ma}} = \frac{7 \text{ ma}}{0.1 \text{ ma}} = 70$$

Notice that this method is almost identical to the method used to obtain parameters from vacuum-tube curves.

TRANSISTOR SPECIFICATION SHEETS

Most transistor manufacturers present transistor information on specification sheets. These sheets are the equivalent of a tube manual. The figure on the next page shows some of the typical data supplied.

Each manufacturer selects some of his own special electrical specifications for presentation on these data sheets. However, many of them are alike for various manufacturers. Notice that the temperature at which these specifications were obtained is mentioned. Many of these specifications differ at other temperatures. The maximum values listed are limiting values. Above these values transistor life and performance are impaired.

TYPICAL TRANSISTOR DATA SHEET

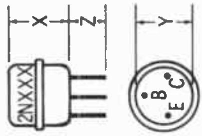
2N XXX JUNCTION TRANSISTOR   AUDIO-FREQUENCY AMPLIFIER

MECHANICAL DATA

WEIGHT: MOUNTING POSITION: CASE: MATERIALS

LEADS: LENGTH
IDENTIFICATION:
COLLECTOR
BASE
EMITTER

DIMENSIONS
X =
Y =
Z =



ELECTRICAL DATA

MAX JUNCTION TEMP °C	MAX COLLECTOR VOLTAGE	MAX COLLECTOR CURRENT ma	AVERAGE CHARACTERISTICS AT 25°C							TYPICAL CIRCUIT OPERATION AT 25°C				
			COLLECTOR VOLTAGE	EMITTER CURRENT ma	COLLECTOR RESISTANCE	BASE RESISTANCE	CURRENT AMPLIFICATION FACTOR	POWER GAIN db	NOISE FACTOR db	CIRCUIT *	INPUT IMPEDANCE	LOAD IMPEDANCE	DC COLLECTOR VOLTS	DC COLLECTOR CURRENT ma
										E				
										B				
										C				

*E COMMON EMITTER
B COMMON BASE
C COMMON COLLECTOR

Q56. Transistor data sheets give ___________ and ___________ specifications.

Your Answer Should Be:

A56. Transistor data sheets give **electrical** and **mechanical** specifications.

WHAT YOU HAVE LEARNED

1. Semiconductors are materials that are neither good conductors nor acceptable insulators.
2. Transistors and solid-state diodes replace vacuum tubes because they are smaller, weigh less, are more rugged, use less power, and have a longer useful life.
3. Intrinsic germanium has no impurities.
4. When an electron leaves a covalent bond, the space it leaves is called a hole.
5. Holes behave as though they were positively charged particles.
6. Adding impurities to intrinsic semiconductors is known as doping. In a semiconductor doped with N-type impurities, the electrons serve as majority current carriers. In a semiconductor doped with P-type impurities, the holes serve as the majority current carriers.
7. The PN junction establishes a barrier region that prevents recombination of holes and electrons.
8. Current flows through a forward-biased PN junction but not through a reverse-biased PN junction.
9. Transistors function like valves to amplify signals.
10. The emitter, base, and collector of a transistor correspond to the cathode, grid, and plate of a triode tube.
11. The collector-base junction must be reverse-biased. The base of the transistor is very thin, so there aren't enough majority carriers in the base to combine with the majority carriers in the emitter. The excess majority carriers are drawn to the collector by the voltage connected to the collector terminal.
12. Transistor current gain (measured from collector to base) is called beta (β) and may be quite large. Another current gain (measured from emitter to collector) is called alpha (α) and is usually less than one.

4

Power Supplies

What You Will Learn

In this chapter you will learn how diodes are used to change AC to pulsating DC. You will learn how filters are used to provide DC that is free from the variations of the original AC. You will also learn how regulated power supplies provide nearly constant DC output.

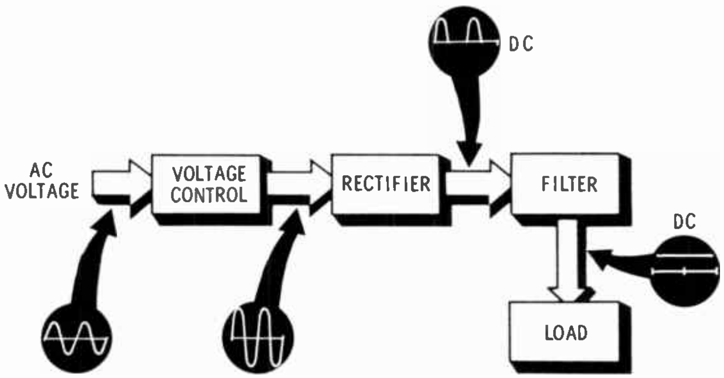
PURPOSE OF A POWER SUPPLY

Some source of electrical power is required for the operation of all electronic equipment. This can be a **prime power source** such as a battery or a generator. Most electronic equipment, however, cannot make direct use of prime power sources. For such equipment it is necessary to convert the output of a prime power source into an electrical form suitable for the particular piece of equipment. The devices used to do this are known as **power supplies.**

COMPONENTS OF A DC POWER SUPPLY

The components of a DC power supply are the voltage control, the rectifier, and the filter. The voltage control serves to adjust the output of the power supply so that it is correct for the circuits that the power supply feeds. The rectifier serves to change the AC voltage into a pulsating DC voltage. (A rectifier may be a vacuum-tube diode, a semiconductor diode, or a metallic-oxide rectifier.) The filter changes the pulsating DC into a smooth DC.

COMPONENTS OF A DC POWER SUPPLY

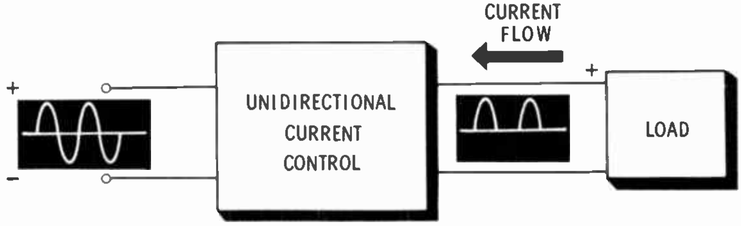


The basic functions of a power supply are to **rectify** and **filter.** The voltage-control function is actually incidental to the operation of the power supply. Once you learn to separate the rectifier and filter circuits from the power supply, you will see that the leftover components are in the voltage-control portion.

THE RECTIFICATION PRINCIPLE

The rectification principle is very simple. If it is desired to change an AC voltage to a pulsating DC voltage, a unidirectional current-control device must be used. The diode is such a device. Any device that accomplishes this result is called a **rectifier.**

RECTIFICATION PRINCIPLE

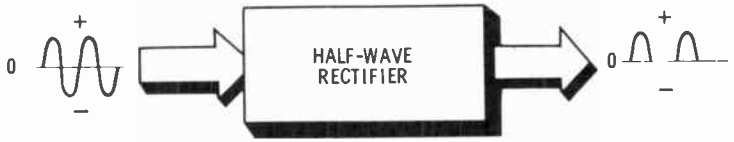


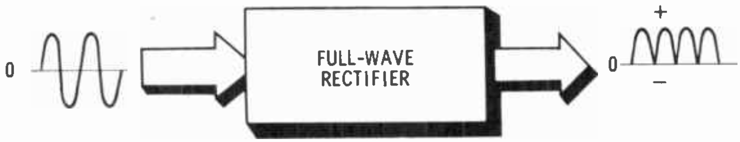
This simple principle is shown above. An AC voltage is applied to a unidirectional current-control device. Current flows only during the positive portions of the input signal.

The output voltage is therefore composed of only the positive portions of the input. This output is called **pulsating DC.**

The two most common rectifiers in use are the **full-wave** and **half-wave.** The differences between the two are obvious from the figure. When an AC voltage is applied to a half-wave rectifier, only half of each cycle is made available to the load. You will see later that not only is this type of rectification inefficient, but it also makes it more difficult to obtain the pure DC voltages required by some electronic circuits.

TYPES OF RECTIFIERS





When AC voltage is applied to a full-wave rectifier, the load receives current during both half cycles. Notice that the negative half cycles have been inverted so that all the half cycles are positive at the output of the rectifier. This type of pulsating DC is much easier to smooth (filter) than the output of the half-wave rectifier. Thus, smaller and less expensive components can be used in the filter section.

Q1. An AC voltage is converted into a DC voltage by a ___________.

Q2. The two major functions of a power supply are to ________ and _______.

Q3. The component of a power supply that changes AC voltage to a pulsating DC voltage is the ___________.

Q4. The component of a power supply that smooths out pulsating DC into almost pure DC is the _______.

Your Answers Should Be:

A1. An AC voltage is converted into a DC voltage by a **rectifier.**

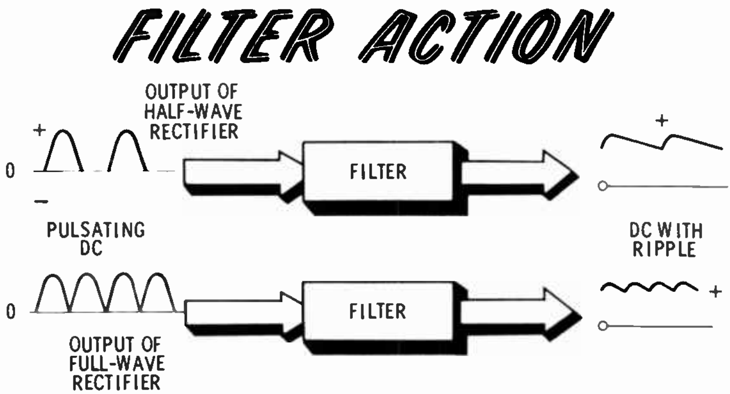
A2. The two major functions of a power supply are to **rectify** and **filter.**

A3. The component of a power supply that changes AC voltage to pulsating DC is the **rectifier.**

A4. The component of a power supply that smooths out pulsating DC to become almost pure DC is the **filter.**

FILTERING ACTION

The function of the filter is to smooth out the pulsating DC and provide an almost pure DC. You can see in the figure that the actual output is not quite pure DC. The amplitude of the ripple is the factor that determines how



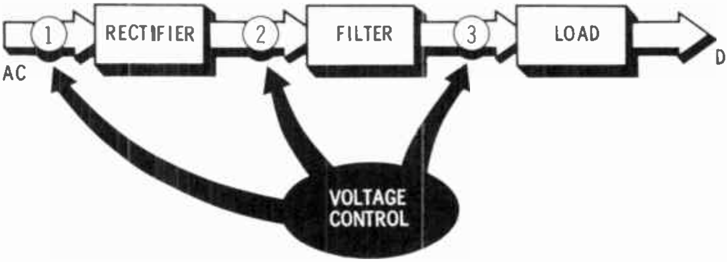
close the output is to DC. The higher the amplitude of the ripple voltage, the farther the output is from DC.

VOLTAGE CONTROLS

Several types of voltage controls are used in power supplies. The figure on the next page shows the locations they may have in a power supply. The types of voltage control can be roughly divided into two classes—automatic and manual. Either type serves the same function, to supply the correct voltage to the load.

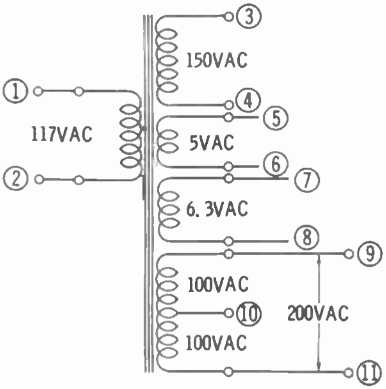
The voltage control used at point 1 is the power transformer. It may be some sort of variable transformer that can be manually controlled to provide the desired output voltage. Or it may be a power transformer with several windings, each of which provides a different voltage.

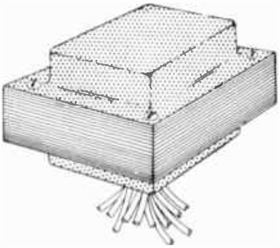
CONTROL CIRCUIT LOCATIONS



The power transformer in the figure below has an input winding (1 and 2), a 5-volt filament winding (5 and 6) for the rectifier, a 6.3-volt filament winding (7 and 8) for the vacuum tubes in the equipment, and two step-up voltage windings to supply voltage to the rest of the load. One of

A POWER TRANSFORMER





these windings (3 and 4) provides 150 volts AC, and the other (9, 10, and 11) provides 200 volts AC with a center tap. The use of this center tap will be explained later.

Q5. The function of a filter is to ______ pulsating DC.

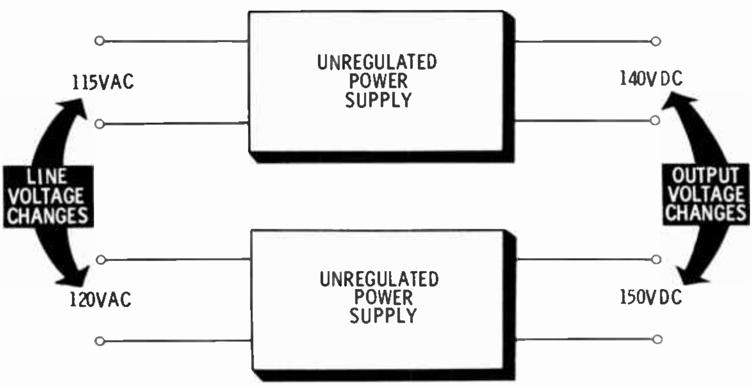
Q6. Voltage controls can be either __________ or _______.

> **Your Answers Should Be:**
>
> A5. The function of a filter is to **smooth** pulsating DC.
>
> A6. Voltage controls can be either **automatic** or **manual.**

The type of voltage control used at point 2 (see the figure near the top of the preceding page) is capable of making automatic voltage changes. This is accomplished by using various types of rectifier circuits that may double, triple, or even quadruple the input voltage.

The type of voltage control used at point 3 can vary the output voltage either automatically or manually, and is called a **regulator circuit.** Its main function is to maintain a steady output voltage from the power supply. A power supply using a regulator is called a **regulated power supply.**

UNREGULATED POWER-SUPPLY ACTION

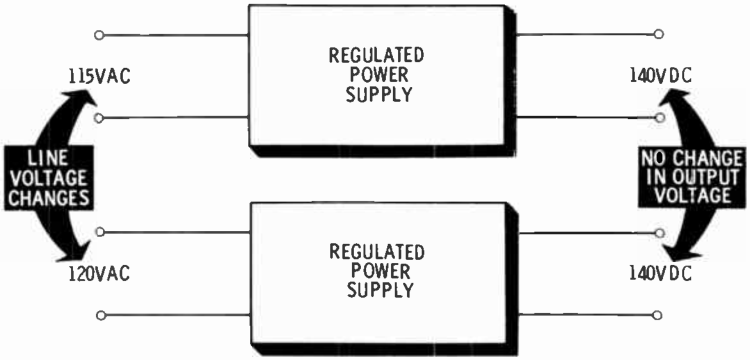


The figure shows an unregulated power supply fed by a line voltage of 115 volts AC. It provides an output voltage of 140 volts DC to its load. Now suppose the line voltage changes to 120 volts AC.

When there is an increase in the line voltage, there is an increase in the output voltage. In the figure it happens to be an increase of 10 volts DC. Many electronic circuits are not affected by this much change. Others are affected only slightly. However, many circuits are disturbed considerably by this type of change, and a voltage regulator must be used to correct it.

The power supply below has a voltage regulator. When he line voltage increases 5 volts, the output voltage remains t 140 volts DC. Changes in the load current will also change he output of a power supply. Voltage regulators are de-

REGULATED POWER-SUPPLY ACTION



signed to prevent changes under these conditions as well. Notice that many voltage regulators can be manually controlled, incorporating an adjustment used for selecting a particular voltage output.

VACUUM-TUBE AND SEMICONDUCTOR RECTIFIERS

A diode is sensitive to the polarity of an applied voltage. A positive voltage applied to the plate, or anode, causes a diode to conduct readily, while a negative voltage applied to the same point results in no conduction (in the case of the vacuum diode) or very slight conduction (in the case of a semiconductor). It is this unidirectional property that makes a diode useful as a rectifier.

Q7. In an unregulated power supply, the output voltage ________ when the input voltage changes.

Q8. The output voltage of an unregulated power supply (changes, does not change) when the load current changes.

Q9. A ________ __________ is used to keep the output voltage of a power supply constant.

Q10. A diode conducts only when its plate, or anode, is _________.

Your Answers Should Be:

A7. In an unregulated power supply, the output voltage **changes** when the input voltage changes.

A8. The output voltage of an unregulated power supply **changes** when the load current changes.

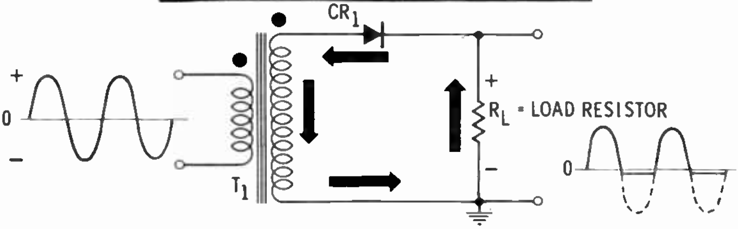
A9. A **voltage regulator** is used to keep the output voltage of a power supply constant.

A10. A diode conducts only when its plate, or anode, is **positive.**

Half-Wave Rectifier Circuits

A half-wave rectifier converts an AC voltage into a pulsating DC voltage. It does this by removing either the positive or negative half cycles from the input voltage. In other words, only half of each sine-wave cycle is used to provide power to the load. It can readily be seen that this type of supply is relatively inefficient.

HALF-WAVE RECTIFIER

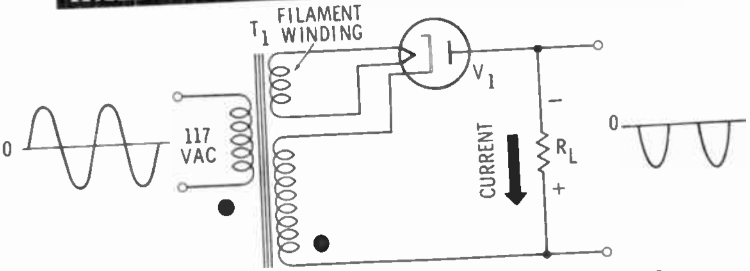


Above is a typical half-wave rectifier with a power transformer in the input. Notice the dots at the top of each winding of T_1. These dots indicate that the transformer is wound in such a fashion that the voltages at the ends of the windings marked with the dots are in phase with each other; when the top of the primary is positive, the top of the secondary is also positive.

When the positive half cycle of the input voltage is applied to the primary winding of T_1, there is a positive voltage applied to the anode of semiconductor CR_1, causing it to be forward-biased. CR_1 then conducts, causing a current flow and a voltage drop across the load resistor (R_L). During the negative half cycle, CR_1 is reverse-biased and very little current flows. There is very little voltage dropped across R_L during this half cycle.

A half-wave rectifier can also be made using a vacuum-tube diode. Such a circuit is shown in the figure below. The small secondary winding is a filament winding to supply heating current to the filament of V_1. (Notice that this winding was not needed for the semiconductor diode on the previous page.) Observe the negative voltage output shown in the figure. This is obtained by connecting the diode so that it permits current to flow down through the load resistor (R_L). Therefore, the diode plate is connected to the top of R_L. The bottom of R_L is connected to the bottom of T_1, and the cathode of V_1 is connected to the top of T_1. The diode could just as easily be connected in the reverse direction to give the opposite polarity.

HALF-WAVE VACUUM-TUBE RECTIFIER



In its operation, this circuit is very similar to the semiconductor half-wave rectifier. On the positive half cycles, a positive voltage is applied to the cathode of the diode, and the diode will not conduct. On the negative half cycles a negative voltage is applied to the cathode, and the diode does conduct. Current flows down through R_L, producing an output of the polarity shown. Thus, only negative half cycles appear at the output.

Q11. A half-wave rectifier passes current to the load during (one half, both halves) of each cycle of applied voltage.

Q12. A half-wave rectifier can be made using a ______________ or ____________ diode.

Q13. Output-voltage polarity depends on the connections to the ______.

Your Answers Should Be:

A11. A half-wave rectifier passes current to the load during **one half** of each cycle of applied voltage.

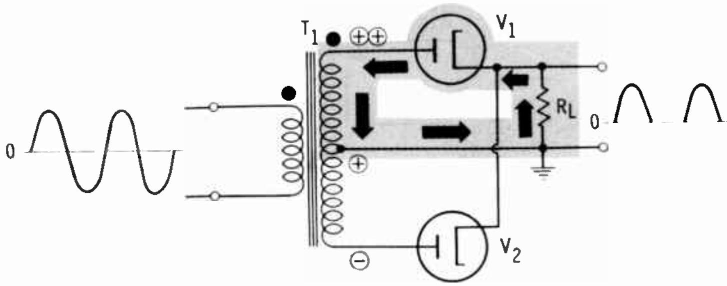
A12. A half-wave rectifier can be made using a **semiconductor** or **vacuum-tube** diode.

A13. Output-voltage polarity depends on the connections to the **diode.**

Full-Wave Rectifier Circuits

A full-wave rectifier differs from a half-wave rectifier in that it utilizes both halves of the input-voltage cycles for its pulsating DC output voltage. Such a rectifier is shown in the figure below.

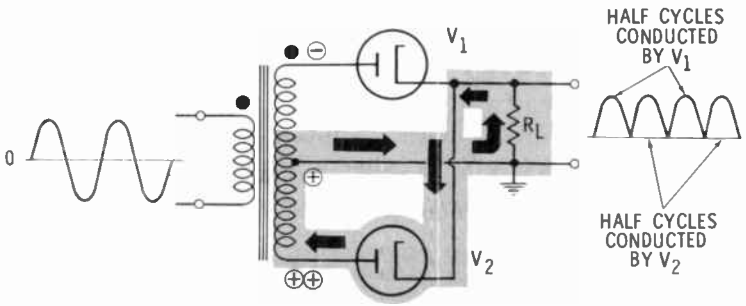
FULL-WAVE RECTIFIER (POSITIVE HALF CYCLE)



Two diodes are employed in this circuit. A special transformer is used with its center tap connected to one side of R_L and to ground. When the dot side of T_1 is positive with respect to the center tap, V_1 will conduct. The plate of V_2 is connected to the other end of T_1, which is negative with respect to the center tap. Thus V_2 will not conduct. The output of the circuit is as shown in the figure. Compare this output with that of the half-wave rectifier.

On the negative half cycle, the top of T_1 is negative with respect to the center tap, so V_1 will not conduct. The bottom of T_1 is positive with respect to the center tap, and V_2 will now conduct. Notice the direction of current flow—through V_2, to the bottom of T_1, out of the center tap, **up through** R_L, and back to the cathode of V_2. Current flows through R_L in the same direction as it did for the positive half cycle. This results in the output half cycles all being positive. The effect is just like passing the positive half cycles and inverting the negative half cycles. The result is the waveform shown in the figure.

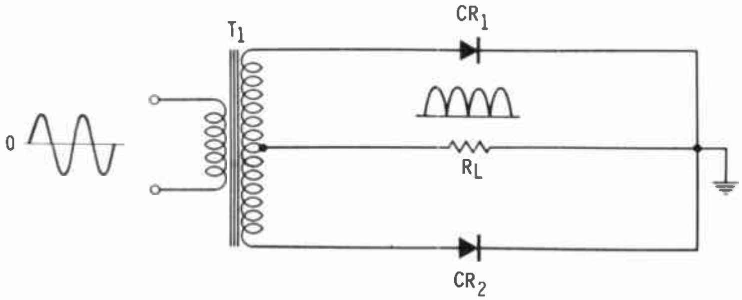
FULL-WAVE RECTIFIER (NEGATIVE HALF CYCLE)



Notice the difference between the pulsating DC from a half-wave rectifier and from a full-wave rectifier. The variation in the output from the half-wave rectifier has half the frequency of the variation from the full-wave rectifier.

A full-wave rectifier can, of course, be made using semiconductor diodes. The circuit below shows this. Although the position of R_L on the diagram has been changed, the circuit is still the same.

FULL-WAVE SEMICONDUCTOR RECTIFIER



Q14. A full-wave rectifier uses a transformer with a ______ ______ secondary.

Q15. A full-wave rectifier conducts during (one half, both halves) of the applied-voltage cycle.

Your Answers Should Be:

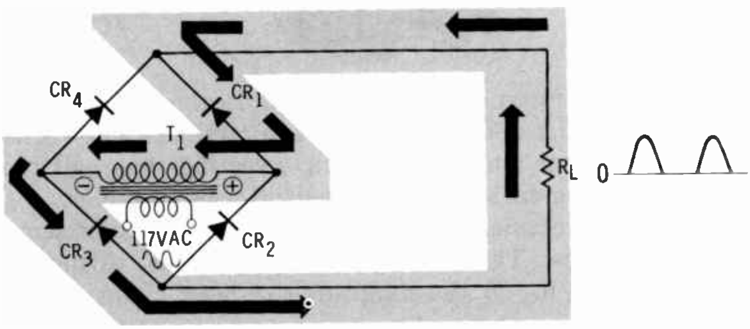
A14. A full-wave rectifier uses a transformer with a **center-tapped** secondary.

A15. A full-wave rectifier conducts during **both halves** of the applied-voltage cycle.

Bridge Rectifier Circuit

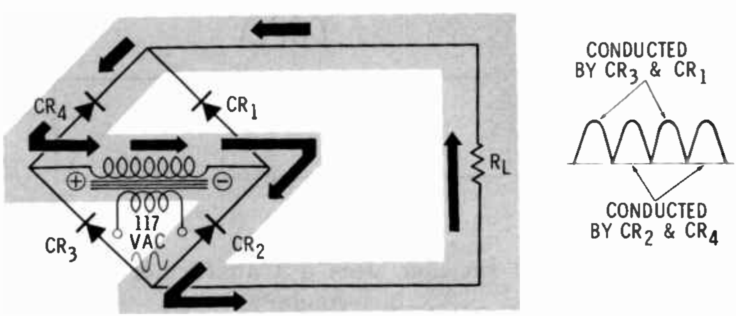
There is a type of full-wave rectifier circuit that does not require a transformer with a center tap. Instead, it uses four diodes. This circuit is called a **bridge rectifier circuit.**

BRIDGE RECTIFIER (POSITIVE HALF CYCLE)



On the positive half cycle, current flows through CR_3, up through the load resistor, and back through CR_1. CR_2 and CR_4 are reverse-biased and act like open switches.

BRIDGE RECTIFIER (NEGATIVE HALF CYCLE)



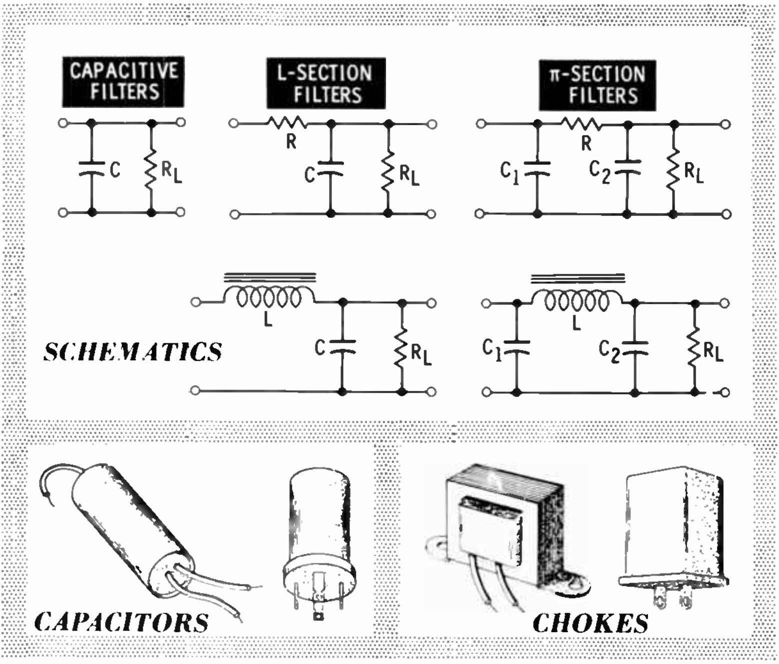
The figure above shows the current direction for the negative half cycle.

The bridge rectifier is usually used in power supplies that must deliver a large amount of current. Since the usual semiconductor diodes are not adequate to carry these large currents, special selenium or copper-oxide metallic rectifiers are usually used.

FILTERS

The filter is the section of a power supply that smooths the pulsating DC to make it almost pure DC. The types of filters most commonly used are shown below. As you see, filters are simply circuits made up of resistors, capacitors, and inductors in various combinations. The operation of filters depends on the ways that L, C, and R affect changing voltages and currents.

FILTER CIRCUITS AND COMPONENTS



Q16. A bridge rectifier is a type of (full-wave, half-wave) rectifier.

Q17. What are the three types of filters most commonly used?

Your Answers Should Be:

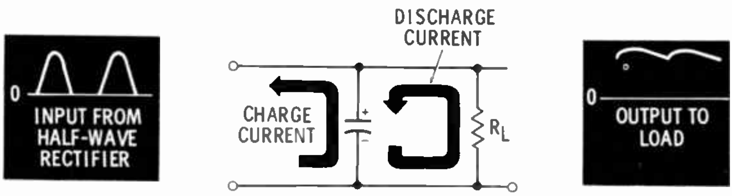
A16. A bridge rectifier is a type of **full-wave** rectifier.

A17. The three types of filters most commonly used are the: 1. **capacitive filter**, 2. **L-section filter**, and 3. **π (pi)-section filter.**

The Capacitive Filter

Basically, the capacitive filter is simply a capacitor connected in parallel with the load resistance. As the pulsating DC voltage from a half-wave or full-wave rectifier is applied across the capacitor, it charges to the peak applied voltage. If there were no load resistance connected across the output, the capacitor would remain charged to the peak voltage.

CAPACITIVE FILTER ACTION



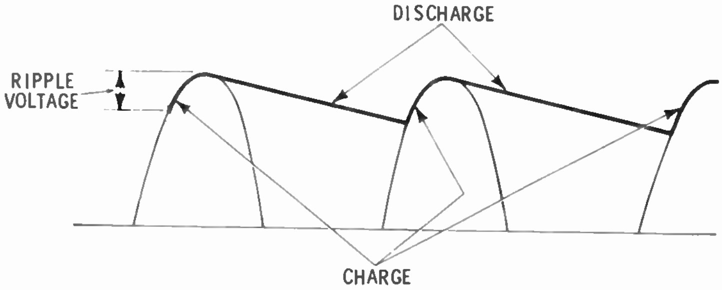
In practice, there is always a load resistance connected across the capacitor. Between peaks, the capacitor discharges through the load resistance, and the voltage gradually decreases. The amount the voltage decreases before the capacitor is charged again by a peak in the pulsating DC is called **ripple voltage.**

The amount of capacitor discharge between voltage peaks is controlled by the RC time constant of the filter capacitor and the load resistance. If the load resistance is large and the capacitance is large, the ripple voltage is small; the pulsating DC has been smoothed out until it is almost a pure, constant DC voltage.

Variations in the output voltage are not desirable because they affect the operation of vacuum-tube or transistor circuits receiving the DC. The increased ripple voltage caused by reduced load resistance is one undesirable feature of the capacitive filter.

A second undesirable feature of a capacitive filter is the large charging current. This excessive current flows into the capacitor to charge it when the power supply is first turned on. This initial current is often called a **surge cur-**

CAPACITIVE FILTER CHARGE AND DISCHARGE



rent. Over a period of time, surge currents can cause injury to fuses and rectifiers, resulting in eventual burnout. Each surge current can cause part of a fuse to melt slightly, for example, until it finally burns out. The same thing can happen to the rectifier. A small surge of current flows through the rectifier during each cycle to recharge the partially discharged capacitor. Under certain conditions these charging surges can become large enough to damage a diode. The remaining two types of filters have components to reduce the effect of ripple-voltage variations and surge currents.

Q18. What will happen to the RC time constant of the capacitor and load resistance if the load resistance is decreased?

Q19. If the load resistance is decreased, the filter capacitor will discharge (more, less) rapidly.

Q20. What will happen to the amount of ripple voltage if the load resistance is decreased?

Q21. The large current that flows for a short time to charge the capacitor is called a(n) ____________.

Q22. If a load resistance is not connected across the filter capacitor, what will happen to the output voltage?

Your Answers Should Be:

A18. If R_L is decreased, the RC time constant will be **shorter.**

A19. If the load resistance is decreased, the filter capacitor will discharge **more** rapidly.

A20. The amount of the ripple voltage **increases** as the load resistance of a capacitive filter is decreased.

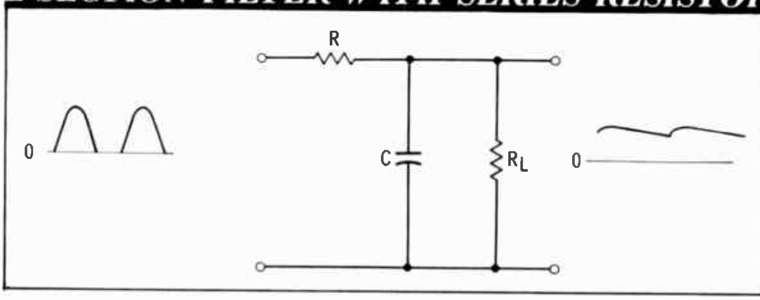
A21. The large current that flows for a short time to charge the capacitor is called a **surge current.**

A22. If a load resistance is not connected across the filter capacitor, the capacitor will charge to the **peak value of the filter input voltage and the outout voltage will remain at this value.**

L-Section Filters

An L-section filter reduces surge currents by using a current-limiting resistor or inductor. This limiting resistor or inductor is connected in series with the capacitor. A limiting resistor controls surge currents by introducing an RC time constant to slow the charging of the capacitor.

L-SECTION FILTER WITH SERIES RESISTOR

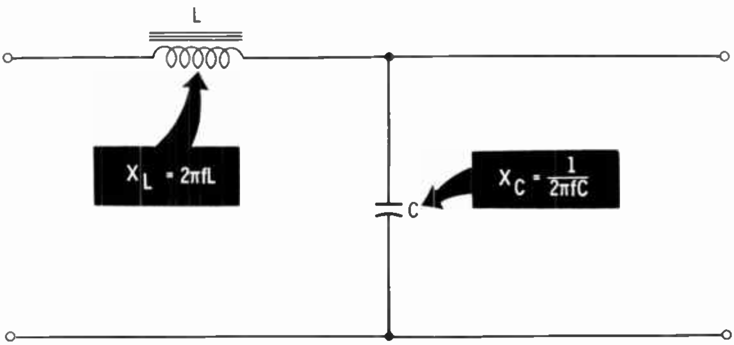


When an inductor is used as the series element, the surge currents are reduced in a different manner. The inductor opposes a change in current by creating a counter emf. As a result, the surge current is greatly reduced and the capacitor charges more slowly.

An inductor used in an L-section filter also adds to the filtering action of the capacitor. The inductor reacts to changes in current caused by the ripple voltage the same way it reacts to the surge current. The counter emf tends to cancel out the effects of the ripple voltage.

The operation of the L-section filter can also be explained in terms of reactance. In a simple capacitive filter, and in an L-section filter with a limiting resistor, the filtering action is the result only of the reactance of the capacitor (X_C). The capacitor presents a low reactance to AC and a very high reactance to DC. The AC part of the input is therefore bypassed through the capacitor, but the DC part goes directly to the load.

L-SECTION FILTER WITH SERIES INDUCTOR



To understand the L-section filter with an inductor, the reactance of the inductor must also be considered. The reactance is high for AC, but it is nonexistent for DC. The inductor presents a high reactance to the AC current produced by the ripple voltage. The inductor therefore tends to block this current. It presents zero reactance to the DC and allows it to pass readily. The AC that is not blocked by the inductor is mostly bypassed by the capacitor.

Q23. In an L-section filter, AC ripple can be blocked by a(n) ---------.

Q24. In an L-section filter, AC ripple can be bypassed by a(n) ----------.

Q25. An L-section filter with a limiting resistor is (more, less) effective than one with an inductor.

Q26. An inductor has a ------ reactance for AC than for DC.

Your Answers Should Be:

A23. In an L-section filter, AC ripple voltages can be blocked by an **inductor.**

A24. In an L-section filter, AC ripple voltages can be bypassed by a **capacitor.**

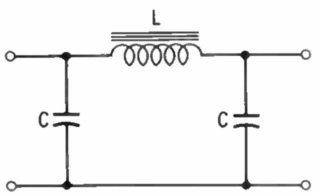
A25. An L-section filter with a limiting resistor is **less** effective than one with an inductor.

A26. An inductor has **higher** reactance for AC than for DC.

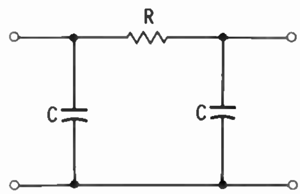
Pi-Section Filters

A pi-section filter has three elements—a shunt input capacitor, a series **choke** (inductor), and a shunt output capacitor. As the input voltage reaches the first capacitor, the capacitor bypasses most of the AC ripple current to ground. This presents a smoother waveshape to the choke. The choke presents a high inductive reactance to the AC ripple

PI-SECTION FILTERS



With Choke (L)



With Resistor

current and tends to block it. To put it another way, the choke opposes a change in current, and so it acts to smooth the current passing through it. Finally, the second capacitor is designed to bypass to ground any remaining AC components. The resulting output is a smooth DC voltage.

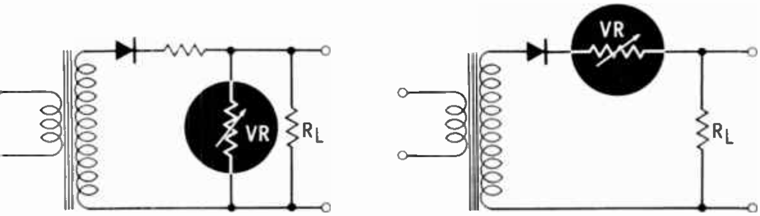
To save money, the choke is sometimes replaced with a resistor. This results in less smoothing action. A pi-section filter using a resistor depends for some of its effectiveness on the long time constant of the series resistor and the output capacitor. If this time constant is much longer than the period of the AC ripple, the output capacitor will charge and discharge very little during any one pulse of the ripple voltage. The waveshape will then be smoothed out. However, the resistor also consumes power. This is an important consideration in a power-supply circuit.

REGULATED POWER SUPPLIES

Regulated power supplies are those that keep the voltage (or current) supplied to the load constant, even if the power-source voltage fluctuates or the load changes.

Basically, the voltage-regulator part of a regulated power supply is a variable resistance that automatically changes as the output voltage changes. (For simplicity, no filter is shown in the figure.)

VOLTAGE REGULATORS REPRESENTED AS VARIABLE RESISTORS



IN SHUNT WITH POWER SUPPLY ***IN SERIES WITH POWER SUPPLY***

A shunt voltage regulator combines with the resistance of the power supply itself, or with an additional resistor, to form a voltage divider. As the shunt resistance increases, more voltage appears across it as an output to the load. As the shunt resistance decreases, less voltage appears across it.

The series voltage regulator forms a voltage divider in series with the load resistance. As the series resistance increases, less voltage appears across the load resistance. As the series resistance decreases, more voltage appears across the load.

Q27. What are the three elements of a pi-section filter?

Q28. A pi-section filter with a resistor gives (better, poorer) filtering action than one with a choke.

Q29. A voltage regulator may be compared to a _________ resistor.

Your Answers Should Be:

A27. The three elements of a pi-section filter are a **shunt input capacitor**, a **series choke or resistor**, and a **shunt output capacitor.**

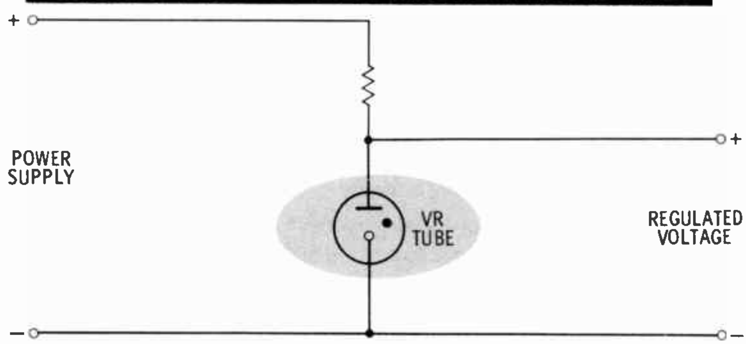
A28. A pi-section filter with a resistor gives **poorer** filtering action than one with a choke.

A29. A voltage regulator may be compared to a **variable** resistor.

The resistance of a shunt voltage regulator increases when the output voltage decreases. It decreases when the output voltage increases. Thus, it automatically returns the output voltage to normal. Similarly, the resistance of a series voltage regulator increases as the output voltage increases and decreases as the output voltage decreases.

There are several ways of achieving resistance that varies with output voltage. One of these is the gaseous voltage-regulator (VR) tube. This is a diode filled with a current-conducting gas. As the voltage applied across this tube increases, the gas becomes more ionized, and the resistance of the tube decreases. This type of tube can be used as a shunt voltage regulator.

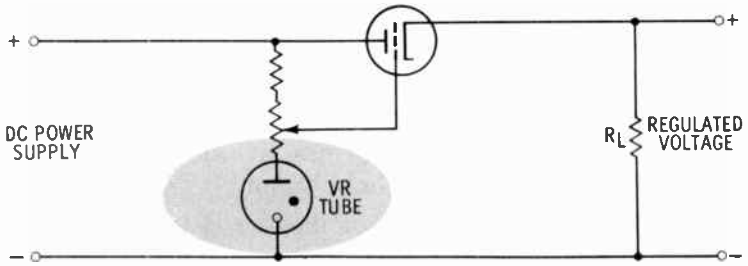
SIMPLE VR-TUBE VOLTAGE REGULATOR



The limiting resistor in series with the VR tube is selected to limit the current through the tube to a safe value. Gaseous voltage regulators keep the output voltage constant to within about 1%. They come in a number of specific voltage ratings. To change the constant output voltage, it is necessary to change the tube. To obtain higher voltage ratings, VR tubes can be connected in series so that only part of the output voltage appears across each one.

The regulated voltage from a VR-tube regulator is fixed in value. Vacuum tubes are often used where it is desirable to vary the value of a regulated voltage.

VACUUM-TUBE VOLTAGE REGULATOR



A vacuum-tube circuit can be used as a series voltage regulator. The current passing through the tube from cathode to plate depends on the grid bias. Another way to say this is that the resistance of the tube depends on the grid bias. Therefore, by varying the voltage on the grid, the tube resistance can be changed as necessary.

A source for the grid bias is needed. This may be a battery or it can be a VR regulator connected to the power source. A potentiometer in the grid circuit makes it possible to adjust the bias.

If the voltage of the power source rises, the voltage at the cathode of the triode also increases. This causes an increase in the negative grid bias and reduces the current through the tube, effectively increasing the plate resistance. The output voltage is thus reduced. If the power source voltage drops, the opposite action takes place. This circuit will also compensate for changes in load resistance. A transistor instead of a tube can be used in a similar circuit.

Q30. The resistance of a shunt voltage regulator decreases as the output voltage __________.

Q31. The resistance of a series voltage regulator __________ as the output voltage decreases.

Your Answers Should Be:

A30. The resistance of a shunt voltage regulator decreases as the output voltage **increases.**

A31. The resistance of a series voltage regulator **decreases** as the output voltage decreases.

WHAT YOU HAVE LEARNED

1. Power supplies are most often used to convert AC voltages into DC voltages.
2. The components of a DC power supply are a voltage control, rectifier, and filter.
3. A power transformer provides AC at desired voltage values as an input to a power supply.
4. A diode (or combination of diodes) is used to convert AC into pulsating DC.
5. There are basically two types of rectifiers—half-wave and full-wave.
6. A bridge rectifier is one type of full-wave rectifier; another type uses two diodes.
7. The filter smooths out the pulsating DC and provides almost pure DC.
8. Three of the most commonly used filters are capacitive, L-section, and pi-section.
9. The AC component of the filtered DC is called ripple voltage.
10. Voltage regulators are used to provide fairly constant DC.
11. Voltage regulators make adjustments in the power-supply output voltage by varying the resistance of vacuum tubes and/or transistors.
12. Voltage regulators are connected in series or in parallel with the load resistance.
13. Gas tubes and triodes are two common devices used to provide a variable resistance in regulator circuits.

5

Amplifiers and Oscillators

What You Will Learn

You will now learn how vacuum tubes are used in practical amplifier circuits, and receive more practice in using tube-characteristic curves. You will find out how to develop equivalent circuits for tubes and learn something about biasing circuits. You will discover the difference between voltage and power amplifiers. The common methods of coupling a series of single-tube amplifiers to produce a multistage, or cascaded, amplifier will be discussed. You will become familiar with the way in which oscillators generate AC voltages by the use of positive feedback.

WHAT IS AN AMPLIFIER?

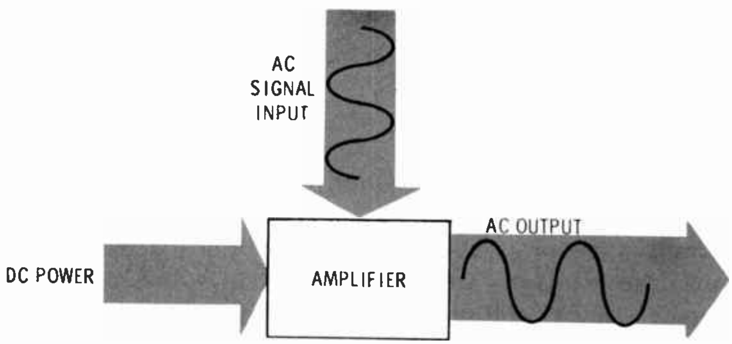
Amplifiers are probably the most common circuits in electronics. They are used everywhere, from radio receivers and television transmitters to radar sets and giant computers.

Everyone knows what a high-fidelity audio amplifier does. It takes a very weak signal from a phonograph pickup or tape head and increases the amplitude of this signal until it has enough strength to drive several large speakers.

All amplifiers increase the amplitude of an input signal until it is large enough for the intended application. One of the main functions of a television receiver is to amplify the extremely weak signal voltages induced in the antenna enough to produce an image on a picture tube.

There are many different kinds of amplifiers. Some have the main function of amplifying a signal voltage; these are voltage amplifiers. Others are power amplifiers for driving final loads. Some are designed for low frequencies; these are DC and operational amplifiers. Others work best in the audio-frequency (AF) range. There are radio-frequency (RF) amplifiers designed for higher frequency ranges. Some have a very narrow passband; they amplify only a narrow range of frequencies. The amplifiers in a radio receiver are an example of this type. They are concerned with amplifying sine waves. Others, like the video signal amplifiers in television sets, must have a fairly wide passband so that complex waveforms are not distorted.

BASIC AMPLIFIER PRINCIPLE



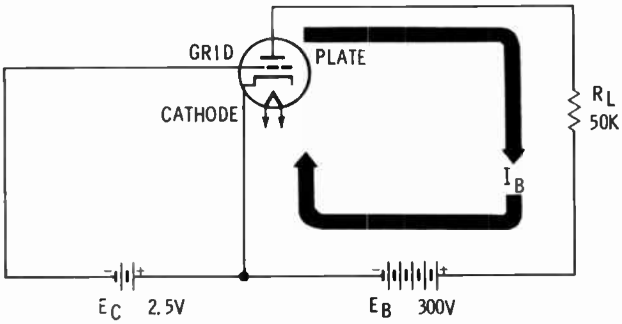
You can see from this diagram that the amplifier does not magically transform a low-power or low-voltage signal into a larger one. You can't get more power out than you put in. Instead, an amplifier controls the DC power from the power supply according to the variations in the AC input signal.

It is often desirable to have an output that is a reasonably good duplication of the input. But due to the limitations of tubes and circuits, this is not always possible. When the output does not follow the input exactly, there is distortion. The amount of permissible distortion depends on the purpose of the output signal. Distortion-free amplifiers are usually complex and costly.

Plate-Current Flow in an Amplifier

Now look at a simple vacuum-tube amplifier. This one uses a triode, a tube with three elements—cathode, grid, and plate. There is also a heater to keep the cathode at emission temperature, but normally it is not considered as an active circuit element.

BASIC TRIODE AMPLIFIER CIRCUIT



As the cathode is heated to emission temperature, it begins to emit electrons into the space around it. A positive voltage (E_B) applied to the plate of the tube attracts the negative electrons. Electrons leave the 300-volt battery from its negative terminal, flow into the cathode, are emitted, and pass into the electron cloud. Then the electrons are attracted to the plate and flow through the load resistor back to the positive terminal of the battery. This is the steady-state DC plate current (I_B).

The tube current flows in a loop, as shown, and encounters several resistances on its way. These include the small internal resistance of the battery, the resistance of the cathode-plate path through the tube (plate resistance R_P), and the load resistance (R_L). The sum of these three resistances and the amount of the battery voltage determine the magnitude of the plate current (I_B). I_B and the battery voltage determine the DC-power input to the amplifier.

Q1. An amplifier has two inputs: a large __ _____ input and a small __ ______ input.

Q2. The output of an amplifier is the __ _____ input altered so that it resembles the ______ input.

Your Answers Should Be:

A1. An amplifier has two inputs: a large **DC-power** input and a small **AC-signal** input.

A2. The output of an amplifier is the **DC-power** input altered so that it resembles the **signal** input.

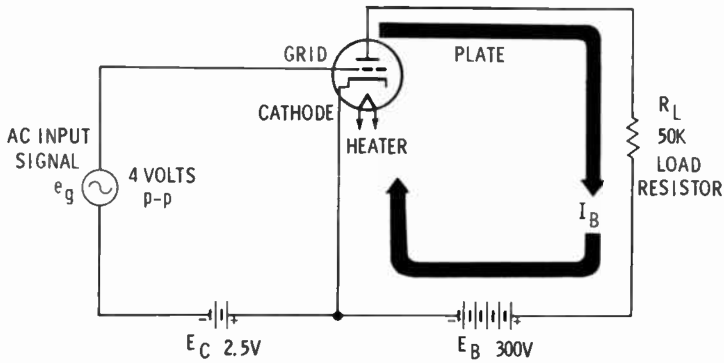
Plate-Current Control

The amplifier circuit diagram shows a small negative voltage (E_C) on the grid. The grid therefore has the effect of repelling the negative electrons in the electron cloud surrounding the cathode. Since the grid is closer than the plate to the cathode, a small change in grid voltage affects plate current as much as a large change in plate voltage. To put it another way, a small grid voltage controls a large plate current, making amplification possible.

Voltage Gain

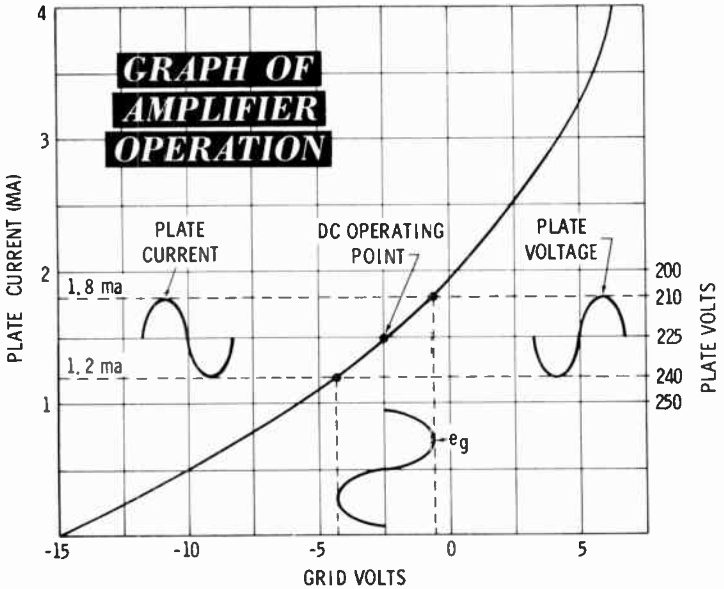
The grid bias (E_C) is adjusted in such a way that it allows a small amount of plate current to flow when no input signal is present. Now an AC input-signal voltage (e_g) is introduced. Suppose the DC grid bias voltage is —2.5 volts and an AC signal that swings 2 volts in each direction (4 volts peak-to-peak) is superimposed on it. The graph on the next page shows how the plate current and voltage change with

AMPLIFIER WITH INPUT SIGNAL



the grid voltage for a particular type of tube used in the circuit shown above. The plate current changes from 1.2 to

1.8 milliamperes. This current, flowing through load resistor R_L, produces a change in voltage drop from 50,000 × 0.0012 = 60 volts to 50,000 × 0.0018 = 90 volts. The voltage drop with just the DC bias applied (no signal input) is 75 volts.



Since the plate-battery voltage is 300 volts, the voltage between plate and cathode will be 300 minus the load-resistor voltage drop (neglecting the small battery resistance). Thus, the plate voltage has a quiescent (no-signal) value of 225 volts, and with the 4-volt (peak-to-peak) input signal it swings between 210 and 240 volts.

An AC signal with a peak of 2 volts was put into the amplifier, and an AC output with a peak amplitude of 15 volts (½ of 240 — 210 volts) was produced. This AC output voltage has 7.5 times the amplitude of the AC input voltage. This is a net voltage gain of 7.5.

Q3. In the circuit shown, the AC input signal is applied to the ____ of the tube.

Q4. The output voltage is produced by changes in the _____ _______ flow through the ____ resistor.

Your Answers Should Be:

A3. In the circuit shown, the AC input signal is applied to the **grid** of the tube.

A4. The output voltage is produced by changes in the **plate-current** flow through the **load** resistor.

Phase Reversal

In the amplifier described on the previous pages, the plate voltage is the difference between the plate-supply voltage and the load-resistor voltage drop. Thus, when the load-resistor drop is greatest, the remaining plate voltage is at the lowest value. The load-resistor drop is greatest (the plate voltage is the lowest) when the grid-signal voltage is at its positive peak. When the grid voltage is at its negative peak, the plate voltage is at its highest value. This means then that a phase difference of 180° exists between the input and output voltages.

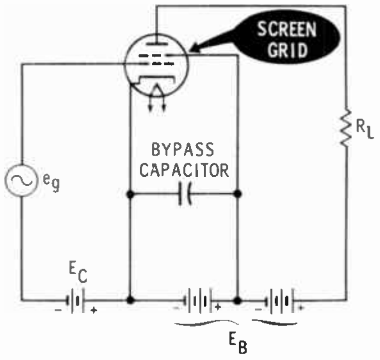
TETRODES AND PENTODES

As you know, many tubes have more electrodes than the three of the triode described so far in this chapter. The **tetrode** (four-electrode) tube has a fourth element, called the **screen grid**, between the control grid and the plate. This tube was developed to overcome a particular shortcoming of triodes.

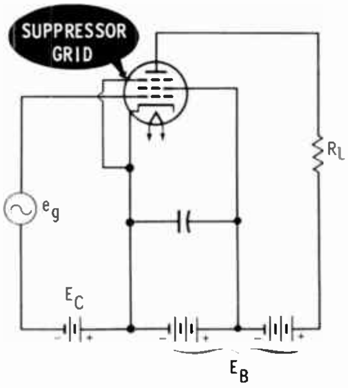
One of the practical limitations of triode amplifiers is that at higher frequencies the **interelectrode capacitance** becomes important. This capacitance exists between cathode and grid, between grid and plate, and between cathode and plate, and is normally very small. As the input frequency increases, the reactances of these capacitances decrease, causing undesirable effects. The capacitive coupling from plate (output) to grid (input) is especially undesirable. This capacitance can result in undesirable feedback, gain reduction, and distortion. The screen grid of a tetrode acts as an electrostatic shield between the grid and plate. In this way it reduces the undesirable plate-to-grid capacitance to a much lower value.

The **pentode** has a third grid placed between the screen grid and the plate. This fifth electrode is called the **suppressor grid**. The purpose of the suppressor grid is to prevent a form of reverse conduction which occurs in tetrodes. When electrons strike the plate with enough velocity, the force dislodges other electrons which bounce back toward the screen grid. This **secondary emission** is, in effect, a reverse current flow from plate to screen grid.

AMPLIFIERS WITH MULTIGRID TUBES



Tetrode



Pentode

The suppressor grid prevents this current from flowing. It is electrically connected to the cathode, making it negative with respect to the plate, and thus repels any electrons that try to travel from the plate to the screen grid. The suppressor grid is actually a fairly coarse screen so that it does not interfere with the main current flow between cathode and plate.

Although tetrode and pentode characteristic curves differ from those of the triode, the basic amplifier action is no different. Throughout this chapter amplifiers will be explained in terms of triodes. It should be understood that, according to the need, tetrodes and pentodes may also be used as amplifiers.

Q5. The phase difference between input and output signals in the voltage amplifier just described is ____.

Q6. The basic amplifier action of tetrodes and pentodes (is, is not) the same as that of triodes.

Your Answers Should Be:

A5. The phase difference between input and output signals in the voltage amplifier just described is 180°.

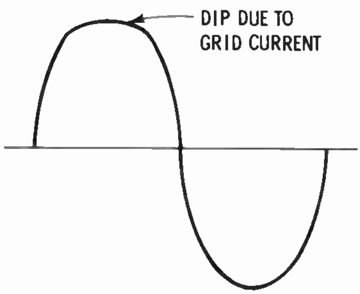
A6. The basic amplifier action of tetrodes and pentodes is the same as that of triodes.

BIASING

The graph on page 143 shows the plate current and voltage for any given grid voltage for one particular amplifier circuit. A point on the curve indicates the DC bias voltage applied to the grid. This is called the **DC operating point**, or the **quiescent point.** With every amplifier circuit, this point must be chosen correctly in order to have proper operation. For an accurate reproduction of the input signal, the grid bias is usually chosen so that:

1. It is greater than the peak value of the signal; thus, the signal-voltage swing never drives the grid positive with respect to the cathode.
2. The entire signal-voltage swing operates over a linear (straight) portion of the characteristic curve.

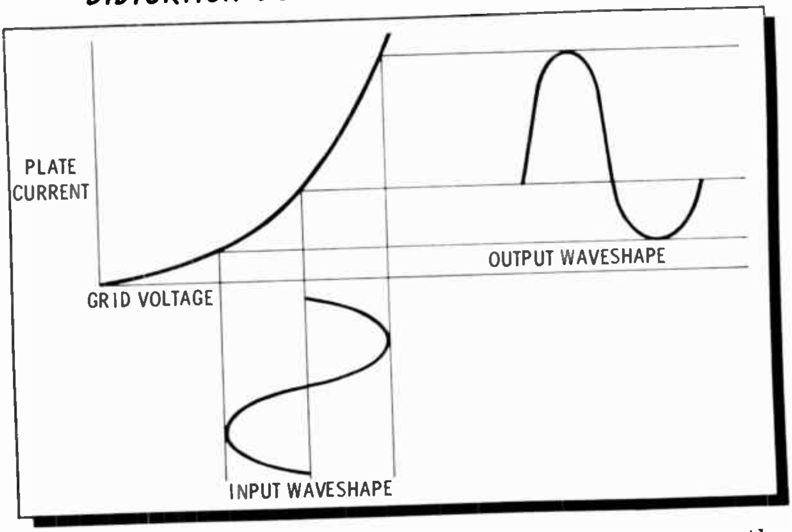
Both of the above rules are ignored in special types of circuits. Normally, however, the grid is not driven positive during any part of the input cycle. If this happens, the positive grid attracts electrons, and a current flows from cathode to grid. This causes distortion because, during the part



DISTORTED PLATE-CURRENT WAVEFORM

of the cycle when grid current flows, the amount of current flowing to the plate is diminished by the amount of the grid current. Therefore, as far as the plate is concerned, there is a dip in the waveform, and the waveshape is distorted. Also, the total power developed at the plate is made smaller, resulting in an overall power loss. If rule 2 is violated and the tube is operated on a curved portion of its characteristic curve, the output wave will be distorted, as shown below. The positive and negative halves of the input

DISTORTION DUE TO NONLINEAR OPERATION

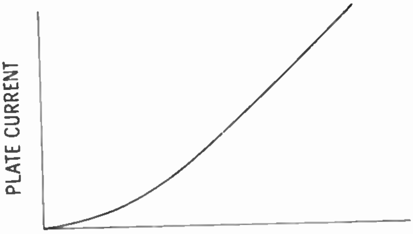


signal are equal, but because of the shape of the curve, the positive and negative halves of the output are quite unequal.

Q7. What are the two rules for determining a suitable DC grid-bias voltage?

Q8. The DC voltage applied to the grid is called ---- ----.

Q9. Indicate on the curve shown below where a suitable DC operating point might be located.

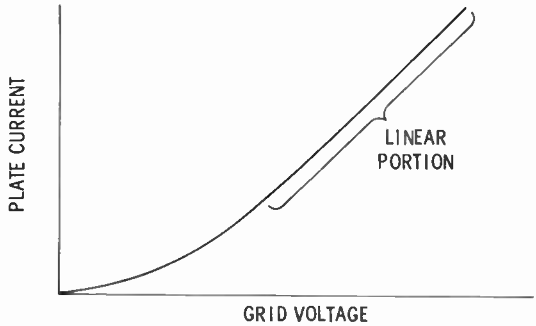


Your Answers Should Be:

A7. The DC grid voltage should be **greater than the highest voltage of the AC signal.** The DC voltage plus the signal voltage **should be on a straight-line portion of the plate-current–grid-voltage curve.**

A8. The DC voltage applied to the grid is called **grid bias.**

A9.



The DC operating point should be located on the **linear portion** of the curve.

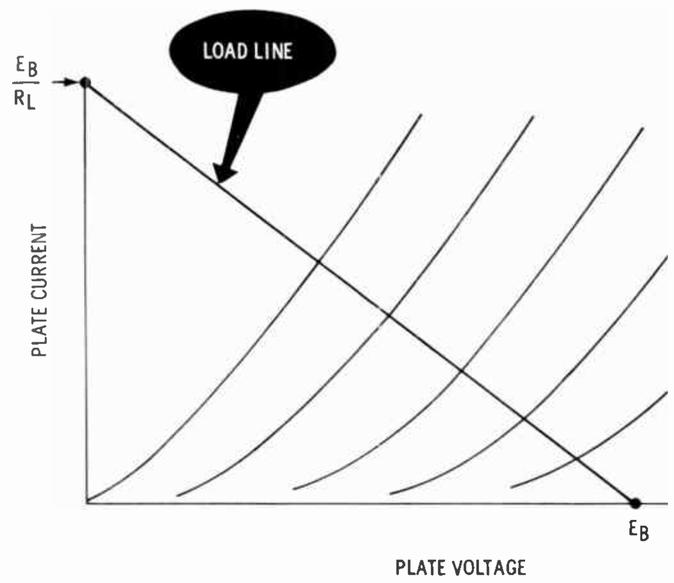
LOAD LINE

A convenient way to analyze an amplifier is with a load line drawn on the plate-characteristic curves of the tube. These curves relate plate current (I_p) to plate voltage (E_p) for different values of grid voltage (E_g).

The load line is drawn as follows. A point corresponding to the value of the plate-supply voltage (E_B) is selected on the horizontal axis. Another point is marked on the vertical axis at a value of I_p equal to the plate-supply voltage divided by the effective value of the load resistance. The load line joins these two points.

These points represent the theoretical extremes the tube could reach. If the grid voltage is such that no current can flow, I_p is zero, and all of voltage E_B appears across the tube. This is the point on the X axis. If the grid voltage is such that the tube conducts so heavily as to have zero resistance, the plate current is limited only by the load resistance, and there is no voltage drop between plate and cathode. This is the point on the Y axis. This point, of course, is only theoretical. The tube is never a perfect conductor, so it can never reach that point on its load line.

A LOAD LINE



Changing the plate-supply voltage changes the position of the load line. Changing the load resistance changes the slope of the load line.

Q10. One end of a load line passes through the point on the horizontal axis corresponding to the ------ ------- voltage.

Q11. The other end of the load line passes through a point on the vertical axis corresponding to what value of plate current?

Q12. How does changing R_L and E_B affect the load line?

Your Answers Should Be:

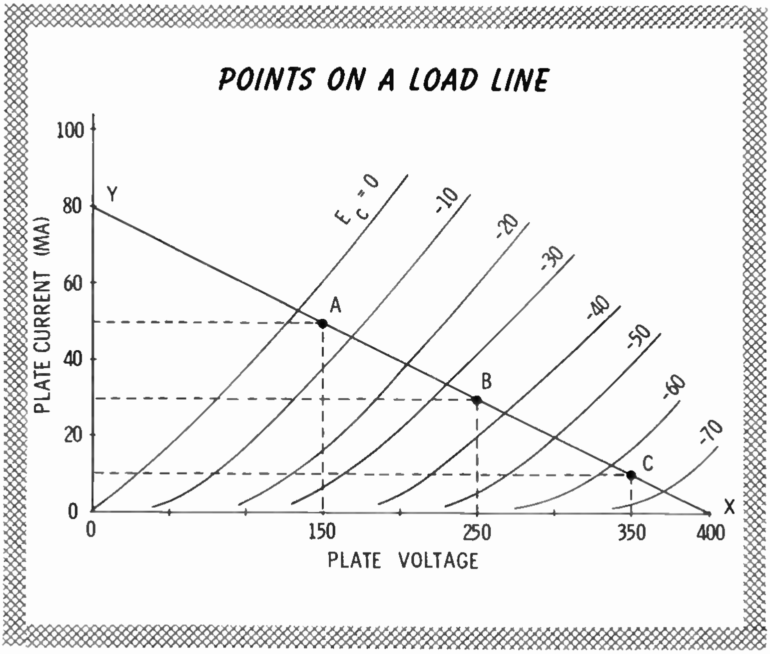
A10. One end of a load line passes through the point on the horizontal axis corresponding to the **plate-supply** voltage.

A11. The other end of the load line passes through a point on the vertical axis corresponding to a value of plate current equal to the **plate-supply voltage divided by the load resistance.**

A12. Changing R_p changes the **slope** of the load line. Changing E_B changes the **position** of the load line.

Operating Point

By marking the load line with the point corresponding to the negative bias applied to the grid, the operating point of the tube is found. This point gives the values of E_p, I_p, and E_g with no input signal applied.



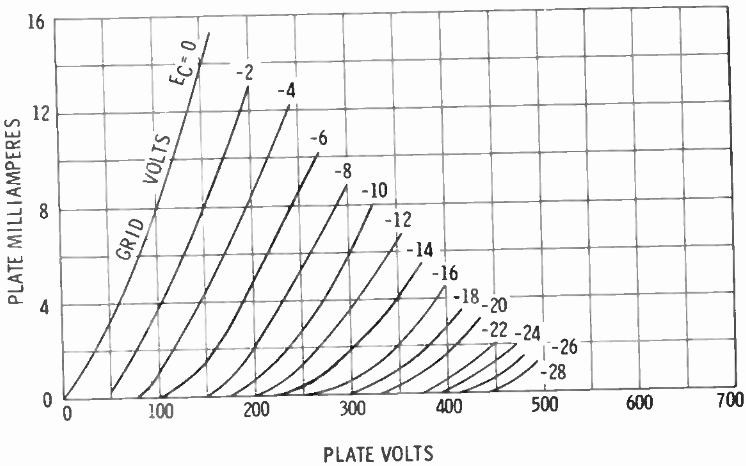
If the amplitude of the AC input signal is known, it can be marked off along the load line, as shown in the figure.

By running vertical and horizontal lines from the two peak E_g points (points A and C in the figure), the corresponding plate current and voltage can be determined.

In the diagram shown, the plate-supply voltage is 400 volts (point X). The quiescent operating point (B) shows that the DC grid bias is —35 volts. A signal having a peak value of 30 volts produces swings of grid voltage from —5 to —65 volts, causing variations of plate current from 10 to 50 milliamperes. The plate voltage swings from 150 to 350 volts.

The slope of the load line depends only on the value of the effective load resistance (R_L). This resistance may be a parallel combination of a load resistor and a grid-leak resistor. Or it may be an equivalent value from the primary of a coupling transformer. In any case, the points for the load line are always calculated as if the load resistance were a single resistor in the plate circuit.

The figure below shows a set of characteristic curves for a tube. Suppose the B voltage is 400 volts and the load resistance is 40K.



Q13. Draw the load line.

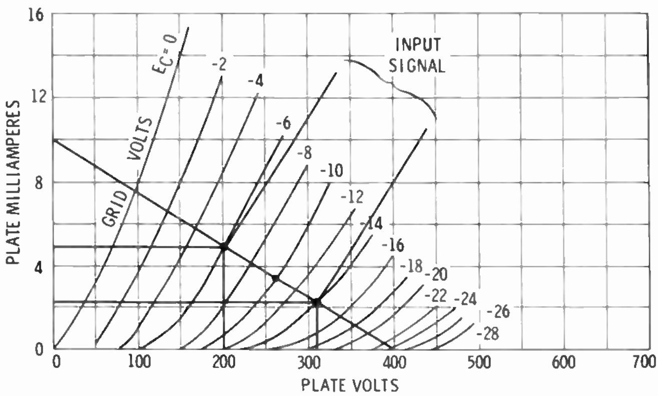
Q14. If the grid bias is —10 volts and the AC signal voltage has a peak value of 4 volts, draw lines to show the limits of plate current and plate voltage.

Your Answers Should Be:

A13. The load line should connect these two points:

$I_p = 0, E_B = 400V; I_p = 10$ ma, $E_B = 0$

A14. Plate current varies between 2 ma and 5 ma, approximately. Plate voltage varies between 200V and 310V, approximately.



AMPLIFIER CLASS

The class of an amplifier depends on the grid-voltage range. A **class-A amplifier** is one in which the grid is never driven positive or to cutoff by the signal voltage. This means that grid current does not flow during any portion of the cycle, and no power is consumed in the grid circuit.

A **class-B amplifier** is one in which the grid is biased at or very near cutoff. The tube conducts during approximately half of the cycle (usually a little less than half). Grid current may flow during a part of the conduction period.

A **class-C amplifier** is one in which the grid voltage is beyond cutoff for most of the cycle but goes positive on positive signal peaks. Grid current flows on these positive signal peaks.

Class-B and class-C amplifiers, as you see, violate the usual rules for establishing a DC operating point. These amplifiers are used when it is unnecessary to obtain accurate reproduction of the entire input signal.

EQUIVALENT CIRCUITS

It is difficult to analyze an amplifier circuit because vacuum tubes are complex circuit elements. A convenient way of analyzing vacuum-tube circuits is by substituting an **equivalent circuit** made up of conventional elements for the tube. For the purpose of the analysis, the equivalent circuit accurately represents the behavior of the tube as far as the AC signal is concerned.

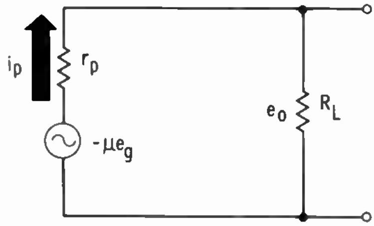
There are two basic equivalent circuits for a vacuum tube. Either one can be used, depending on which is more convenient. These equivalent circuits make use of the concepts of the constant-voltage generator and the constant-current generator.

In Chapter 2 you learned about tube parameters. These are the amplification factor, μ (mu); the transconductance (g_m) in micromhos; and the plate resistance (r_p) in ohms. You also learned the relationship between these three quantities: $\mu = g_m \times r_p$.

Constant-Voltage Generator

The equivalent circuit with a constant-voltage generator represents a vacuum tube as a voltage source of $-\mu e_g$ volts in series with a resistance r_p. The symbol e_g represents the signal voltage applied to the grid. The voltage at the output terminals of this circuit depends on the load resistance (R_L). The output voltage e_o is developed across R_L.

EQUIVALENT CIRCUIT USING CONSTANT-VOLTAGE GENERATOR



Q15. What class of amplifier must be used when minimum signal distortion is desired?

Q16. What is an equivalent circuit?

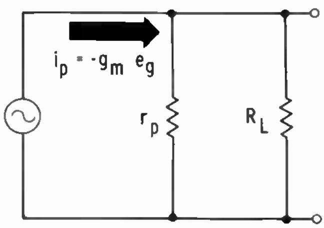
Your Answers Should Be:

A15. A **class-A amplifier** must be used when minimum signal distortion is desired.

A16. An equivalent circuit is a circuit **made up of conventional elements and used to represent a vacuum-tube circuit.**

Constant-Current Generator

The constant-current generator representation uses a constant-current source. This source generates a current of $g_m e_g$ amperes. (Remember that $I = E/R$, and conductance $= 1/R$.) The total current is i_p, the plate current. This current source is always in parallel with r_p, and the entire circuit is connected to a load (R_L).



EQUIVALENT CIRCUIT USING CONSTANT-CURRENT GENERATOR

The two equivalent circuits produce the same results. Usually, when dealing with currents you will want to use the constant-current circuit. When dealing with voltages, the constant-voltage circuit is usually most convenient.

One word of caution—the two equivalent circuits can be used safely only for small values of signal voltage. This is because they are based on linear tube-characteristic curves. Actual tubes do not have straight-line characteristics. When the circuit is operating over a wide range of voltages, the straight-line approximation is no longer correct.

GAIN AND LOAD RESISTANCE

The **voltage gain**, or **amplification**, of an amplifier circuit is given by the formula:

$$\text{amplification} = \mu \frac{R_L}{R_L + r_p}$$

With a given tube, the only variable in this formula is the load resistance (R_L). If the plate resistance is increased, the gain will be increased; but it can never become greater than the ideal amplification factor (μ) of the tube. It will approach this value as R_L becomes appreciably larger than the plate resistance (r_p).

VOLTAGE AND POWER AMPLIFIERS

To obtain high amplification of **voltage**, a load resistor that is large compared to r_p must be used. However, as the value of the load resistor is increased, the output voltage across it rises more and more slowly. Finally, any further increase of R_L produces only a negligible increase in output voltage. This is because the tube begins to operate on a nonlinear portion of the grid characteristic curve as the load resistance is increased. This, as you have seen, results in a low output and produces distortion. The best value of load resistance is normally one that will give a reasonable amount of gain. A load with a resistance about four times that of the plate resistance of the tube is usually a satisfactory value.

Maximum **power** is obtained from the output of a vacuum-tube amplifier when the value of the load resistance is equal to r_p. However, distortion of the output signal occurs when this value of load resistance is used. For triodes, the best balance between power output and distortion exists when R_L is two to four times r_p. For pentodes, the best value for R_L is about one tenth of r_p.

Q17. If a triode tube being used as an amplifier has a plate resistance of 32,000 ohms and a load resistance of 68,000 ohms, it is probably being used to produce an output of maximum -----, with minimum ----------.

Q18. What is the amplification of a circuit if the tube has a μ of 100, a plate resistance of 32,000 ohms, and a load resistance of 50,000 ohms?

Q19. What is the gain if R_L is increased to 100,000 ohms?

Q20. What is the gain if R_L is increased to 1 megohm?

Your Answers Should Be:

A17. If a triode tube being used as an amplifier has a plate resistance of 32,000 ohms and a load resistance of 68,000 ohms, it is probably being used to produce an output of maximum **power** with minimum **distortion.**

A18. $\text{Gain} = \frac{\mu R_L}{R_L + r_p} = \frac{100 \times 50{,}000}{50{,}000 + 32{,}000} = 61$

A19. Gain = 76

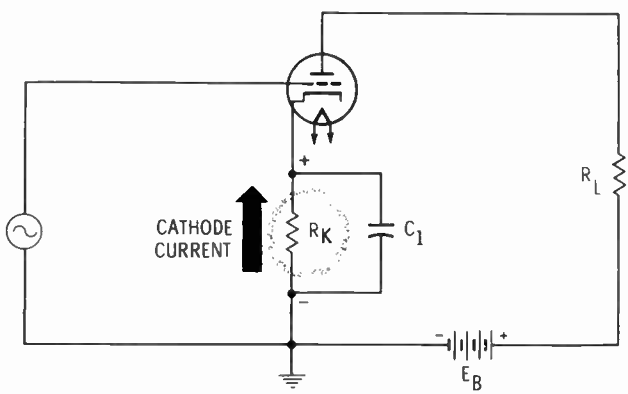
A20. Gain = 97

AUTOMATIC GRID BIAS

In the amplifier circuits shown so far, a battery (E_C) has been used to provide the small negative voltage for grid biasing. This is not always a practical arrangement, however. It is also possible to get the bias voltage from a resistance voltage divider in the power supply. The voltage-divider method and the battery method provide what is known as **fixed** bias.

In practical circuits, another common method of supplying grid voltage is by **automatic** bias. One type of automatic

CIRCUIT USING CATHODE-BIAS RESISTOR



bias is provided by the use of a cathode-bias resistor. The circuit for this is shown above. There are other types of automatic bias that work on similar principles.

In the circuit shown, the full cathode current flows through resistor R_K. The cathode current in a triode circuit equals the plate current. In a tetrode or pentode circuit the cathode current is the sum of the plate and screen-grid currents.

Current through R_K results in a voltage drop which makes the cathode more positive than the negative end of the plate-supply voltage to which the grid is connected. This is the same thing as making the grid negative with respect to the cathode.

If the desired grid-bias voltage and the total cathode current are known, the required value of resistor R_K can be calculated. For example, if E_c is to be —5 volts and the cathode current for this grid bias is 0.25 milliampere, the value of R_K is:

$$R_K = \frac{E_c}{I_K} = \frac{5V}{0.25\ ma} = 20K$$

In this arrangement the bias voltage depends on the amount of the cathode current. The current, in turn, depends on the plate voltage of the tube. As the plate voltage increases, the bias automatically increases (becomes more negative). As the plate voltage is reduced, the bias becomes less negative. This is why this circuit is called an automatic biasing circuit.

However, it is not desirable to have the bias affected by a continuously varying signal voltage. Therefore, biasing resistor R_K is bypassed with capacitor C_1 so that the AC component of the cathode current has no effect on the bias voltage. Capacitor C_1 is chosen so that its reactance at the signal-voltage frequency is small compared to R_K, usually about one tenth. DC current must pass through R_K because the capacitor appears as an open circuit to DC. However, the AC signal component can pass through C_1 ten times more easily than through the resistor. The AC voltage across the resistor is therefore very small. The cathode is then at ground potential as far as AC is concerned.

Q21. How does a cathode-bias resistor produce grid bias?

Q22. Why is a capacitor placed across a cathode-bias resistor?

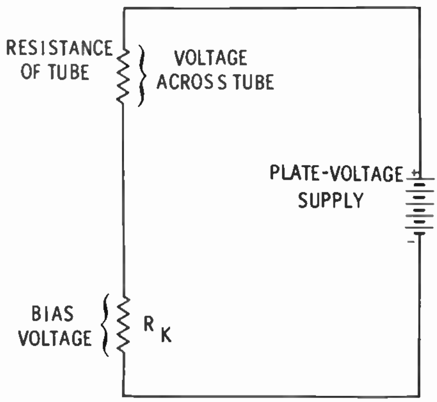
Your Answers Should Be:

A21. The flow of cathode current through the cathode-bias resistor causes a voltage drop which makes the **cathode positive with respect to the grid.** This is the **same as making the grid negative with respect to the cathode.**

A22. The capacitor across the cathode-bias resistor **prevents a signal-frequency voltage from appearing across the resistor.**

Effect of Cathode Bias

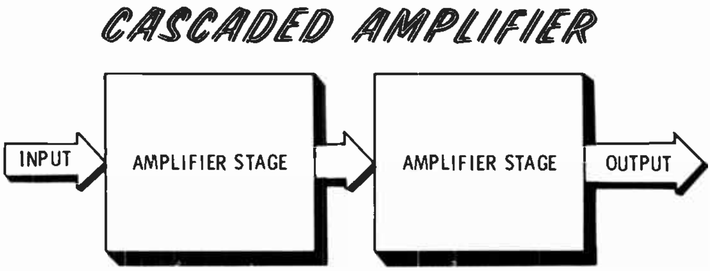
When using a cathode-bias resistor, it is necessary to have a plate-supply voltage higher than needed with fixed bias. The grid-bias voltage is, so to speak, taken from the plate-voltage supply by a voltage divider consisting of the biasing



resistor and the DC plate resistance of the tube. The plate voltage as seen by the tube is only that part of the supply voltage appearing across the plate resistance. Therefore, the plate-voltage supply must provide the bias voltage in addition to the plate voltage.

MULTISTAGE AMPLIFIERS

In many applications a single-tube amplifier cannot provide all the amplification that is required. It is then necessary to connect two or more amplifier circuits (called stages) one after the other. Each stage then amplifies the output of the preceding stage, until the desired amount of amplification is reached. This happens, for example, in television receivers that have several IF amplifiers connected in sequence. This arrangement is sometimes called a **cascaded amplifier.**



In a multistage amplifier chain, voltage amplifiers are generally used for all but the output stage. In this way only very small currents are handled. The signal is gradually developed to a higher voltage but with very little power. Only in the last stage is the signal converted into the necessary power output.

When several amplifier stages are coupled together, it is necessary to have some means of connecting them for maximum signal transfer without affecting the biasing of the individual tubes.

There are four main ways of coupling vacuum-tube amplifier stages. These are **resistance-capacitance, impedance-capacitance, transformer**, and **direct** coupling. The first two use a coupling capacitor to block the DC; the third accomplishes the same thing with a transformer.

Some special amplifiers are designed to amplify very low frequencies, even down to zero cps (DC). The stages of these amplifiers are coupled directly, because a coupling capacitor or transformer would block DC and very low-frequency signals.

Q23. In an amplifier having a cathode-bias resistor the plate voltage is less than the plate-supply voltage by the amount of the ____ _______.

Q24. What are the four ways of coupling vacuum-tube amplifier stages?

Your Answers Should Be:

A23. In an amplifier having a cathode-bias resistor the plate voltage is less than the plate-supply voltage by the amount of the **bias voltage.**

A24. The four ways of coupling vacuum-tube amplifier stages are **resistance-capacitance, impedance-capacitance, transformer,** and **direct** coupling.

Impedance Matching

When coupling two amplifier stages together, or an amplifier stage and an output device such as a speaker, it is important to consider the output and input impedances involved.

Consider, for example, the coupling of an amplifier to a speaker. A vacuum-tube amplifier is a device that operates best at a rather low current level and a rather high voltage level (in the plate circuit). On the other hand, a speaker is a device that operates with high current and low voltage. Another way of saying this is that the amplifier has a high output impedance but the speaker has a low input impedance.

For maximum transfer of energy between two stages (or other electrical circuits), it is necessary that the output and input impedances be matched (made equal). If they are not equal, they can be matched by an **impedance-matching network.**

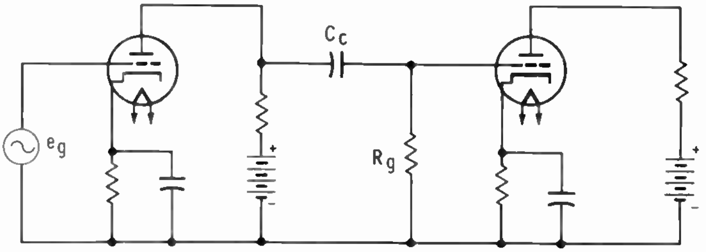
Remember that this applies only to energy transfer and not to voltage transfer. When coupling a voltage amplifier to the following stage, it is desirable to make the load resistor as high as practical, even though this does not result in maximum power transfer.

Resistance-Capacitance Coupling

Resistance-capacitance coupling is the most common and simplest manner of cascading amplifier stages. **RC-coupled** amplifiers are used in audio systems, video amplifiers, oscilloscopes, radar systems, etc.

Coupling between stages of an RC-coupled amplifier is accomplished by taking the changing voltage across the load resistance of one stage and connecting it through a coupling capacitor (C_c) to the grid of the tube in the next stage. The high DC plate voltage of the first stage is blocked by C_c. The proper value of C_c is determined by the lower limit of the range of frequencies to be amplified. If C_c is too small, it will block the lower frequencies in the desired signal range.

RESISTANCE-CAPACITANCE COUPLED AMPLIFIER



Resistor R_g is called the **grid-leak resistor.** This resistor serves to keep the grid at ground potential, thus preserving the voltage difference between the grid and cathode. This resistor actually serves a dual purpose, also being used as the component across which the signal voltage from the preceding stage is developed.

Resistor R_L is called the load resistor, as before. However, notice that R_L is **not** the entire load seen by the first tube. It has the combination of C_c and R_g in parallel with it. The true load impedance is, therefore, always smaller than R_L.

An RC-coupled amplifier is sensitive to frequency. One reason is that the reactance of C_c varies with frequency. Another reason is that every circuit has several stray (unintentional) but unavoidable capacitances. At high frequencies these capacitances have low reactance values and begin to play a part in the circuit performance.

Q25. If two impedances are not the same, they can be matched by using a(n) ---------- --------- --------.

Q26. Impedance matching is usually not employed when coupling a ------- ---------- stage to the following stage.

Q27. In an RC-coupled amplifier, the true load is (equal to, less than, greater than) R_L.

Your Answers Should Be:

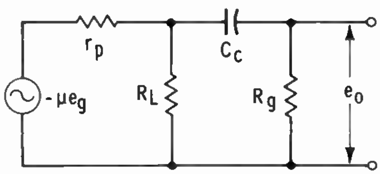
A25. If two impedances are not the same, they can be matched by using an **impedance-matching network.**

A26. Impedance matching is usually not employed when coupling a **voltage-amplifier** stage to the following stage.

A27. In an RC-coupled amplifier, the load seen by the tube is **less than R_L.**

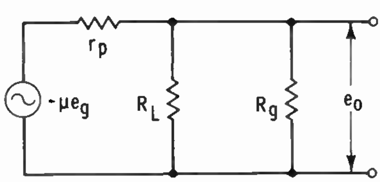
Effect of Frequency in RC Coupling

In order to analyze a circuit accurately, the changing reactances previously mentioned must be taken into account. Since these reactances vary with frequency, a separate analysis must be made for the low, intermediate, and high frequencies. For each frequency range an equivalent circuit is chosen that will be a fairly accurate representation of the behavior of the amplifier. Remember that equivalent-circuit analysis is valid only for reasonably small signals. The three equivalent circuits for an RC-coupled triode amplifier designed to operate in the audio range are shown in the following three illustrations.



LOW-FREQUENCY EQUIVALENT CIRCUIT

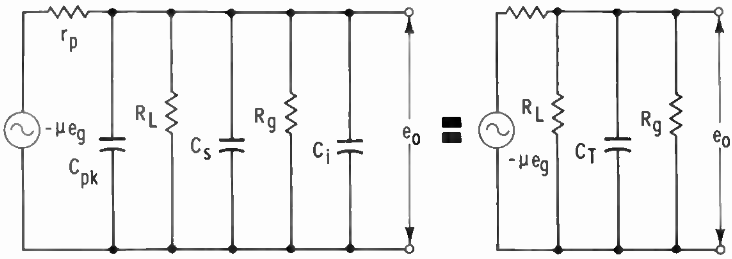
In the low-frequency range (up to 1,000 cps) no stray capacitances need be considered, but the coupling capacitor C_c has a sizable reactance. The circuit above applies. Simple circuit techniques can be used to determine the voltage e_o, which appears at the grid of the next stage.



MEDIUM-FREQUENCY EQUIVALENT CIRCUIT

The middle-frequency range is one in which coupling capacitor C_c can be neglected because it has a very small reactance compared to R_g. The stray capacitances likewise do not show any appreciable effect in this range.

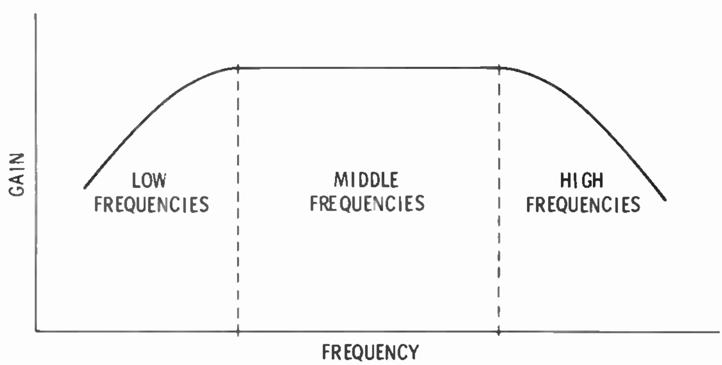
HIGH-FREQUENCY EQUIVALENT CIRCUIT



In the high-frequency range, three unwanted capacitances become important. They are the plate-cathode capacitance (C_{pk}), the stray capacitance of the wiring (C_s), and the capacitance of the input circuit of the second stage (C_i). Since the equivalent circuit is a parallel one, all three capacitances may be combined into a total stray capacitance (C_T).

The graph below shows how the gain of a typical RC-coupled amplifier varies as the signal frequency changes.

GRAPH SHOWING RELATIONSHIP OF GAIN TO FREQUENCY



Q28. What factors affect the gain of an RC-coupled amplifier at different frequencies?

Q29. To fully analyze the performance of an RC-coupled amplifier, _____ frequency ranges must be considered.

Your Answers Should Be:

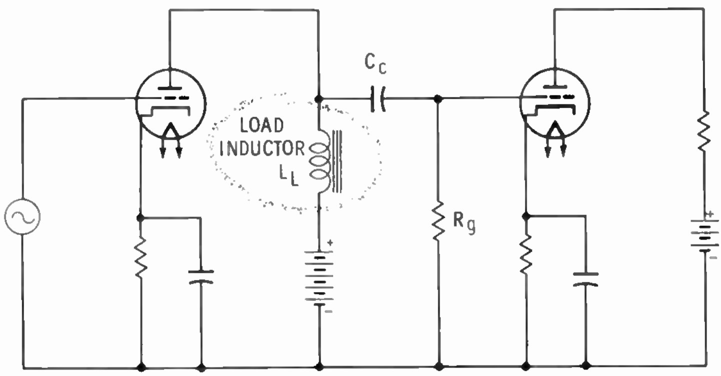
A28. At low frequencies the gain of an RC-coupled amplifier depends on μ, r_p, R_L, R_g, and the reactance of C_c. At middle frequencies the factors are μ, r_p, R_L, and R_g. At high frequencies the factors are μ, r_p, R_L, R_g, C_{pk}, stray capacitance, and the input capacitance of the following stage.

A29. To fully analyze the performance of an RC-coupled amplifier, three frequency ranges must be considered.

Impedance Coupling

In the resistance-coupled amplifier there is a sizable DC voltage drop across the load resistor. This voltage drop is sometimes undesirable because it requires a power supply with a high voltage. The voltage drop can be minimized by using an inductor in place of the load resistor. The inductor, or choke, has low DC resistance but high reactance to AC. This makes possible a plate-supply voltage only a little higher than the plate voltage needed. The winding of the inductor develops only a small voltage drop due to the resistance of the wire.

IMPEDANCE-COUPLED AMPLIFIER



In practice, **impedance-coupled amplifiers** are not often used. They are most likely to be encountered in power-amplifier circuits.

The distributed stray capacitance between the turns of the coil reduces the gain of the amplifier at the higher frequencies. At low frequencies, the choke (inductor) has a low reactance, thus causing a relatively small voltage drop to be developed across it. At the same time, the coupling capacitor has a very high reactance, preventing a good transfer of signal to the next stage. These two factors combine to reduce the low-frequency gain.

The choke is usually chosen to have a high impedance at the frequencies to be amplified so that a high signal-frequency voltage may be developed across it.

Circuit analysis and calculation of voltage gain for impedance-coupled amplifiers are very similar to those for the RC-coupled amplifier. The voltage-gain values obtained are of the same general magnitude.

Transformer Coupling

Transformer coupling is a very popular method of cascading amplifiers. It has the same advantage as impedance coupling in that no large DC drop appears across the primary winding of the transformer in the plate circuit. DC isolation is achieved by the natural isolation provided between the transformer windings (a transformer can transfer only alternating voltages).

Transformer coupling also has the advantage of good impedance matching between stages. This makes maximum power transfer possible. Transformer coupling is suitable for use in power stages, such as in the output circuits of audio amplifiers. The frequency response of a transformer-coupled amplifier can be excellent using modern transformer-design techniques. The major disadvantage of transformer coupling is its relatively high cost as compared to other coupling means.

Q30. The gain of an impedance-coupled amplifier at low frequencies is (good, fair, poor).

Q31. A load inductor is also called a ______.

Q32. The impedance of the load inductor __________ as the signal frequency decreases.

Q33. Transformer coupling (is, is not) suitable for use in power amplifiers.

Your Answers Should Be:

A30. The gain of an impedance-coupled amplifier at low frequencies is **poor.**

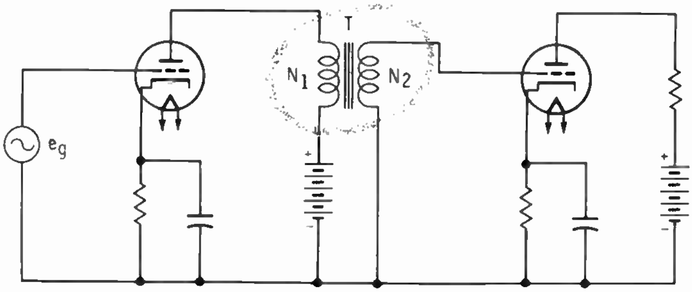
A31. A load inductor is also called a **choke.**

A32. The impedance of the load inductor **decreases** as the signal frequency decreases.

A33. Transformer coupling is suitable for use in power amplifiers.

Now you will see how a coupling transformer is used in an amplifier. The DC component of plate current flows through the primary winding without inducing any voltage in the secondary. But any fluctuations, such as AC currents, flowing through the primary induce corresponding AC voltages in the secondary winding connected directly to the grid of the next tube.

TRANSFORMER COUPLING



Since the tube is operated so that the grid is never driven positive, no grid current flows and no power is taken from the secondary winding. This means that no interaction takes place between the secondary and the primary and, therefore, the primary does not have to deliver any power to the secondary. The primary circuit sees only the impedance of the primary winding, as if it were a single coil, and its value can be chosen for the right value of reactance for maximum gain in the first stage. The voltage developed across the secondary winding depends on the turns ratio of the transformer. This voltage is equal to n_2/n_1 times the primary voltage.

The secondary voltage, and therefore the gain, can be made quite high if the transformer winding ratio is high enough. In the early days of radio, when available tubes had very low amplification, transformers with high winding ratios were used extensively to achieve more gain.

However, there is a practical limit to the winding ratio. In order to achieve a high ratio, the secondary winding must have a large number of turns. As the frequency of the signal goes up, such a winding has enough stray capacitance to limit its high-frequency response. For a more uniform (flatter) frequency response in high-quality amplifiers, the turns ratio rarely exceeds 5 to 1.

It is important to connect the transformer correctly in a transformer-coupled amplifier. One reason, of course, is that the turns ratio must not be reversed. A more important reason is that the secondary winding is not made to carry any appreciable amount of current. But the primary does have to carry considerable plate current. Connecting the transformer into the circuit backwards may cause the secondary to burn out.

It is also important not to reverse the two leads of either winding, especially where a wide range of frequencies is concerned. The windings are wound in such a way that one end has less capacitance to ground than the other. Color coding is used to indicate the correct connections and should always be followed.

The methods used to couple amplifier stages discussed so far block all DC voltages and are for AC-signal use only. It is sometimes necessary to amplify DC signals, however.

Q34. Only __ flowing in the primary of a coupling transformer induces signals in the secondary.

Q35. The primary circuit sees the impedance of the ________ ________.

Q36. The voltage developed across the secondary winding is equal to the primary voltage times the _____ _____.

Q37. A winding with a large number of turns has a large _____ ___________.

Q38. Transformer leads in a transformer-coupled amplifier (may, should not) be interchanged.

Your Answers Should Be:

A34. Only AC flowing in the primary of a coupling transformer induces signals in the secondary.

A35. The primary circuit sees the impedance of the **primary winding.**

A36. The voltage developed across the secondary winding is equal to the primary voltage times the **turns ratio.**

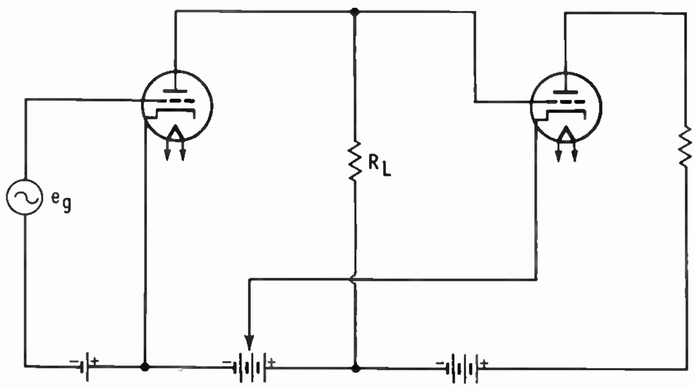
A37. A winding with a large number of turns has a large **stray capacitance.**

A38. Transformer leads in a transformer-coupled amplifier **should not** be interchanged.

DIRECT-CURRENT VACUUM-TUBE AMPLIFIERS

Direct-current vacuum-tube amplifiers are known interchangeably as **direct-current amplifiers** or **direct-coupled** amplifiers (DC amplifiers for short). They are called direct-coupled amplifiers because there is no capacitor or transformer between the output of one stage and the input of the next, allowing DC signals to pass from stage to stage. Special means must be used to prevent the high DC plate potential of one stage from affecting the operation of the grid circuit of the next stage.

LOFTIN-WHITE CIRCUIT



One of the main difficulties encountered with DC amplifiers is **drift**, the gradual change in output voltage without a change in the input. It is, of course, desirable to have no output voltage at all when the input is zero. Drift can be caused by a gradual change in the values of circuit components or even by replacement of a tube.

The figure on the opposite page shows one of the most common DC-amplifier circuits, the Loftin-White. Notice how the grid bias is obtained by dividing the plate-supply voltage of the previous stage. In a practical circuit the batteries are replaced by a resistor voltage divider in the main DC power supply. Because of the complexity of the required power supply, the tendency of the amplifier to drift, and the necessity for compensating networks, DC amplifiers are not used as widely as RC- or transformer-coupled units.

WHAT IS AN OSCILLATOR?

Oscillators are circuits that produce AC signals which have various applications in electronic equipment. Oscillators generate the radio-frequency carriers for radio and television transmissions. The audio or video signal is then superimposed on the carrier. Every superheterodyne radio receiver employs a local oscillator, and some electronic organs have a series of oscillators that produce different tone frequencies. All these are **sinusoidal** oscillators; that is, their output resembles a sine wave.

A second important class of oscillator circuits includes the nonsinusoidal types—circuits that produce AC other than sine waves. These types of oscillators are often called **pulse** or **square-wave generators.** They include pulse generators for radar, square-wave generators for television testing, etc., sawtooth-wave generators in television display, marker oscillators, and a host of others.

Q39. One of the most common direct-coupled amplifiers is the ______ _____ circuit.

Q40. In a DC amplifier the gradual change in output voltage without a corresponding change in the input is called _____.

Q41. Why is a direct-coupled amplifier so named?

Your Answers Should Be:

A39. One of the most common direct-coupled amplifiers is the **Loftin-White** circuit.

A40. In a DC amplifier the gradual change in output without a corresponding change in the input is called **drift.**

A41. A direct-coupled amplifier is so named because **the output signal of one stage is fed directly to the grid of the next stage** without going through a coupling capacitor.

OSCILLATOR OPERATION

How does an oscillator work? Suppose an amplifier capable of amplifying a desired frequency is turned on. Without any input there will, of course, be no output. Now connect the output back to the input, in a sort of loop, making sure that the phase relationship is such that this **feedback** will reinforce, not reduce, any input to the amplifier.

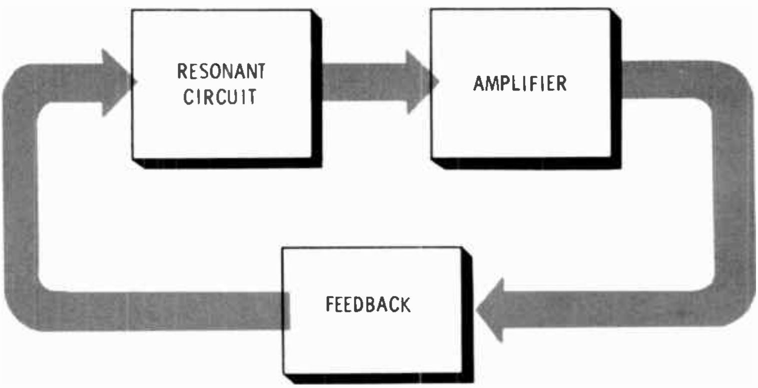
Any small signal at the input terminals will be amplified, fed back to the input, amplified again, and so on. The signal keeps going around the loop. Since all electronic circuits are frequency sensitive to some degree, this will happen only in a certain range of frequencies. The circuit oscillates; that is, it generates an AC signal without any external AC input. The oscillations may even be started by a very small amount of random noise in the tube.

There are two conditions for oscillation in a circuit. First, a feedback from output to input in the correct phase is required. This is known as **positive feedback** and may be accomplished by various kinds of coupling networks. Second, the amount of feedback must be enough to overcome any internal losses in the circuit so that the oscillations do not gradually die away.

It is important to keep in mind that the tube itself does not oscillate; it merely amplifies. The actual oscillation takes place in the **resonant circuit** that is part of the complete oscillator circuit. That is to say, the circuit constants determine the frequency of oscillation. The resonant circuit, also called a **tank**, functions like a flywheel rotating at its natural speed. There are some losses caused by resistance in the circuit. The power supply furnishes small amounts of energy every cycle to replace these losses and keep the oscillations going.

Thus, a basic oscillator has three necessary parts—the oscillating system, which usually is a resonant tank circuit; an amplifying device, such as a tube or transistor, to control the small amounts of energy furnished during each cycle; and a feedback system which may be either a circuit network or the interelectrode capacitance of a tube.

FEEDBACK OSCILLATOR



The type of oscillator discussed in this chapter produces an output waveform that is considered to be a sine wave. An oscillator producing such an output is sometimes called a sinusoidal oscillator. You will learn about nonsinusoidal oscillators later in this volume.

Q42. An oscillator can be made by adding ________ ________ to an amplifier.

Q43. Another name for the resonant circuit in an oscillator is the ____ ________.

Q44. In what part of the oscillator do the actual oscillations take place?

Q45. What usually starts the oscillations in an oscillator circuit?

Your Answers Should Be:

A42. An oscillator can be made by adding **positive feedback** to an amplifier.

A43. Another name for the resonant circuit in an oscillator is the **tank circuit.**

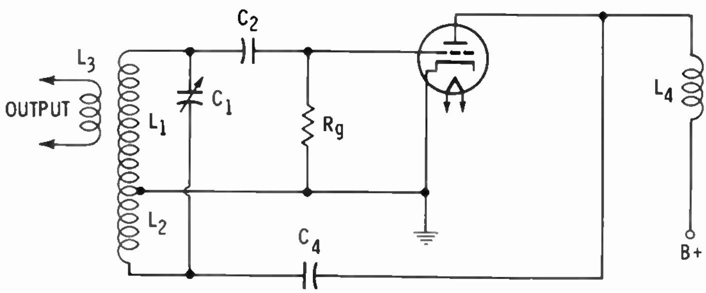
A44. The actual oscillations take place **in the tank circuit.**

A45. **Random noise** usually starts the oscillations in an oscillator circuit.

Hartley Oscillator

One of the most common oscillator circuits is the **Hartley.** The circuit shown below is a **shunt-fed Hartley oscillator,** which has the advantage that all DC is blocked from the oscillating tank circuit by capacitors.

Shunt-Fed Hartley Oscillator



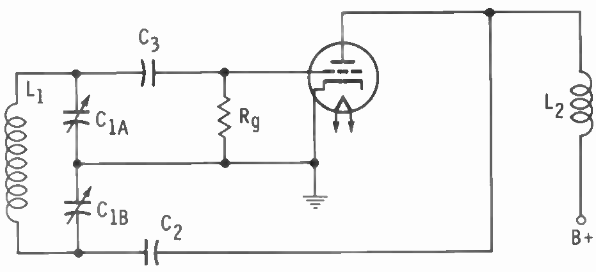
Random noise will produce small inputs to the parallel-resonant circuit composed of L_1, L_2, and C_1. This is the tank circuit. The noise input causes a circulating current to build up in this loop at the resonant frequency. A large current flows back and forth between the inductive and capacitive components at this frequency with only a small voltage applied. Notice that L_2, the lower half of the tapped tank coil (coil with a center connection), is also in the AC plate circuit. Thus, L_2 serves to couple the AC energy in the plate circuit to the tank circuit by means of the mutual inductance (transformer action) between the two coil halves (L_1 and L_2). This produces an oscillating tank circuit (made up of L_1, L_2 and C_1) and an amplifier. The DC in the plate circuit is blocked from the tank circuit by C_4.

The oscillating voltage in the tank circuit is coupled to the grid of the amplifier tube by RC coupling like that used between amplifier stages. The coupling network is composed of C_2 and R_g. Notice that the grid signal is taken from one end of the coil. The amplifier reverses the phase of this signal and returns it to the opposite end of the coil, where it is of the proper phase to increase the oscillations rather than cancel them. Varying the capacitance of C_1 changes the resonant frequency of the tank circuit and thus the output frequency of the oscillator.

Colpitts Oscillator

The **Colpitts** is another common oscillator circuit. This type of oscillator resembles the shunt-fed Hartley except that a split capacitor is used instead of a tapped coil.

COLPITTS OSCILLATOR



C_{1A}, C_{1B}, and L_1 make up the tank circuit. The resonant frequency of the tank is changed by varying C_{1A} and C_{1B}. (These capacitors are usually on a common shaft so that both of them can be adjusted at the same time.) The output of the amplifier is introduced into the tank circuit through capacitors C_2 and C_{1B}. The tank-circuit voltage is introduced into the grid of the amplifier by the coupling network consisting of C_3 and R_g.

Q46. How is feedback obtained in a Hartley oscillator?

Q47. How does a Colpitts oscillator differ from a Hartley oscillator?

Q48. How is feedback obtained in a Colpitts oscillator?

Your Answers Should Be:

A46. Feedback is obtained in a Hartley oscillator by **returning the amplifier output to part of the coil** in the resonant circuit.

A47. A **Colpitts oscillator** uses a **split capacitor** in the tank circuit. A **Hartley oscillator** uses a **split coil** in the tank circuit.

A48. Feedback is obtained in a Colpitts oscillator by **returning the amplifier output to part of the split capacitor** in the resonant circuit.

WHAT YOU HAVE LEARNED

1. An amplifier is a circuit that acts like a valve, controlling a large amount of DC power to reproduce a small AC signal input.
2. Tetrode and pentode amplifiers operate on the same basic principle as triode amplifiers.
3. A DC operating point can be selected for a tube by examining the grid-characteristic curves of the tube.
4. By drawing a load line on a set of plate characteristic curves, values of plate current and plate voltage for a given signal voltage can be obtained.
5. The grid never goes positive in a class-A amplifier.
6. For class-A amplifiers, grid bias should be such that the signal voltage is always on a linear portion of the grid characteristic curve.
7. Class-B amplifiers are amplifiers in which the tubes conduct for about half the input cycle.
8. Class-C amplifiers are amplifiers in which the tubes conduct for less than half an input cycle.
9. The greater the load resistance of a tube amplifier, the greater is the voltage amplification.
10. The greatest power amplification is obtained when the load resistance is equal to the plate resistance of the tube.
11. An automatic grid-bias circuit varies grid bias as the

13. Amp... transformer, or direct cou...
14. The first three coupling methods above are u... pass only AC signals from stage to stage, while the last can also pass DC signals.
15. Equivalent circuits for vacuum tubes can be drawn to simplify the analysis of amplifier circuits.
16. Sinusoidal oscillators are used to produce sine-wave outputs.
17. Nonsinusoidal oscillators are used to produce pulse-type waveforms.
18. A sinusoidal oscillator is basically a combination of a resonant circuit, an amplifier, and positive feedback connections.
19. A Hartley oscillator obtains feedback from a tap in the inductive part of the resonant circuit.
20. A Colpitts oscillator obtains feedback from a tap in the capacitive part of the resonant circuit.

6

Transistor Circuits

What You Will Learn

When you have finished this chapter, you will know how to calculate the voltage and power gain of a transistor amplifier. You will understand several biasing arrangements and will know how the appropriate biasing voltages and currents are selected. You will learn about RC coupling, transformer coupling, direct coupling, and tuned coupling of transistor amplifiers.

TRANSISTOR AMPLIFIERS

Like a triode vacuum tube, a transistor can amplify. This means that it can control the flow of a large current by using a small signal. An amplifier provides an output signal having a **greater amplitude** than the input signal. Ideally, that is all it does; it leaves the shape of the signal waveform unchanged. If the output and input signals differ in any way other than amplitude, the amplifier is said to introduce **distortion.**

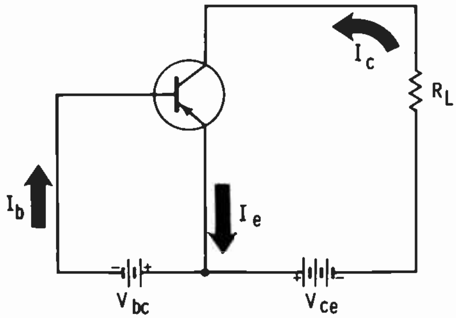
Amplification, or **gain,** is measured by comparing the output to the input. Care must be taken to compare the same quantities. The current gain is the output current divided by (compared with) the input current. The voltage gain is the output voltage divided by the input voltage. In order to have amplification, gain must be more than one.

Any individual amplifier has quite different figures for current gain, voltage gain, and power gain. In transistor circuits, gain also depends on how the transistor is connected. It can be used in a common-emitter, common-base, or common-collector circuit.

Current Gain

In the chapter on transistors you learned that in a common-emitter amplifier circuit, such as shown below, the current gain is $\beta = \frac{\Delta I_c}{\Delta I_b}$. This is also called the **common-emitter, forward-current transfer ratio** because, in a simple common-emitter circuit, it represents the current gain of the transistor (if the collector voltage is held constant).

COMMON-EMITTER CIRCUIT



As you know, α is the ratio of collector-current change to emitter-current change and is equal to $\frac{\Delta I_c}{\Delta I_e}$. It is also called the **common-base, forward-current transfer ratio.** If the transistor were connected in a common-base circuit, α would represent its current gain (with the collector voltage held at a constant value).

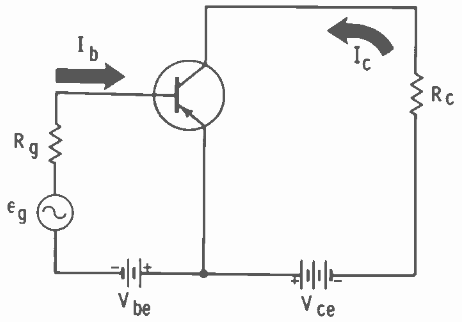
A transistor, when connected in a common-emitter circuit, has a current gain of β. This means that every change in the input (base-circuit) current is magnified β times in the collector circuit. Typical values of β range from 20 to 50. α (also called h_{fb}) and β (also called h_{fe}) are related to each other by the relations $\beta = \frac{\alpha}{1 - \alpha}$ and $\alpha = \frac{\beta}{1 + \beta}$.

Voltage Gain

In order to convert current amplification into voltage gain, it is necessary to know the resistances in the input and the output circuits.

In the diagram below, the load resistance is R_L, and R_g is the internal resistance of the AC signal source (e_g). The signal current in the base circuit is ΔI_b. Using Kirchhoff's law in the base circuit, the AC voltage between base and emitter is equal to the source voltage (e_g) less the voltage drop across R_g, or $e_g - \Delta I_b R_g$. The base-emitter voltage is also $\Delta I_b R_i$, where R_i is the input resistance of the transistor. Remember that R_i is a property of the transistor and not a separate resistance in the circuit.

COMMON-EMITTER CIRCUIT WITH AC SIGNAL SOURCE



The voltage across load resistance R_L (which is a separate property of the circuit) is $\Delta I_c R_L$, where ΔI_c is the signal current in the collector circuit.

The voltage gain can now be determined as the ratio of the voltage across the load resistance to the input voltage between emitter and base, or $\frac{\Delta I_c R_L}{\Delta I_b R_i}$. Note that $\frac{\Delta I_c}{\Delta I_b}$ is not β because the collector voltage must be constant when β is measured.

Q1. When an amplifier changes the characteristics of a signal other than the amplitude, this is called ___________.

Q2. When measuring the gain of an amplifier, output voltage must be compared with _____ _______, or output current must be compared with _____ _______.

Q3. To what is the voltage gain of a common-emitter amplifier equal?

Your Answers Should Be:

A1. When an amplifier changes the characteristics of a signal other than the amplitude, this is called **distortion.**

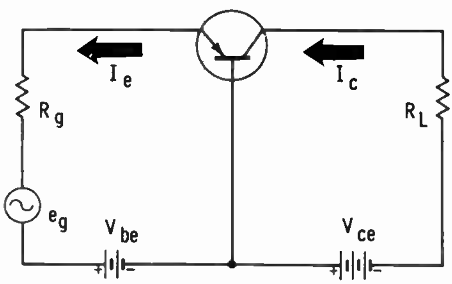
A2. When measuring the gain of an amplifier, output voltage must be compared with **input voltage,** or output current must be compared with **input current.**

A3. The voltage gain of a common-emitter amplifier is equal to $\frac{\Delta I_c R_L}{\Delta I_b R_i}$.

Signal Amplification

Now try to determine the voltage gain of a common-base amplifier circuit. Again, the voltage from emitter to base is e_g minus the voltage across R_g; that is, $e_g - I_e R_g$. This is also

COMMON-BASE CIRCUIT WITH AC SIGNAL SOURCE



equal to $\Delta I_e R_i$. The voltage across the load resistor is $\Delta I_c R_L$. The voltage gain in this case is $\frac{\Delta I_c R_L}{\Delta I_e R_i}$. Note that $\frac{\Delta I_c}{\Delta I_b}$ in this case is not α because the collector voltage does not remain constant.

Input Resistance

The preceding gain formulas make use of transistor input impedance R_i. This is the AC base-to-emitter resistance. It can be written as $R_i = \frac{\Delta V_{be}}{\Delta I_b}$ for the common-emitter circuit and $R_i = \frac{\Delta V_{be}}{\Delta I_e}$ for the common-base circuit. Since Kirchhoff's law holds true in the input-loop circuit, the source voltage (e_g) must be equal to the voltage drops across resistance R_g and across the transistor-input resistance. From this, resistance R_i can be figured as $\frac{\Delta e_g}{\Delta I_b} - R_g$ for the common-emitter circuit and the common-base circuit. The input resistance of a transistor is not a simple, fixed value that can be measured with an ohmmeter.

Power Gain

The power gain of a transistor amplifier can be calculated by multiplying the voltage gain by the current gain. The power gain of the common-emitter amplifier is therefore:

$$\left(\frac{\Delta I_c}{\Delta I_b}\right)\left(\frac{\Delta I_c R_L}{\Delta I_b R_i}\right) = \left(\frac{\Delta I_c}{\Delta I_b}\right)^2 \frac{R_L}{R_i}$$

The power gain of the common-base amplifier is:

$$\left(\frac{\Delta I_c}{\Delta I_e}\right)^2 \frac{R_L}{R_i}$$

The various gain formulas for the different types of transistor amplifiers are shown in the following table.

	Common Emitter	Common Base
Current Gain	$\frac{\Delta I_c}{\Delta I_b}$	$\frac{\Delta I_c}{\Delta I_b}$
Voltage Gain	$\frac{\Delta I_c}{\Delta I_b} \frac{R_L}{R_i}$	$\frac{\Delta I_c}{\Delta I_e} \frac{R_L}{R_i}$
Power Gain	$\left(\frac{\Delta I_c}{\Delta I_b}\right)^2 \frac{R_L}{R_i}$	$\left(\frac{\Delta I_c}{\Delta I_e}\right)^2 \frac{R_L}{R_i}$

Q4. What happens to the voltage gain of a common-base amplifier as the load resistance increases?

Q5. What effect would an increase in input resistance have on the voltage gain of a transistor amplifier?

Q6. If you knew the current gain and the voltage gain of an amplifier, how would you determine the power gain?

Your Answers Should Be:

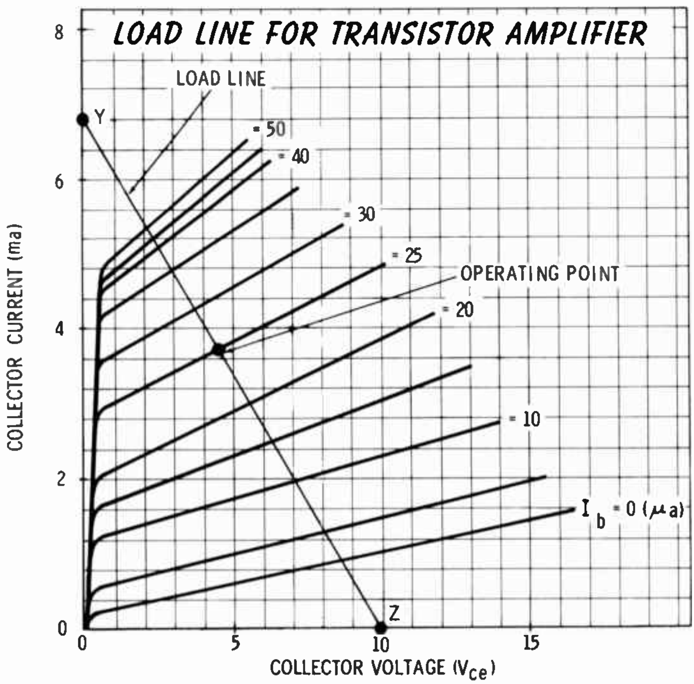
A4. An increase in load resistance causes an **increase in voltage gain,** provided other factors do not change.

A5. An increase in input resistance causes **a decrease in voltage gain,** provided other factors do not change.

A6. Power gain of an amplifier may be obtained by **multiplying the current gain times the voltage gain.**

OPERATING POINT

So far only the AC operation of transistor amplifiers has been considered. In the chapter on semiconductor devices you learned about transistor-characteristic curves of collector current (I_c) plotted against collector-emitter voltage (V_{ce}) for different constant values of base current (I_b).



When designing a transistor amplifier, it is often important to make certain that the transistor will operate on a linear (straight-line) portion of the curve; otherwise, the output will be distorted.

As with vacuum tubes, a set of transistor-characteristic curves can be used to determine the points on the curves between which it is desired for the transistor to operate. The point at which the load line intersects a suitable base-current line is chosen as the operating point of the transistor. This means that with no signal input (the quiescent state of the amplifier), the collector current, collector-to-emitter voltage, and base current will be at the values which determine the point on the curves. When a signal input is applied, the conditions change along a straight line passing through the operating point. The greater the input, the farther the operating conditions will swing from the operating point. The line along which the conditions move is the load line. Its slope is determined by the value of the load resistance. An example of an operating point and load line is shown on the opposite page.

Notice how similar the determination of the operating points for a transistor amplifier is to finding the operating points for a triode vacuum-tube amplifier.

Fixed Bias

Having determined from the curves where the operating point should be, the correct voltages and currents must be provided for operation at this quiescent point. This method is similar to the one used with vacuum tubes. In that case, the correct plate and grid-bias voltages were provided. In a transistor, the biasing consists of supplying a forward-bias voltage across the emitter-base junction and a reverse-bias voltage across the base-collector junction. These junction biases are essential for proper transistor operation.

Q7. What is a load line?

Q8. The point on the load line which shows the operating conditions of the transistor with no signal is the ---------- point.

Q9. The slope of the load line is determined by the ----------- of the ---- ---------.

Your Answers Should Be:

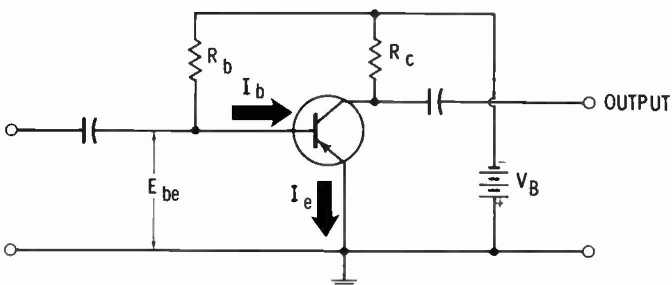
A7. A load line is a **line drawn on a set of characteristic curves. It shows the path followed by the operating point when** a **signal is applied.**

A8. The point on the load line which shows the operating conditions of the transistor with no signal is the **operating** point.

A9. The slope of the load line is determined by the **resistance** of the **load resistor.**

To establish the operating point on the characteristic curve, the correct values of collector voltage and emitter current must be supplied. This can be done using only one battery, as shown below, resulting in a **fixed-bias** circuit.

CIRCUIT FOR APPLYING FIXED BIAS

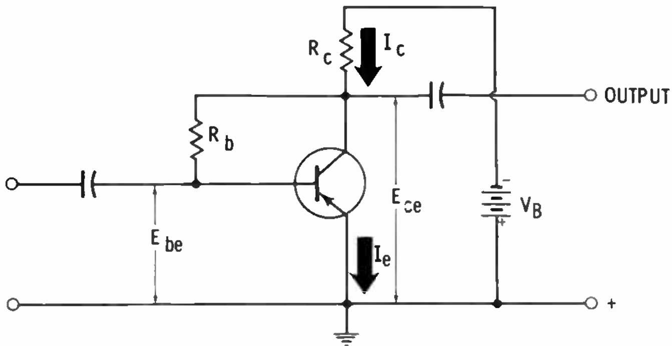


The base-bias voltage is obtained from resistor R_b. The resistance of R_b is $\frac{V_B - E_{be}}{I_b}$. Since E_{be} is usually small compared to V_B, it can be disregarded when determining biasing voltages. So $R_b = \frac{V_B}{I_b}$. I_b is the chosen quiescent base-current value. R_b is usually between 100K and 1 meg.

A disadvantage of the fixed-bias circuit is that the collector current varies with temperature changes. In addition, the current may not be the same for all transistors of the same type. Generally, it is necessary to provide compensation for the temperature effects on I_c, which is a highly temperature-sensitive quantity. As the temperature increases, the collector current also increases. This tends to heat the transistor, thus causing a further current increase. If this chain reaction is allowed to continue, a condition called **thermal runaway** may occur, and the transistor will be destroyed by excessive heat.

A temperature-compensating circuit is shown below. Although its gain is not as great as that of the previous circuit, it is more stable.

BIAS-STABILIZING CIRCUIT



If I_c increases in the above circuit, the voltage drop across R_c increases. Since the supply voltage (V_B) is relatively constant, E_{ce} must decrease as the voltage across R_c increases. The base-emitter junction and R_b are connected in series across E_{ce}. Therefore, the base current depends on E_{ce}. This means that as E_{ce} decreases, base current and I_c decrease, and the original increase in I_c is opposed.

Q10. If the operating temperature of a transistor rises, the collector current __________.

Q11. On the diagram above, trace the circuit that provides the base current.

Q12. If I_c increases, the voltage drop across R_c __________.

Q13. If I_c increases, the voltage between emitter and base __________.

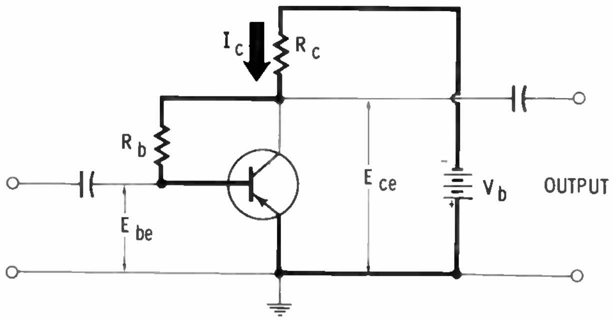
Q14. If the emitter-base voltage decreases, what effect will this have on the base current?

Q15. What effect will a decrease in the base current have on I_c?

Your Answers Should Be:

A10. If the operating temperature of a transistor rises, the collector current **increases.**

A11. The heavy line shows the base-current path.



A12. If I_c increases, the voltage drop across R_c **increases.**

A13. If I_c increases, the voltage between emitter and base **decreases.**

A14. If the emitter-base voltage decreases, this causes the base current to **decrease.**

A15. The decrease in base current will tend to **decrease** I_c.

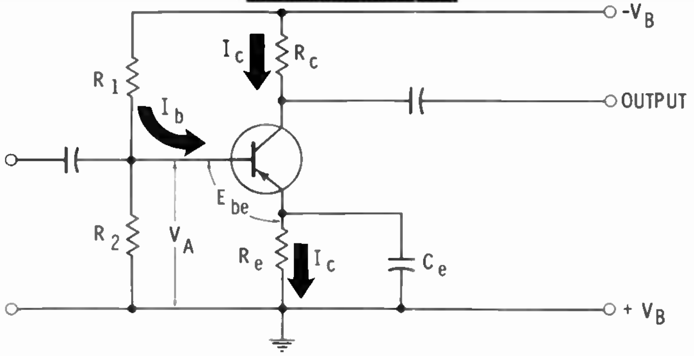
Emitter Stabilizing Resistor

Another very common stabilizing circuit uses a resistor in series with the emitter. Such a circuit is shown in the figure on the next page.

R_1 and R_2 form a voltage divider across voltage supply V_B, providing the base with a voltage $V_A = \frac{R_2}{R_1 + R_2} V_B$. (Current I_b is assumed to be so small that it can be neglected.) In order to have good compensation, V_A must remain unaffected by variations in I_b. This is done by choosing the resistance values so that the current through R_1 and R_2 is much larger than I_b.

Resistor R_e in the emitter circuit causes E_{be} to be reduced if I_c increases due to temperature changes. It does this because when I_c increases, the voltage across R_e also increases. When this happens, E_{be} is reduced because voltage V_A is very nearly constant. A drop in E_{be} then causes a decrease in I_b and in I_c.

CIRCUIT USING EMITTER STABILIZING RESISTOR



Capacitor C_e is connected across R_e to bypass the AC signal current. If this capacitor were not used, signal voltage would be present across R_e. If this happened, the action just described would tend to reduce the gain of the amplifier. This is one type of negative feedback and is the same action that takes place in a triode amplifier in which the cathode resistor is not bypassed.

Although the input resistance of a common-emitter amplifier is usually about 1,000 ohms, the voltage divider reduces this to about 750 ohms.

Q16. Because of the voltage divider formed by resistors R_1 and R_2, the voltage between base and ground (V_A) will always equal ________.

Q17. The voltage between base and emitter equals V_A minus the voltage drop across resistor ____.

Q18. In the circuit above, what effect will an increase in collector current have on the voltage between the emitter and the base?

Q19. In the circuit above, what effect will an increase in collector current have on base current?

Your Answers Should Be:

A16. Because of the voltage divider formed by resistors R_1 and R_2, the voltage between base and ground (V_A) will always equal

$$\frac{R_2}{R_1 + R_2} V_B$$

A17. The voltage between base and emitter will equal V_A minus the voltage drop across resistor R_e.

A18. If the collector current increases, the voltage between the emitter and the base will then **decrease.**

A19. If the collector current increases, the base current will then **decrease.**

TWO-STAGE AMPLIFIERS

Often a single-transistor amplifier will not give the necessary amount of amplification. In this case, two or more amplifiers can be connected together to form a two-stage, three-stage, or longer chain. Each stage adds a share of amplification to the total. For the purpose of explanation, only two stages will be considered.

To have a two-stage amplifier, some method for feeding the output of the first stage to the input of the second stage is needed. In choosing an interstage coupling network, the following factors must be considered.

Frequency response—The network must have an equal effect on each of the desired frequencies. It is also sometimes necessary to filter out, or remove, all other frequencies. The range of desired frequencies is called the **passband.**

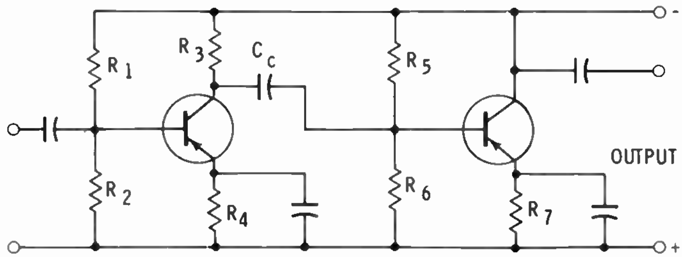
Impedance matching—The network should present the correct output impedance to the first stage for maximum gain. It should also present the correct impedance to the second-stage input so that maximum energy transfer can take place.

Operating points—The two stages may require different voltages, currents, and polarities to establish their best operating points. The interstage coupling network should be such that the DC conditions in the separate stages are not affected by each other.

RC-Coupled Amplifiers

The simple, small-signal, audio-frequency amplifier shown below has two stages with resistor-capacitor coupling. Each of the two stages is stabilized by the familiar voltage-divider method.

RC-COUPLED TRANSISTOR AMPLIFIER



The output of the first stage is developed as a voltage across the load resistor (R_3) and is fed to the base circuit of the second stage through coupling capacitor C_c. This capacitor represents an open circuit to all DC voltages. Thus, the biasing circuits of the two stages are not influenced by the DC voltages on the other elements.

The value of coupling capacitor C_c determines the lower limit of the passband of the complete amplifier. There is no abrupt cutoff point. The response of the unit decreases gradually as the frequency decreases. For practical purposes this lower frequency limit is usually taken as the frequency at which the capacitive reactance of C_c equals the total resistance in series with C_c. This total resistance is the sum of the output resistance of the first stage and the input resistance of the second stage.

Q20. Which resistors stabilize the transistors in the circuit above?

Q21. Can DC signals pass from stage to stage? Why?

Q22. The capacitor does not pass ___ frequencies readily.

Your Answers Should Be:

A20. Resistors R_4 and R_7 provide stabilization.

A21. DC signals cannot pass from stage to stage **because the coupling capacitor blocks them.**

A22. The capacitor does not pass **low** frequencies readily.

The gain of a two-stage amplifier is the product of the gains of the individual stages. If something is increased 25 times and then the result of that increase is, in turn, increased 25 times, the final result will be an increase of 625 times the original quantity. If each stage of a two-stage transistor amplifier has a gain of 25, the total gain is $25 \times 25 = 625$.

The gain of each stage depends on its load resistance. When a second stage is connected to the output, the effective load resistance of the first stage is lowered. This is because the load resistance is in parallel with the input resistance of the next stage.

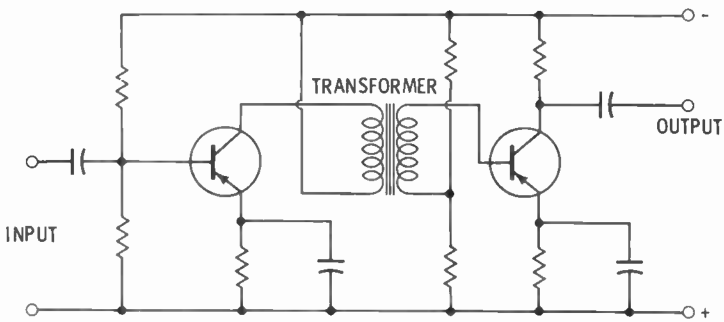
Suppose the load resistor of the first stage is 3,000 ohms and the input resistance of the second stage is 1,000 ohms. The **effective** load resistance of the first stage is the parallel combination of these two resistances, or $\frac{3{,}000 \times 1{,}000}{3{,}000 + 1{,}000} =$ 750 ohms. The first-stage gain is then reduced by $\frac{750}{1{,}000}$, or 0.75. If the first-stage gain was 25 before the second stage was added, then its actual gain is only $0.75 \times 25 = 18.75$ after the second stage is added.

Transformer-Coupled Amplifier

RC-coupled amplifiers are suitable for providing voltage amplification when the gain does not need to be very high. For somewhat higher gain, a **transformer-coupled** amplifier can be used, such as the circuit shown on the next page. Notice that the transformer does not pass DC. As with the RC-coupled amplifier, the gain of a transformer-coupled amplifier decreases at both the low- and high-frequency ends of the frequency range.

In order to get maximum energy transfer from the first stage to the second, it is desirable to choose a coupling transformer with a turns ratio that matches the output resistance of the first-stage transistor (usually about 25K) to the lower input resistance of the second-stage transistor (about 1,000 ohms).

TRANSFORMER-COUPLED TRANSISTOR AMPLIFIER



Suppose the output impedance of the first stage is 25K and the input impedance of the second stage is 1,000 ohms. What turns ratio would the coupling transformer need? In a transformer, the impedance ratio is equal to the square of the turns ratio. The required turns ratio may be calculated as follows:

$$\frac{N_1^2}{N_2^2} = \frac{Z_1}{Z_2} = \frac{25{,}000}{1{,}000}$$

$$\frac{N_1}{N_2} = \sqrt{\frac{25}{1}} = \frac{5}{1}$$

The turns ratio should therefore be 5 to 1.

Q23. If the gain of each stage of an amplifier is known, how would the gain of the amplifier be calculated?

Q24. When RC coupling is used between two stages, what effect does adding the second stage have on the gain of the first stage?

Q25. Transformer coupling permits -------- gain than RC coupling.

Q26. How can impedance matching between amplifier stages be obtained?

Your Answers Should Be:

A23. The gain of an amplifier is calculated by **multiplying the gain values of the individual stages** in the amplifier.

A24. When RC coupling is used between stages, **the input impedance of the second stage is in parallel with the load resistance of the first stage.** This reduces the load seen by the first stage and therefore **reduces the gain of the first stage.**

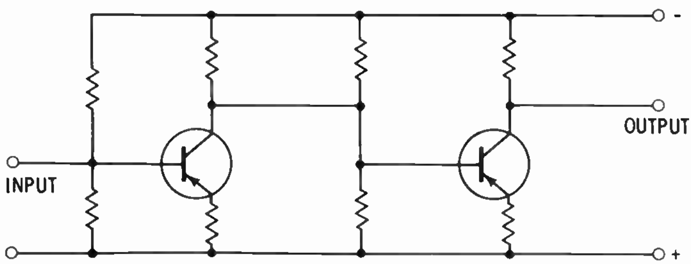
A25. Transformer coupling permits **greater** gain than RC coupling.

A26. **A coupling transformer** can be used to match the output impedance of the first stage to the input impedance of the second stage.

Direct-Coupled Amplifiers

It is sometimes necessary to amplify signals that include very low frequencies, even DC. Low frequencies and DC

DIRECT-COUPLED TRANSISTOR AMPLIFIER



cannot be amplified when capacitors or transformers are used for interstage coupling. But amplifiers can be coupled without using capacitors or transformers. Connecting the collector of the first stage directly to the base of the next stage, as shown above, is known as **direct coupling.** Such amplifiers are called **direct-coupled amplifiers, direct-current amplifiers,** or simply **DC amplifiers.**

Coupling the collector of the first stage directly to the base of the second stage presents several special problems. The base of the second stage is placed at the same potential as the collector of the first stage. Such an arrangement is acceptable only if the emitter and collector voltages of the second stage can be adjusted to provide the required operating bias.

The fact that the biasing voltages of the two stages are not isolated from each other makes for a more complicated power-supply circuit. This is because the operating point for each stage must be adjusted without causing any interaction with the other stages. The power supplies must also be very accurate and stable. A DC amplifier will amplify DC voltages, so any power-supply variations will be transmitted from stage to stage and thus affect the final output of the amplifier.

The DC amplifier is usually intended to deliver an output that is proportional to the input signal. The amplification should be constant. It is very important that when the input is zero, the output is also zero. This is made difficult by the fact that there are no blocking capacitors or transformers between the stages. Any change in the operating point of one stage therefore affects all the other stages. Such a change may be brought about by temperature variations, which always affect the collector **leakage** current (I_{co}) of a transistor.

As a result, it is very important to use good temperature-compensating and stabilizing circuits in a DC amplifier. Otherwise **drift** results, and the output is no longer strictly proportional to the input.

The resistors shown in the emitter leads are used for stabilization. There are no bypass capacitors because this circuit is used for low frequencies where the capacitors would have a very high reactance and therefore would not pass a signal.

Q27. Why are RC- and transformer-coupled amplifiers not suitable for amplifying very low-frequency signals?

Q28. When is it acceptable to connect the collector of one stage of a transistor amplifier directly to the base of the next stage?

Q29. When the input to a DC amplifier is zero, the output should be ____.

Your Answers Should Be:

A27. RC- and transformer-coupled amplifiers are not suitable for amplifying very low-frequency signals because the **coupling capacitors or transformers block these signals.**

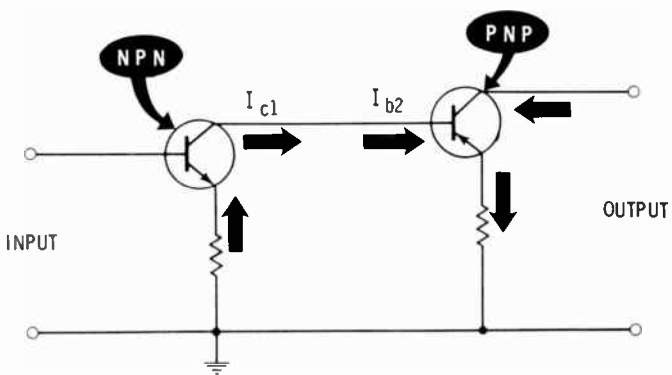
A28. The collector of one stage may be connected to the base of a second stage **if the emitter and collector voltages of the second stage can be adjusted to maintain the proper bias.**

A29. When the input of a DC amplifier is zero, the output should be **zero.**

Complementary Circuits

One way of coupling the stages of a DC amplifier takes advantage of the fact that there are two types of transistors—PNP and NPN. This type of circuit alternates the two kinds and is known as a **complementary** circuit.

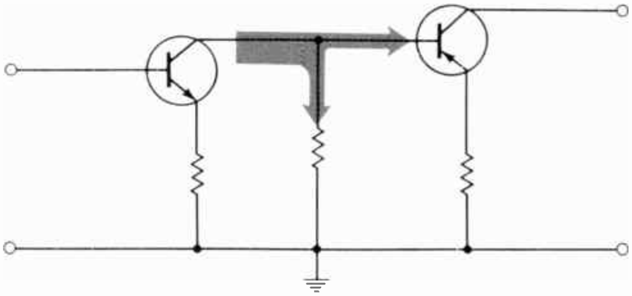
COMPLEMENTARY DC-AMPLIFIER CIRCUIT



In the NPN transistor of the first stage, the collector current flows out of the transistor. In the base circuit of the second-stage PNP transistor, the base circuit flows into the transistor. If the NPN collector is coupled directly to the PNP base, the current between them flows in the same direction. (For simplicity the power supplies are not shown on the diagram.)

It is sometimes necessary to have a first-stage collector current that is considerably larger than the base current of the second stage. This can be taken care of by bypassing some of the current with a resistor, as shown below.

COMPLEMENTARY AMPLIFIER WITH COLLECTOR CURRENT GREATER THAN BASE CURRENT



Tuned Amplifiers

Tuned amplifiers amplify only a narrow band of frequencies (i.e., a small frequency range as compared to the center frequency). Thus, tuned amplifiers are **selective.**

Tuned amplifiers are used widely in communications applications, such as radio and television receivers, to amplify RF and IF frequencies. Tuned amplifiers make it possible to select one desired station from among a group of many stations whose signals may reach the receiver. Tuned circuits make possible the separation of sound and picture signals in a TV receiver. In transmitters, tuned amplifiers are used to generate large amounts of power at the assigned frequency of the station.

Q30. In the circuit on the opposite page, what is the relationship between the base current of the second stage and the collector current of the first stage?

Q31. What would be the purpose of a resistor between the base of the second stage and ground?

Q32. Tuned amplifiers are designed to amplify only a ______ ____ of frequencies.

Your Answers Should Be:

A30. The base current of the second stage and the collector current of the first stage **are identical.**

A31. A resistor between the base of the second stage and ground would bypass some of the current so that the **base current of the second stage would be less than the collector current of the first stage.**

A32. Tuned amplifiers are designed to amplify only a **narrow band** of frequencies.

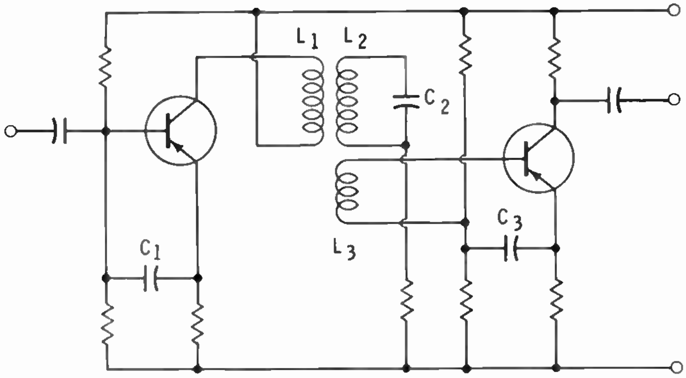
Selectivity, or tuning, is achieved in tuned amplifiers by using coupling networks that are essentially filters. That is, they pass energy between stages only in a narrow frequency band and reject signals at all frequencies outside this band. These coupling networks are almost always **parallel-resonant** (tuned) circuits. A parallel-resonant circuit has a high impedance at and near its resonant frequency. The current output of the first stage develops a voltage across the tuned circuit only in a very narrow tuned band. Therefore the following stage receives an input current only for signals in this frequency band.

The same principle is used in vacuum-tube tuned amplifiers. These are easier to build because tube amplifiers have high input and output resistances. The problem is more difficult with transistors because they have a relatively low resistance at both input and output. When a transistor amplifier stage is coupled to a parallel-resonant circuit, the low resistance of the transistor reduces the Q of the resonant circuit. This reduces the selectivity.

This makes it necessary to design a circuit that will somehow match the resistances of the stages and still leave the effective Q of the coupling as high as possible for adequate selectivity. Such a circuit is shown on the next page. This is a single-tuned amplifier using a resonant circuit having a **tertiary** (third) winding. The tuned circuit (L_2C_2) is transformer-coupled to the collector circuit of the first transistor through windings L_1 and L_2. It is coupled to the base circuit of the second transistor through windings L_2 and L_3. To secure the maximum energy transfer between stages, the winding ratios must match the first-transistor output resistance to the second-transistor input resistance.

Selectivity is provided in this circuit by tuned circuit L_2C_2. When a signal at the resonant frequency is applied, a large current circulates between the capacitor and inductor

TUNED TRANSISTOR AMPLIFIER



of the tuned circuit. Energy is easily transferred to L_3 by transformer action. At all other frequencies the circulating current is much less, and the energy transfer is very low.

In actual practice, it is also necessary to use other components in transistor circuits. One of the component networks often used is for counteracting signal feedback from output to input. Such components form what are known as **unilateralization** networks.

Q33. A parallel-resonant circuit has a ____ impedance at resonance.

Q34. What effect does connecting a transistor-amplifier stage to a tuned circuit have on the Q of the tuned circuit?

Q35. Another name for a third winding is ________ winding.

Q36. What determines the selectivity of a tuned amplifier?

Q37. Unilateralization networks are used to prevent ________.

Your Answers Should Be:

A33. A parallel-resonant circuit has a **high** impedance at resonance.

A34. Connecting a transistor amplifier stage across a tuned circuit **lowers the Q of the circuit.**

A35. Another name for a third winding is **tertiary** winding.

A36. The selectivity of a tuned amplifier is determined by the **Q of the resonant circuit.**

A37. Unilateralization networks are used to prevent **feedback.**

WHAT YOU HAVE LEARNED

1. The voltage gain of a transistor amplifier depends on its current gain and on the ratio of its load resistance to its input resistance.
2. The input resistance of a transistor amplifier is a property of a particular circuit.
3. An operating point for a transistor is selected by drawing a load line through a set of characteristic curves.
4. To maintain the desired operating point, the appropriate base current, collector-emitter voltage, and collector current must be provided.
5. A fixed-bias circuit uses a single power source and voltage-dropping resistors.
6. Voltage-divider stabilizing circuits can compensate for the effects of temperature changes.
7. The low-frequency response of an RC-coupled amplifier is limited by the coupling capacitor.
8. RC coupling passes only AC signals.
9. Transformer coupling affects the frequency response of the amplifier and passes only AC.
10. DC coupling will pass low-frequency or DC signals but complicates the biasing arrangements in doing so.
11. NPN and PNP transistors can be combined in a DC-coupled amplifier to simplify the biasing problems.
12. Parallel-resonant circuits are used in tuned amplifiers.

7

Pulse Circuits

What You Will Learn

In this chapter you will learn how pulse circuits differ from sine-wave circuits. The importance of transient response in pulse circuits will be discussed. You will discover how pulse circuits can count, add numbers, shape waveforms, and act as switches. You will learn to recognize these circuits and how to diagram some of them. You will also learn some of the applications for pulse circuits.

WHAT ARE PULSE CIRCUITS?

You have already learned about power-supply circuits, in which AC is converted to specific DC voltages. You have also studied amplifier and oscillator circuits that are designed to generate and amplify sine-wave signals. These circuits are used extensively in electronics, especially in radiocommunications, television, and the reproduction of sound.

By contrast, pulse circuits are designed to handle **nonsinusoidal** signals. Typical signals found in pulse circuits are square waves, sawtooth waves, spike voltages, and wide rectangular pulses. Pulse circuits are used to count and perform mathematical operations; for switching, for example in dial-telephone systems; and to synchronize the operation of other circuits. In television and radar, for example, many different circuits must be turned on and off at exactly the same moment for the system to operate properly.

All pulse waveforms are actually complex combinations of sine-wave frequencies. This means that the frequency response of a circuit is important to proper pulse waveform reproduction. Pulse circuits must often respond well to a very wide band of frequencies. Pulse signals are often large compared to sine-wave signals, and signal levels often change from cutoff to saturation (from one end of the load line to the other) almost instantaneously.

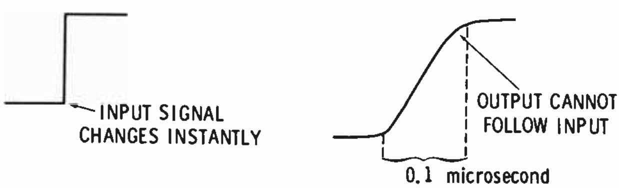
TRANSIENT OPERATION

Transient operation describes the way circuits and components react to rapid changes in signal level. In radio circuits, tubes and transistors usually operate along the linear portion of their characteristic curves, and the transient operation of the tube or transistor is not very important.

On the other hand, pulse-circuit operations normally involve large signals. This means that amplifier operation may change very rapidly from a nonconducting state to the saturated stage, or vice versa. The transient response of tube and transistor circuits in either of these extreme states is most important in pulse-circuit operation.

The time required to turn a tube or transistor on may be as short as 0.08 to 0.10 microsecond. Turn-off time may be as short as 0.10 to 0.12 microsecond. But pulses often rise and fall sharply. Their entire duration may be measured in microseconds. Therefore, the time it takes for electrons to

LIMITED TRANSIENT RESPONSE OF A TRANSISTOR



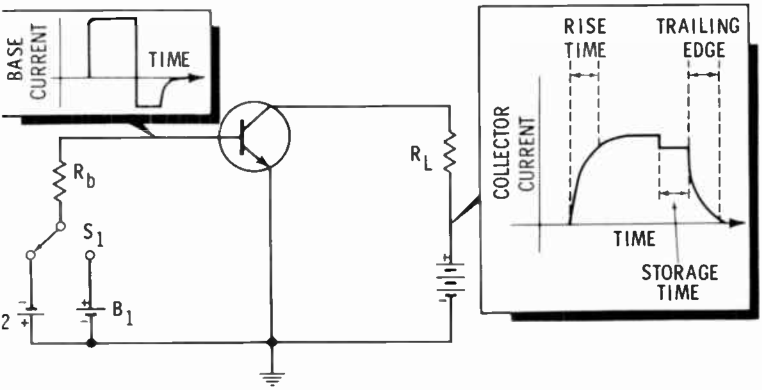
travel from cathode to plate in a vacuum tube is no longer negligible. For the same reason, the time for holes or electrons to diffuse from emitter to collector in a transistor must be considered.

Other factors affecting transient performance are the load impedance, the transistor- or tube-element capacitances, and the operating conditions before the arrival of the pulse.

TRANSISTOR TRANSIENT OPERATION

The figure below shows an NPN transistor connected as a ommon-emitter amplifier. With switch S_1 as shown, the mitter-base junction is reverse-biased, and no collector curent flows. When S_1 is switched to the other position, the

TRANSIENT RESPONSE OF A CIRCUIT



oltage of battery B_1 forward-biases the emitter-base junc-ion. The base current quickly reaches maximum. The colector current also increases. The time required for it to ncrease from 10% to 90% of maximum is the **rise time.**

When S_1 is returned to its original position, the base curent drops quickly and overshoots. This reversal is due to he minority carriers stored in the base during the forwardias period. The reverse polarity of battery B_2 causes a everse-current flow. The collector current does not change mmediately during base-voltage cutoff. This delay is called **torage time.** It is the time required to collect the minority arriers remaining in the base.

As the current in the base decays, so does the current in he collector. This portion of the waveform is referred to s the **trailing edge.** The time it takes the trailing edge to lecrease from 90% to 10% of the maximum collector curent is the **decay time.**

Q1. What period might also be called "fall time"?

Q2. Pulse signals usually have _____ amplitudes.

Q3. A pulse amplifier must have a ____ bandwidth.

Your Answers Should Be:

A1. The **decay** time may also be called fall time.

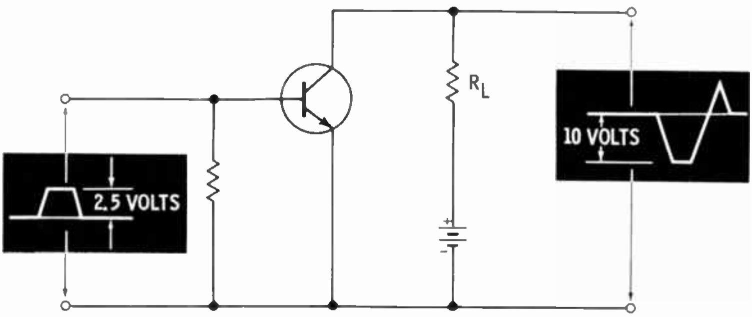
A2. Pulse signals usually have **large** amplitudes.

A3. A pulse amplifier must have a **wide** bandwidth.

TRANSISTOR STATES

A transistor can be operated in the cutoff, active, or saturated state. Consider the circuit below. In the **cutoff** state, no collector current flows. This condition exists when there is no current through the base-emitter junction. The **active** state is the operating condition of the transistor in which it can be used as an amplifier. This is the state you studied in an earlier chapter. In the **saturated** state the transistor has reached a point where an increase in the input can produce no further increase in the output.

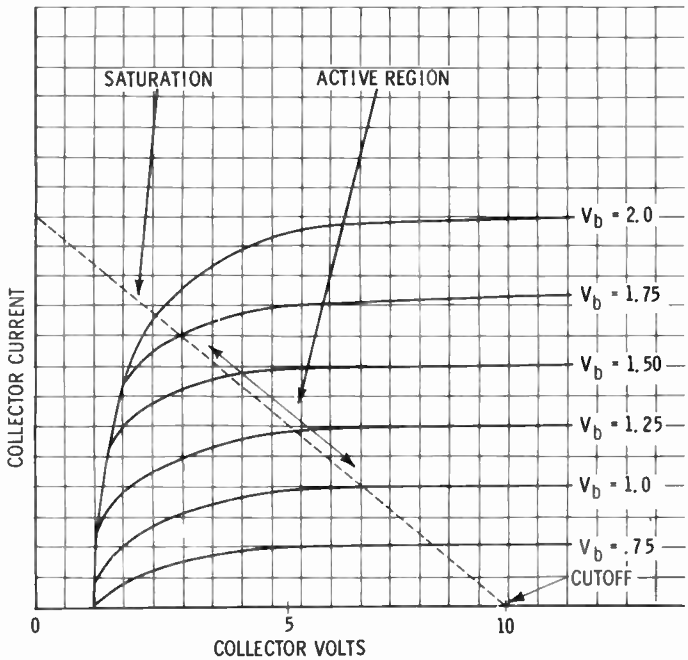
A PULSE-AMPLIFIER CIRCUIT



With no signal applied to the base in the circuit above, no collector current flows (neglecting leakage). The transistor is in the cutoff state. With a large signal applied to the base, the transistor rapidly passes through the active state into the saturated state, and maximum current flows. The collector current rises at a rate that depends on capacitance, electron-hole diffusion time, and load impedance. The collector voltage decreases due to the voltage drop across R_L. Now collector current is at maximum. The collector voltage is lower than the 2.5-volt base voltage. Both junctions are now forward-biased.

Cutoff occurs at the maximum-voltage end of the transistor load line (see below). Saturation occurs near the maximum-current end, although the current at saturation never reaches the theoretical maximum. The cutoff and sat-

TRANSISTOR CHARACTERISTIC CURVES



uration regions are called the **quiescent** and **stable** states, respectively. When the emitter-base and collector-base junctions are reverse-biased, the transistor is in the quiescent state. When both junctions are forward-biased, the transistor is in the saturated state.

Q4. A transistor can be operated in the ______, ______, or __________ state.

Q5. In the circuit just discussed, the collector voltage __________ when the collector current increases.

Q6. When both junctions are forward-biased, the transistor is in the __________ state.

Your Answers Should Be:

A4. A transistor can be operated in the **cutoff**, **active**, or **saturated** state.

A5. In the circuit just discussed, the collector voltage **decreases** when the collector current increases.

A6. When both junctions are forward-biased, the transistor is in the **saturated** state.

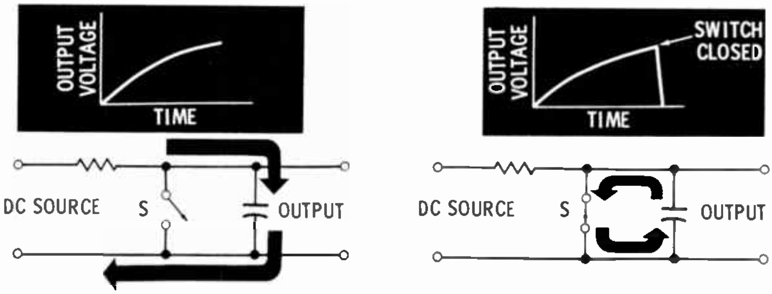
PULSE GENERATION

There are many ways of generating pulse signals. The telegraph key and the telephone dial are two common mechanical devices that are used in the generation of pulses. Both are simple switches that open and close circuits, thus generating rectangular pulses.

Sawtooth Generator

Accurately timed and shaped pulses are generated in electronic circuits. One good example is the sawtooth **generator**. Its operating frequency and output waveshape are controlled by the charging and discharging of an RC, RL, or RCL circuit.

SAWTOOTH-GENERATOR ACTION

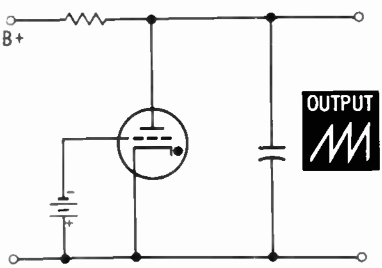


CHARGE ***DISCHARGE***

Most sawtooth generators use RC circuits. You have learned that a capacitor takes a certain amount of time to charge through a resistor. This time is determined by the RC time constant of the particular combination. If a capacitor is charged until the voltage across it reaches a given level and then allowed to discharge quickly, a sawtooth voltage results. The voltage gradually builds up until it reaches the discharge voltage—then it suddenly decreases to zero. The three requirements of a sawtooth generator are a power source, an RC circuit, and a voltage-controlled switch.

A gas-filled tube called a **thyratron** can act as a voltage-controlled switch. The thyratron conducts only when its plate voltage reaches a certain level. The more negative the grid is with respect to the cathode, the higher the plate potential must be to start conduction. After firing, the thyratron continues to conduct until its plate voltage has dropped to a specific lower value, called the **extinction potential.** The extinction potential depends mainly on the type of tube used.

A THYRATRON SAWTOOTH GENERATOR



During conduction, the thyatron has practically zero impedance. When not conducting, the thyratron presents a very high impedance. With power applied to the RC circuit, the capacitor charges exponentially. When the capacitor voltage reaches the necessary potential, the thyratron conducts. This discharges the capacitor quickly. When the plate voltage drops to the extinction potential, the thyratron stops conducting. This starts the charging cycle over again. The output voltage varies between the conduction and extinction voltages at a frequency determined by the time constant of the RC circuit, the supply voltage, and the grid voltage.

Q7. What factors affect the frequency of a sawtooth generator?

Your Answer Should Be:

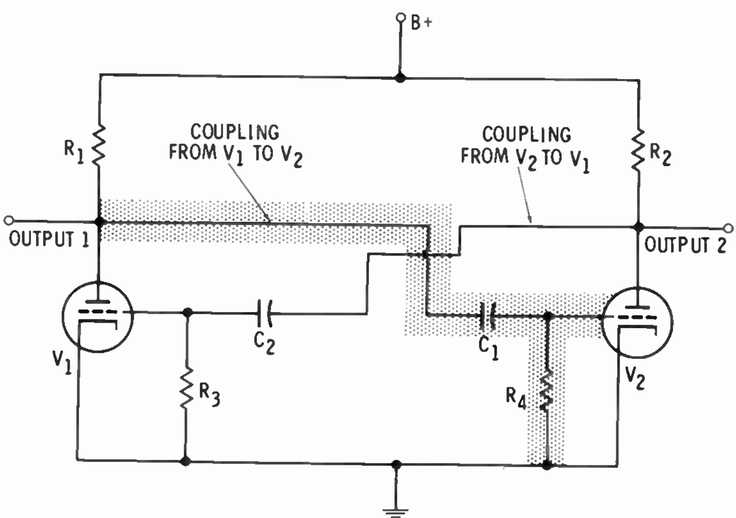
A7. The frequency of a sawtooth generator is determined by the **charging voltage applied to the RC circuit**, by the **R and C** values (which determine the RC time constant), and by the **grid voltage of the thyratron.**

Multivibrators

The **multivibrator** is a circuit used to generate square or rectangular pulses. Like the sawtooth generator, its frequency is determined by the time constant of an RC circuit. Like a conventional sine-wave oscillator, it makes use of positive feedback.

A basic multivibrator is a simple two-stage, RC-coupled amplifier in which the output of the second stage is coupled back to the input of the first stage. This forms a closed loop. The output signal of the first stage (output 1) is RC-coupled to the grid of the second stage (input 2). The output signal of the second stage (output 2) is RC-coupled to the grid of the first stage (input 1).

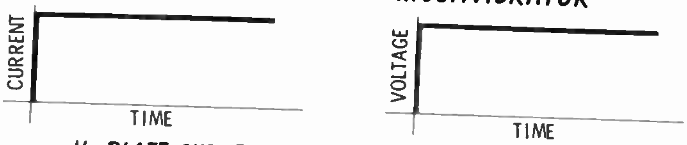
A MULTIVIBRATOR CIRCUIT



How does this circuit work? When the B voltage is applied, both tubes begin to conduct, as in a normal amplifier. If the current in both tubes were precisely the same, that is all that would happen. However, because of slight differences in the tubes or other components, one tube will conduct a little more than the other.

For example, if V_1 begins to conduct slightly more than V_2, this increase in conduction becomes an input signal to V_2, causing V_2 to conduct less. This decrease in conduction of V_2 then becomes an input signal to V_1, causing it to conduct more heavily. This process continues until V_2 is very quickly cut off.

IDEAL SWITCHING IN A MULTIVIBRATOR



V_1 PLATE CURRENT V_2 PLATE VOLTAGE

The entire initial action—one tube reaching maximum conduction and the other being cut off—occurs almost instantly. If the voltage across V_2 is used as the output of this circuit, it will have changed from minimum to maximum value very quickly.

Q8. If V_1 begins to conduct slightly more than V_2, what happens to the voltage drop across R_1?

Q9. The plate of V_1 becomes (more, less) negative with respect to B+.

Q10. When this signal is coupled through C_1 to the grid of V_2, the grid of V_2 becomes more (positive, negative).

Q11. This causes the plate current in V_2 to ________.

Q12. This causes the voltage drop across R_2 to ________.

Q13. The plate of V_2 becomes (more, less) negative with respect to B+.

Q14. When this signal is coupled through C_2 to the grid of V_1, the grid of V_1 becomes ____________.

Q15. What effect does this have on current through V_1?

Your Answers Should Be:

A8. If V_1 begins to conduct slightly more than V_2, the voltage drop across R_1 **increases.**

A9. The plate of V_1 becomes **more** negative with respect to B+.

A10. When this signal is coupled through C_1 to the grid of V_2, the grid of V_2 becomes more **negative.**

A11. This causes the plate current in V_2 to **decrease.**

A12. This causes the voltage drop across R_2 to **decrease.**

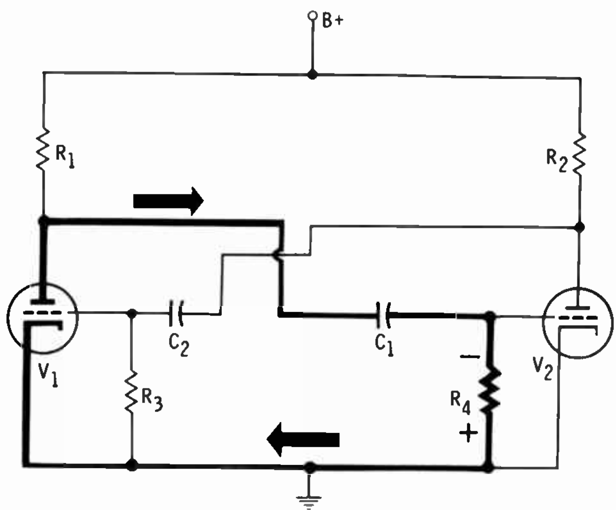
A13. The plate of V_2 becomes **less** negative with respect to B+.

A14. When the signal is coupled through C_2 to the grid of V_1, the grid of V_1 becomes **less negative.**

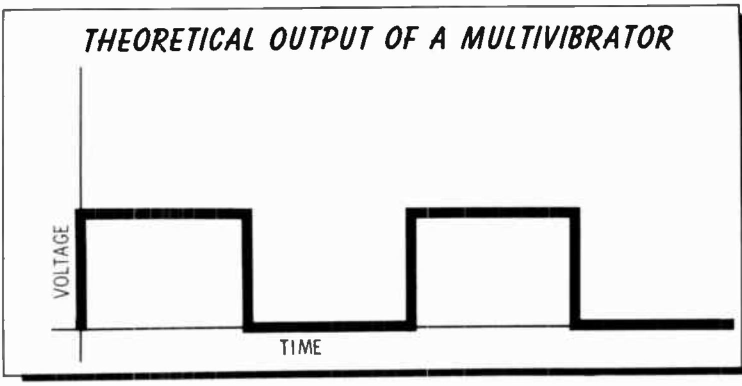
A15. This **increases the current through** V_1.

In the first step of the circuit action, V_2 goes to cutoff and V_1 conducts heavily. When the tubes reach this steady state and the signals are no longer changing, the RC coupling is no longer effective. The voltage holding V_2 in its cutoff state will gradually diminish.

DISCHARGE PATH IN A MULTIVIBRATOR



It is easy to see what happens if you look at the coupling between V_1 and V_2. The grid of V_2 was driven negative by the changing plate voltage of V_1, coupled through C_1. When the plate voltage of V_1 stops changing, the grid of V_2 is held negative by the charge of coupling capacitor C_1. But C_1 discharges gradually through V_1, which is conducting heavily, and R_4. When V_2 begins to conduct, a process exactly like the first step begins. V_1 is driven to cutoff, and V_2 begins to conduct heavily. Then the coupling capacitor between V_2 and V_1 will discharge, and the cycle will repeat itself.



To review, a basic multivibrator is two amplifiers RC-coupled to each other. When they begin to operate, one is immediately driven to cutoff and the other conducts heavily. They continue in this state until the RC coupling network discharges enough to permit the cut-off amplifier to again conduct. When this happens, the first amplifier is driven to cutoff and the second conducts heavily. The two amplifiers continue to alternate conducting states at a rate determined by the time constant of the RC coupling networks.

Q16. The rate at which C_1 discharges is determined by the ____ ________ of the RC coupling network.

Q17. What happens to the current in V_2 as C_1 discharges?

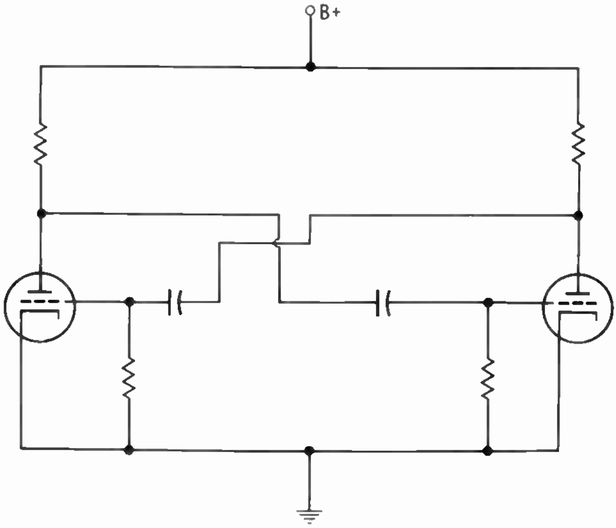
Q18. Draw a schematic of a basic multivibrator. Begin by drawing a two-stage, RC-coupled amplifier, and then add the extra coupling circuit.

Your Answers Should Be:

A16. The rate at which C_1 discharges is determined by the **time constant** of the RC-coupled network.

A17. As C_1 discharges, the grid voltage of V_2 **decreases.** When the grid voltage passes the cutoff level, V_2 **begins to conduct.**

A18. Your schematic should look like this.



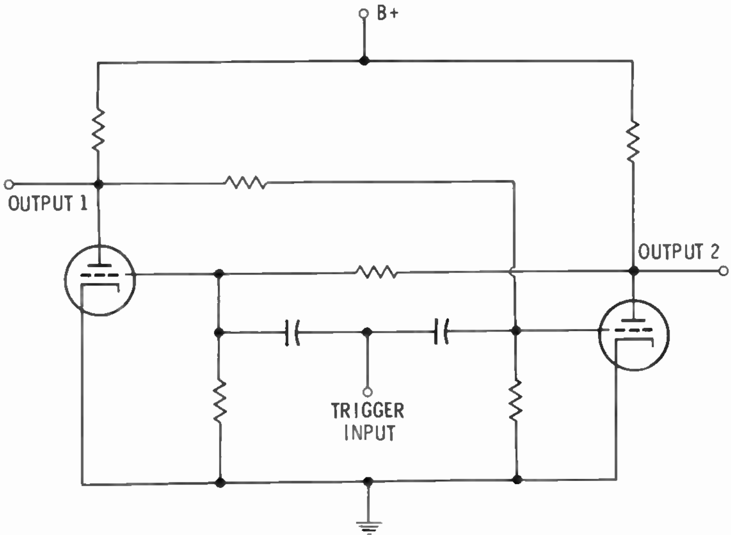
Bistable Multivibrators

A **bistable multivibrator, or flip-flop,** is a very useful variation of the basic multivibrator. As you will see later in this chapter, it is one of the basic circuits of digital computers.

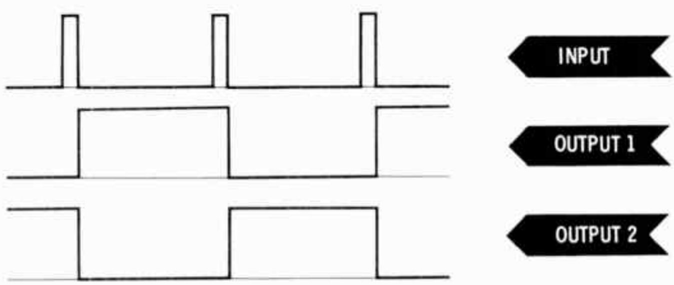
Like the basic multivibrator, the bistable multivibrator consists of a two-stage amplifier with its output coupled to its input. The difference between the two circuits is that the stages are direct-coupled instead of RC-coupled. Thus, there are no coupling capacitors to charge and discharge and control tube conduction. Once the circuit has assumed one state, it stays that way until an outside signal is applied to start the changeover process. Then the multivibrator "flips" or "flops" into the opposite state.

In the circuit below, a positive pulse at the trigger input will have no effect on the tube that is already conducting, but it will cause the cut-off tube to start conducting and thus initiate the changeover process.

A BISTABLE-MULTIVIBRATOR CIRCUIT



BISTABLE-MULTIVIBRATOR ACTION



Q19. Which tube in a bistable multivibrator will be affected by a negative pulse? How will it be affected?

Q20. How many input pulses are required to produce a single output pulse from a bistable multivibrator?

Your Answers Should Be:

A19. A negative pulse will **cause the conducting tube to conduct less.** This will, in turn, allow the other tube to start conducting a little, and the **change-over process will take place.**

A20. **One input pulse** is required to turn the cut-off tube of a bistable multivibrator **on** and a **second input pulse** is required to turn it **off.** Thus, **two input pulses are required to produce one output pulse** from a bistable multivibrator.

PULSE-CIRCUIT APPLICATIONS

One of the most important uses of pulse circuits is for various kinds of switching. In these applications, pulse circuits simply turn each other or other circuits on and off. Other pulse circuits are used for counting or to change the shape of waveforms.

Electronic Switches

An ideal switch has infinite resistance when open and zero resistance when closed. Also, it has a means of being opened and closed. Vacuum tubes and transistors can act as switches that are opened and closed electronically. Instead of increasing and decreasing an output signal according to the variations of an input signal, the output is turned on or off. The tube or transistor is made to go from cutoff to saturation and vice versa instead of operating in its linear amplification region.

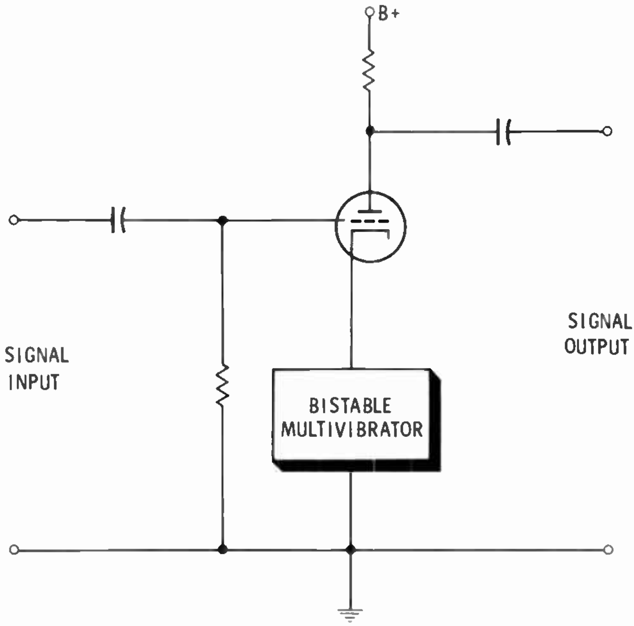
Electronic switches operate much faster than mechanical switches. Using mechanical and relay switches in a device such as a computer would make it too slow to be useful. Electronic switches operate rapidly and silently, are more sensitive than mechanical ones, and have no moving parts or contacts to wear out.

Vacuum-Tube Switch

The illustration on the next page shows an electronic switch that can be turned on or off by a single pulse. The input signal will be amplified only when the electronic switch is closed.

The triode is connected to one of the outputs of the bistable multivibrator. When the multivibrator is in one state, the triode amplifies in the usual way. This is because of the voltage applied to the cathode. The amplifier can be turned off by applying a pulse to the multivibrator, causing it to change states. Now the multivibrator output applies

A SIMPLE SWITCHING CIRCUIT



a large positive voltage to the cathode. This has the same effect as making the grid negative, and the tube is cut off. Another pulse to the multivibrator causes it to change states again, the cathode of the tube is returned to its operating voltage and the tube is able to amplify.

Q21. In switching circuits, tubes and transistors operate from ______ to ___________.

Q22. In the circuit above, switching action depends on changing the voltage of the _______.

> **Your Answers Should Be:**
>
> **A21.** In switching circuits, tubes and transistors operate from **cutoff** to **saturation.**
>
> **A22.** In the circuit above, switching action depends on changing the voltage of the **cathode.**

Turning Circuits On and Off Automatically

You have seen how an electronic switch can turn a device on or off. One practical example of automatic switching is in television. The picture-tube beam must be turned off and on 15,750 times a second. To do this, **blanking pulses** are sent out by the broadcasting station at this frequency. The receiver uses these pulses to operate an electronic switch. Each time a blanking pulse is received, the picture signal is interrupted to allow the electron beam to return across the picture tube in order to start a new line. If this arrangement were not used, the returning beam would tend to fill in the dark areas in the picture.

Gating Signals to Different Destinations

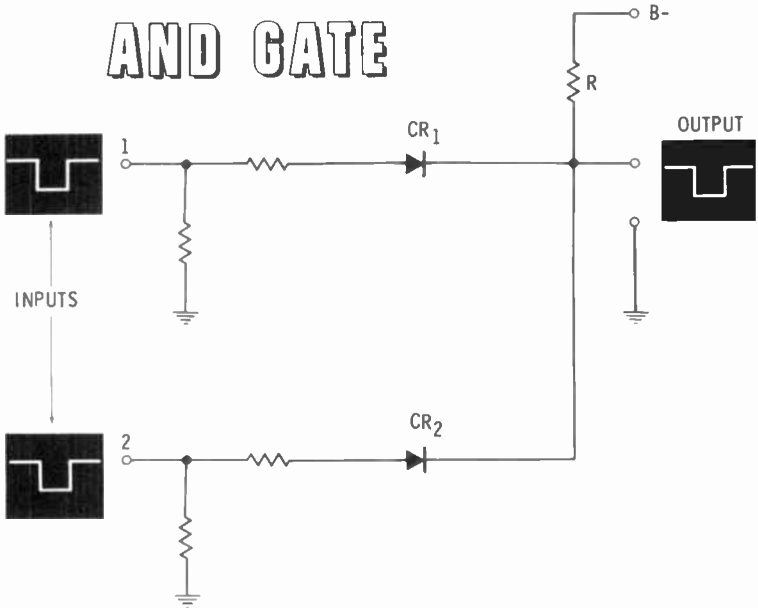
More complicated switching actions are often performed by **gate circuits.** A gate circuit allows signals to go through only when certain conditions are satisfied, but no signals can pass when these conditions are not satisfied.

Transistor gate circuits are used frequently in computer applications. They function as gates to direct signal flow to various points in the overall circuitry. Because they are able to determine computer operation from their input conditions, these circuits are referred to as **logic circuits.** AND gates and OR gates are two kinds used for logic operations. AND gates can use tubes, transistors, or semiconductor diodes, the latter being the most common.

The AND gate shown on the opposite page requires that both inputs be present before an output is generated. Without signals, current flows from the negative battery terminal through the large resistor (R) and both diodes to ground.

As a result, the output is a constant, small negative voltage. A negative pulse at point 1 reverse-biases diode CR_1. But current still flows through diode CR_2. Since R is very large compared to the other two resistors, the output remains almost unchanged. To see why this is true, notice that the total current flow is determined mainly by the resistance of R. Therefore, the voltage drop across R changes only a small amount when CR_1 stops conducting.

When negative pulses appear at points 1 and 2 at the same time, both diodes become reverse-biased. Current flow stops, and the output voltage becomes the same as the voltage of



the negative battery terminal for the duration of the input pulses. Therefore, to produce an output, pulse 1 AND pulse 2 must be present. The condition necessary to produce an output from this AND gate is that two negative input pulses must occur at the same time.

Q23. What is a gate circuit?

Q24. In an AND circuit with two inputs, there is an output only if two input pulses occur at (the same time, different times).

Q25. The most common type of AND gate is the ______________ _____ type.

Q26. Gate circuits (are, are not) used in computers.

Your Answers Should Be:

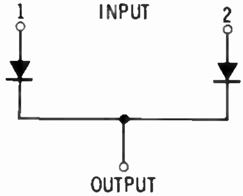
A23. A gate circuit is one which **allows signals to go through only when certain conditions are satisfied.**

A24. In an AND circuit with two inputs there is an output only if two input pulses occur at **the same time.**

A25. The most common type of AND gate is the **semiconductor-diode** type.

A26. Gate circuits **are** used in computers.

The OR gate below requires either input 1 **OR** input 2 to produce an output. This circuit is used when many inputs are to be gated into a single circuit.

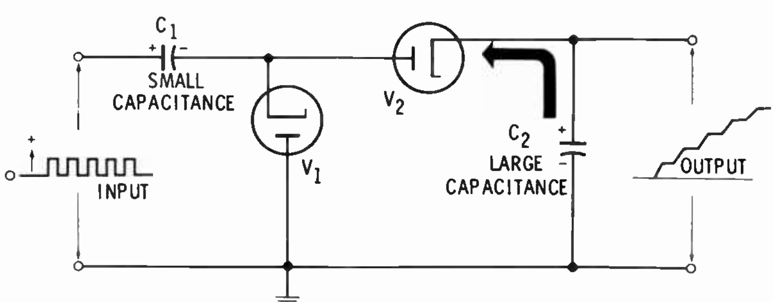


OR GATE

Frequency-Divider Circuits

One of the most common functions of pulse circuits is counting. A **step-counter** or a **frequency-divider** circuit does this. Such a circuit may be used to count a given number of input pulses or to divide the frequency of input pulses into a lower frequency. A step counter is shown below.

A PULSE-COUNTER CIRCUIT

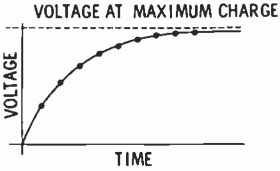


When the first positive pulse is applied, electrons are removed from the left-hand plate of C_1. This causes electrons to move from the top plate of C_2, through diode V_2, to the right-hand plate of C_1. As a result, C_1 and C_2 become charged with the polarities shown. No electrons flow through V_1 because its plate is negative with respect to its cathode. At the end of the pulse, the input voltage returns to zero. Capacitor C_1 can now discharge through the pulse source and V_1. The charge on C_2 makes the cathode of V_2 positive with respect to its plate. Therefore, V_2 cannot conduct, and capacitor C_2 cannot discharge.

Each additional pulse causes an additional charge to be added to C_2. As this cycle is repeated, the voltage across C_2 builds up in steps.

Now suppose a thyratron or another voltage-sensitive switching device is connected across the output. When the voltage across C_2 reaches the desired value, the switching device closes and C_2 is discharged. The switching device then opens, and the entire process starts over. In this example, the switching device produces an output pulse for every five input pulses; the input frequency is divided by five.

CAPACITOR CHARGING CHARACTERISTIC



The figure above shows the way a capacitor charges. The dots show the voltage increase for each input pulse. The actual amount of voltage depends on the nature of the pulses and the circuit. It is not desirable to design the counter so that C_2 discharges near its maximum-charge value. This is because each additional pulse causes a smaller increase in voltage, and it is difficult to be sure that the capacitor will discharge after the desired number of pulses.

Q27. A counter circuit counts pulses by using them to ______ _ __________.

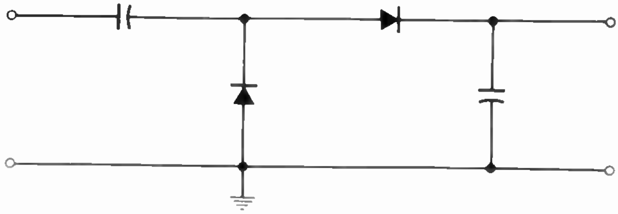
Q28. Draw a counter circuit that uses solid-state diodes.

Q29. What is an OR circuit?

Your Answers Should Be:

A27. A counter circuit counts pulses by using them to **charge a capacitor.**

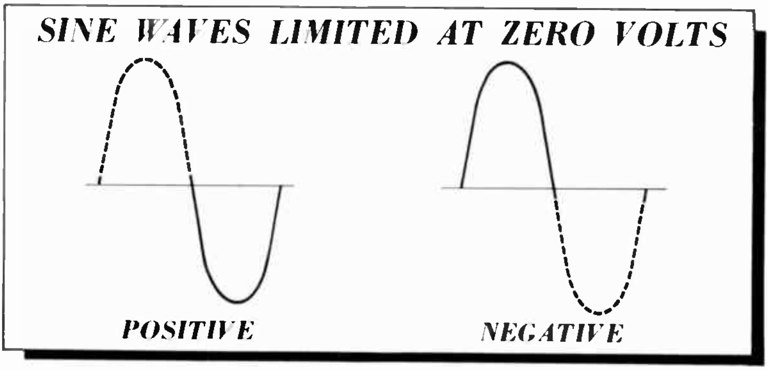
A28.



A29. An OR circuit is a gating circuit that **produces an output when a signal is applied to any of its inputs.**

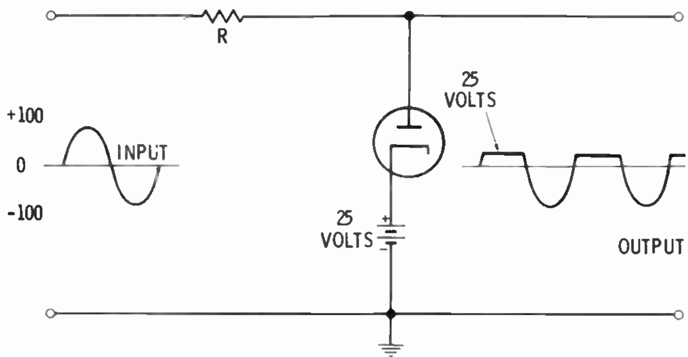
Limiters

The simplest **limiting** circuit is the positive crystal limiter. The input is a sine wave. The circuit allows only the negative half of the sine wave to pass. It blocks, or limits, the positive half—hence its name, positive limiter. Obviously, negative limiting is obtained by reversing the diode connections. This type of limiter uses zero voltage as its reference. However, other reference potentials can be used.



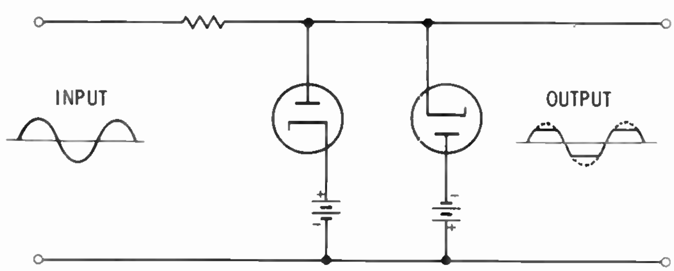
The vacuum-tube diode can be used to obtain a positive-limited waveform at a positive potential. In other words, less than half of the input sine wave is removed. This is accomplished by keeping the cathode at the limiting value. The battery in the illustration maintains the cathode at 25 volts positive with respect to ground. When the sine-wave input rises to 25 volts, the plate voltage rises to this amount. The tube then begins to conduct. As the input voltage increases, the plate current also increases. The voltage drop across R also increases, but the plate voltage cannot fall below 25 volts. Therefore, the plate voltage remains at 25 volts. When the sine-wave voltage goes below 25 volts positive, the plate voltage follows the input voltage.

A LIMITER CIRCUIT



When a pair of diodes is biased so that one is negative and the other positive, both positive and negative limiting are obtained. The output waveform is referred to as a **trapezoidal** waveform.

A POSITIVE AND NEGATIVE LIMITING CIRCUIT



Q30. How could the limiter circuit at the top of this page be used for negative limiting?

Q31. Positive and negative limiting of a waveform can be obtained by using ___ ______.

Your Answers Should Be:

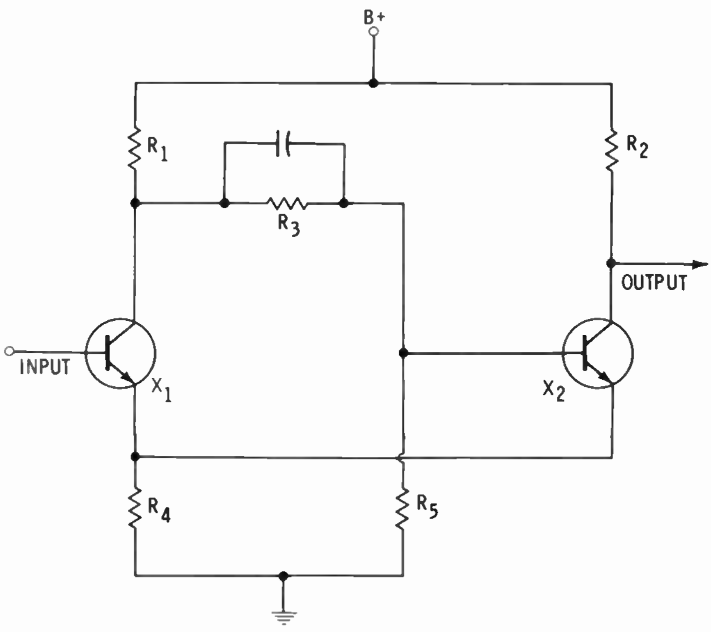
A30. If the **battery and diode connections** were **reversed**, negative limiting would occur. In this case the reference voltage is —25 volts. The output voltage varies from —25 volts to 100 volts. The negative portion of the input sine wave is limited to —25 volts.

A31. Positive and negative limiting of a waveform can be obtained by using **two diodes.**

Squaring Circuit

A typical **squaring** circuit is the **Schmitt trigger** shown here. This circuit can convert many input waveforms to a square-wave output. Note how it resembles a multivibrator circuit in its action.

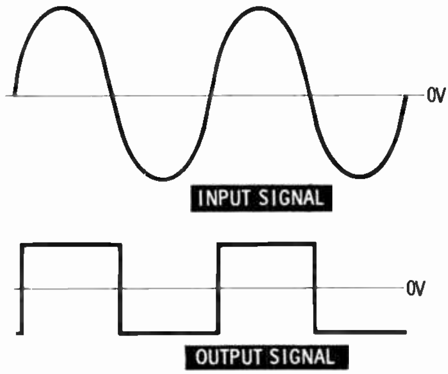
A SCHMITT-TRIGGER CIRCUIT



With no input, transistor X_1 is cut off, and its collector voltage equals the battery voltage. This voltage is coupled to the base of X_2 through R_3. Transistor X_2 is therefore saturated. Due to the emitter current of X_2, the top of resistor R_4 is positive.

Now a sine-wave input is placed on the base of X_1. The positive-going signal voltage soon exceeds the emitter voltage. This causes X_1 to conduct. The X_1-collector voltage drops slightly, and this change is coupled to the base of X_2. This reduces the X_2-emitter current slightly, and the top of resistor R_4 becomes less positive. This causes X_1 to conduct more. The current in transistor X_1 increases regeneratively until X_1 saturates. This immediately cuts off transistor X_2, and its collector voltage instantly rises to its maximum positive value.

SCHMITT-TRIGGER WAVEFORMS



This state continues until the input sine wave goes negative. This reduces the X_1-base forward bias to decrease the collector current. The X_1-collector voltage rises. This change is coupled to the base of X_2, causing this transistor to conduct. This condition is aided by the rising potential at the top of resistor R_4. Transistor X_1 suddenly cuts off, and transistor X_2 suddenly saturates. The X_2-collector voltage drops to its lowest value. Hence a square wave has been generated from the sine-wave input.

Q32. The Schmitt trigger circuit produces a ---------- output from a sine-wave input.

Q33. The transistors in a Schmitt trigger circuit switch between ------ and -----------.

Your Answers Should Be:

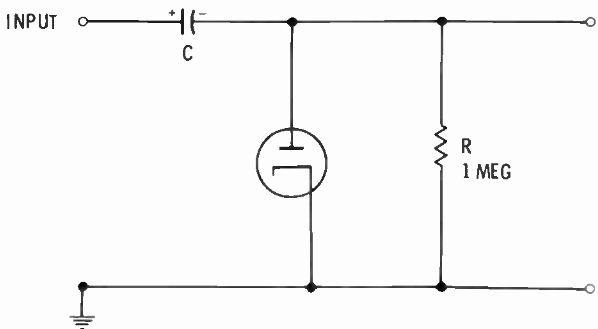
A32. The Schmitt trigger circuit produces a **square-wave** output from a sine-wave input.

A33. The transistors in a Schmitt trigger circuit switch between **cutoff** and **saturation.**

DC Restorer

A **DC restorer** shifts a waveform to a level above or below a certain voltage. This is accomplished essentially by charging a capacitor to the desired level. This is also referred to as **clamping** the waveform to this level.

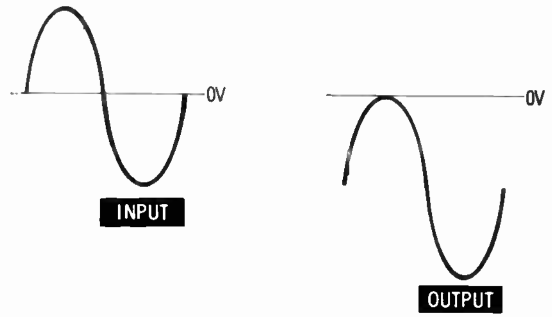
A NEGATIVE DC RESTORER



Because of the presence of the diode, electrons can flow easily into the capacitor when the input voltage is positive. However, the diode does not conduct in the opposite direction, so the discharge path is through the high resistance of R. Capacitor C therefore discharges only slightly between positive half cycles. This small amount of charge is replaced during the next positive half cycle. After a few cycles of the input voltage, capacitor C becomes charged to the peak voltage of the input sine wave.

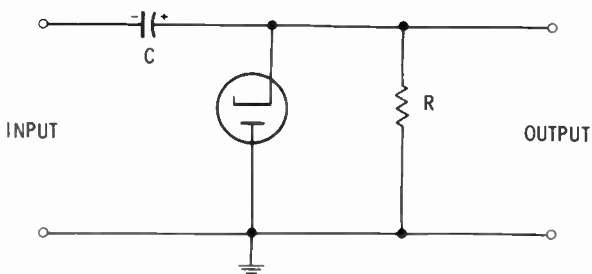
With the capacitor charged as shown on the circuit diagram, the capacitor voltage subtracts from the input voltage when the input is positive. The voltages add when the input is negative. The result is that the output voltage is always negative, reaching zero only when the input voltage is at its positive peak.

WAVEFORMS IN A NEGATIVE DC RESTORER



In this way the entire waveform has been shifted below the zero level to clamp the top of the waveform to zero volts. This circuit is known as a **negative DC restorer. A positive DC restorer** can be obtained by reversing the diode. In this

A POSITIVE DC RESTORER



case the entire waveform is shifted above the zero level to clamp the bottom of the waveform to zero.

Q34. Another name for shifting a waveform to a level above or below a certain voltage is _________.

Q35. Clamping depends primarily on _________ a capacitor.

Q36. A positive DC restorer can be made from a negative DC restorer by _________ ___ _____.

Your Answers Should Be:

A34. Another name for shifting a waveform to a level above or below a certain voltage is **clamping.**

A35. Clamping depends primarily on **charging** a capacitor.

A36. A positive DC restorer can be made from a negative DC restorer by **reversing the diode.**

WHAT YOU HAVE LEARNED

1. Pulse circuits are operated by large signals that are a combination of a wide range of sine-wave frequencies.
2. This kind of operation places a tube or transistor in the nonlinear portion of its characteristic curve.
3. Tubes and transistors are often driven rapidly from cutoff to saturation; therefore, their transient response is quite important to circuit performance.
4. Pulses instead of sinusoidal inputs are usually the primary signal sources in pulse circuits.
5. Sine waves can be converted to pulses by Schmitt triggers or other shaping circuits.
6. Pulse circuits can be used to count, shape waveforms, switch circuits on and off rapidly, and perform logical functions.
7. Pulse circuits are used extensively in computers, radar, and television, and in applications requiring logic operations.
8. DC restorers are used to maintain the relationship of a waveform to some reference voltage.

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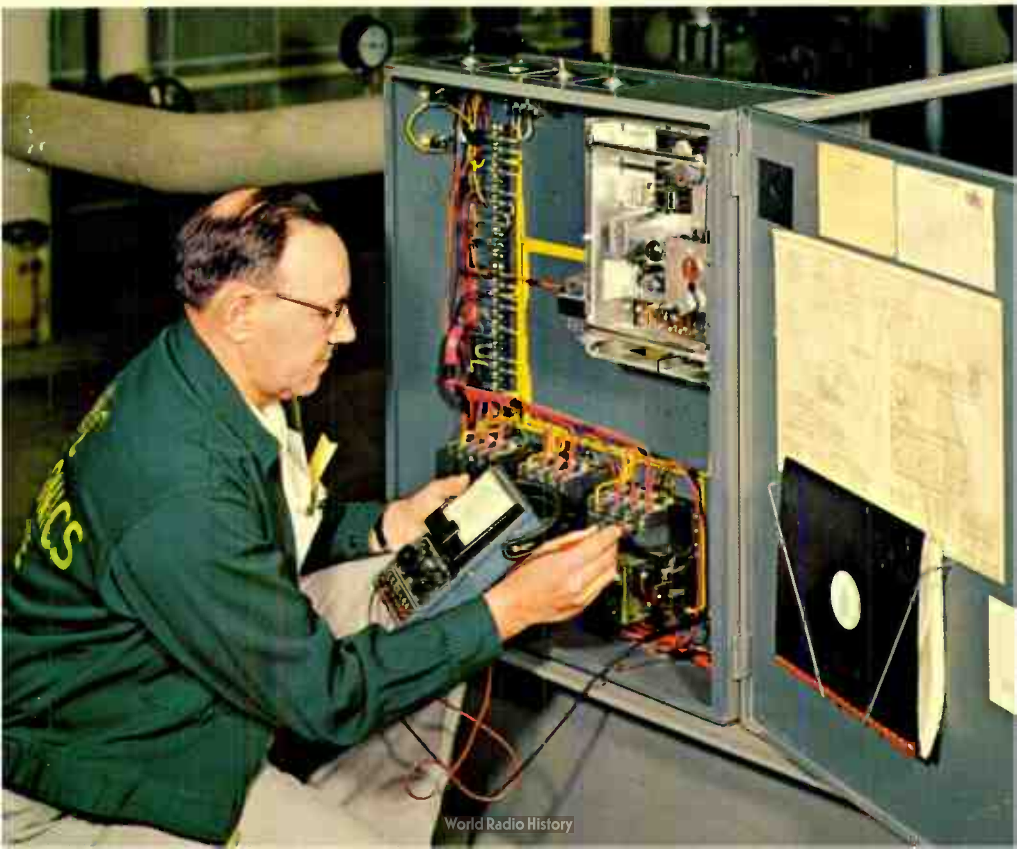

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UNDERSTANDING & USING TEST INSTRUMENTS

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SEYMOUR D. USLAN, *Editor-in-Chief,*
Training & Retraining, Inc.

Introduction

This fourth volume in the series covers test equipment, a specialized but highly important part of the field of electronics. In addition to explaining how each type of measuring equipment works, the text also discusses the proper way to use the instruments. Examples of practical applications are given. In this way your interest in the subject is maintained, and the learning process is made easier. Your study is centered around the principles and design of commonly used test instruments. Thus the knowledge you gain from this volume can be put to practical use in troubleshooting electrical and electronic equipment.

WHAT YOU WILL LEARN

The most important types of electronic test equipment are discussed in considerable detail in this volume. You will learn the operating principles of the voltmeter, ammeter, and ohmmeter, and you will see how the functions of these three instruments are combined in the multimeter. The operation of the basic meter movement is explained, and a discussion of meter-scale reading is included. The vacuum-tube voltmeter is discussed extensively.

You will learn that the oscilloscope is able to display waveforms for study and that for this reason it is a widely used test instrument. The way in which the oscilloscope functions is described in detail. The cathode-ray tube, sawtooth generator circuits, amplifiers, and other important parts of the oscilloscope are all discussed. The text explains the uses of the oscilloscope in making measurements and in troubleshooting.

Tube and transistor testers are also covered. You will learn how they work, and you will be shown their capabilities and their limitations.

One chapter is devoted to bridge instruments. The discussion shows how they can be used to measure resistance, capacitance, and inductance.

You will learn how signal generators provide a controllable signal source for use in troubleshooting and maintaining electronic equipment. Both audio-frequency and radio-frequency signal generators are discussed, and the text shows how each type can be effectively used. The proper way to align a radio receiver is given. The signal-substitution and signal-tracing methods of troubleshooting are explained.

One of the most important uses of electronic test equipment is in troubleshooting other electronic equipment. The final chapter of this volume is devoted to the subject of logical troubleshooting. You will learn how you can use test equipment along with your knowledge of electronics principles to conduct a systematic search for a defect in a piece of electronic equipment.

WHAT YOU SHOULD KNOW BEFORE YOU START

Before you study this book, it is essential that you have a good background in the principles of electricity and electronics, including the fundamentals of tube and transistor circuits. This background can be obtained by studying the first three volumes of this series. With the proper background, however, you should have no trouble understanding this text. All new terms are carefully defined. Enough math is used to give precise interpretation to important principles, but if you know how to add, subtract, multiply, and divide, the mathematical expressions will give you no trouble.

WHY THE TEXT FORMAT WAS CHOSEN

During the past few years, new concepts of learning have been developed under the common heading of programmed instruction. Although there are arguments for and against each of the several formats or styles of programmed textbooks, the value of programmed instruction itself has been proved to be sound. Most educators now seem to agree that the style of programming should be developed to fit the needs of teaching the particular subject. To help you progress successfully through this volume, a brief explanation of the programmed format follows.

Each chapter is divided into small bits of information presented in a sequence that has proved best for learning purposes. Some of the information bits are very short—a single sentence in some cases. Others may include several paragraphs. The length of each presentation is determined by the nature of the concept being explained and the knowledge the reader has gained up to that point.

The text is designed around two-page segments. Facing pages include information on one or more concepts, complete with illustrations designed to clarify the word descriptions used. Self-testing questions are included in most of these two-page segments. Many of these questions are in the form of statements requiring that you fill in one or more missing words; other questions are either multiple-choice or simple essay types. Answers are given on the succeeding page, so you will have the opportunity to check the accuracy of your response and verify what you have or have not learned before proceeding. When you find that your answer to a question does not agree with that given, you should restudy the information to determine why your answer was incorrect. As you can see, this method of question-answer programming insures that you will advance through the text as quickly as you are able to absorb what has been presented.

The beginning of each chapter features a preview of its contents, and a review of the important points is contained at the end of the chapter. The preview gives you an idea of the purpose of the chapter—what you can expect to learn. This helps to give practical meaning to the information as it is presented. The review at the completion of the chapter summarizes its content so that you can locate and restudy those areas which have escaped your full comprehension. And, just as important, the review is a definite aid to retention and recall of what you have learned.

HOW YOU SHOULD STUDY THIS TEXT

Naturally, good study habits are important. You should set aside a specific time each day to study in an area where you can concentrate without being disturbed. Select a time when you are at your mental peak, a period when you feel most alert.

Here are a few pointers you will find helpful in getting the most out of this volume.

1. Read each sentence carefully and deliberately. There are no unnecessary words or phrases; each sentence presents or supports a thought which is important to your understanding of electricity and electronics.
2. When you are referred to or come to an illustration, stop at the end of the sentence you are reading and study the illustration. Make sure you have a mental picture of its general content. Then continue reading, returning to the illustration each time a detailed examination is required. The drawings were especially planned to reinforce your understanding of the subject.
3. At the bottom of most right-hand pages you will find one or more questions to be answered. Some of these contain "fill-in" blanks. Since more than one word might logically fill a given blank, the number of dashes indicates the number of letters in the desired word. In answering the questions, it is important that you actually do so in writing, either in the book or on a separate sheet of paper. The physical act of writing the answers provides greater retention than merely thinking the answer. Writing will not become a chore since most of the required answers are short.
4. Answer all questions in a section before turning the page to check the accuracy of your responses. Refer to any of the material you have read if you need help. If you don't know the answer even after a quick review of the related text, finish answering any remaining questions. If the answers to any questions you skipped still haven't come to you, turn the page and check the answer section.

5. When you have answered a question incorrectly, return to the appropriate paragraph or page and restudy the material. Knowing the correct answer to a question is less important than understanding **why** it is correct. Each section of new material is based on previously presented information. If there is a weak link in this chain, the later material will be more difficult to understand.
6. In some instances, the text describes certain principles in terms of the results of simple experiments. The information is presented so that you will gain knowledge whether you perform the experiments or not. However, you will gain a greater understanding of the subject if you do perform the suggested experiments.
7. Carefully study the review, "What You Have Learned," at the end of each chapter. This review will help you gauge your knowledge of the information in the chapter and actually reinforce your knowledge. When you run across statements you don't completely understand, reread the sections relating to these statements, and recheck the questions and answers before going to the next chapter.

This volume has been carefully planned to make the learning process as easy as possible. Naturally, a certain amount of effort on your part is required if you are to obtain the maximum benefit from the book. However, if you follow the pointers just given, your efforts will be well rewarded, and you will find that your study of electricity and electronics will be a pleasant and interesting experience.

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1

Multimeters

What You Will Learn

In this chapter you will learn the functions and operations of the multimeter, the instrument most frequently used by all electronic technicians. After finishing this chapter, you will be able to measure voltage, current, resistance, and (with some multimeters) other electrical characteristics. You will learn how to use this instrument for its intended purpose, the transfer of information from the circuit to the technician.

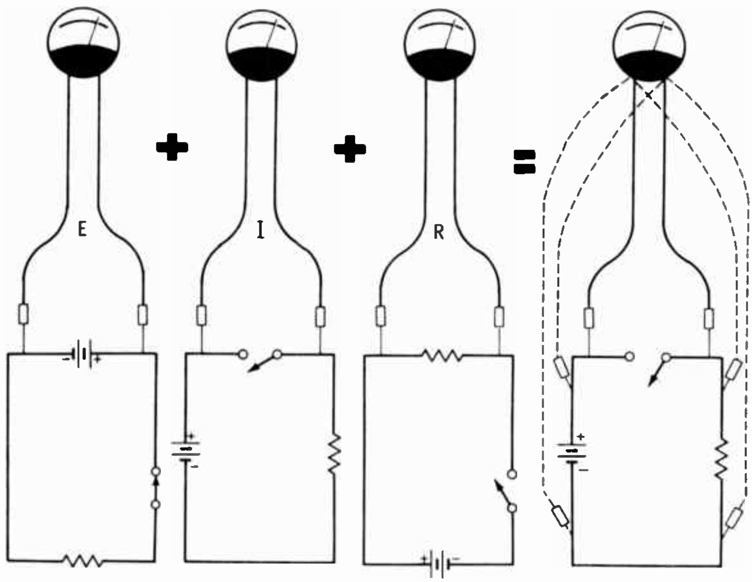
TEST EQUIPMENT MOST OFTEN USED

There are several basic classes of test equipment. The multimeter is an example of one class; oscilloscopes represent another. There are many types, or models, in each class. Some types have greater precision than others. Some instruments are easier to set up or use than others. Equipment may also vary in the type or amount of information that the instrument can provide.

Types of instruments within a test-equipment class may vary, but the way they function and the procedures for using them correctly are basically the same. For this reason there is no need to learn the step-by-step procedures for using each of the hundreds of different models. A technician can gain ability in electronics by first learning a set of underlying fundamentals and then developing skill through practice in applying them.

A **multimeter** combines the features of a **voltmeter,** an **ammeter,** and an **ohmmeter** in a single instrument having but one meter movement.

A MULTIMETER IS SEVERAL METERS IN ONE



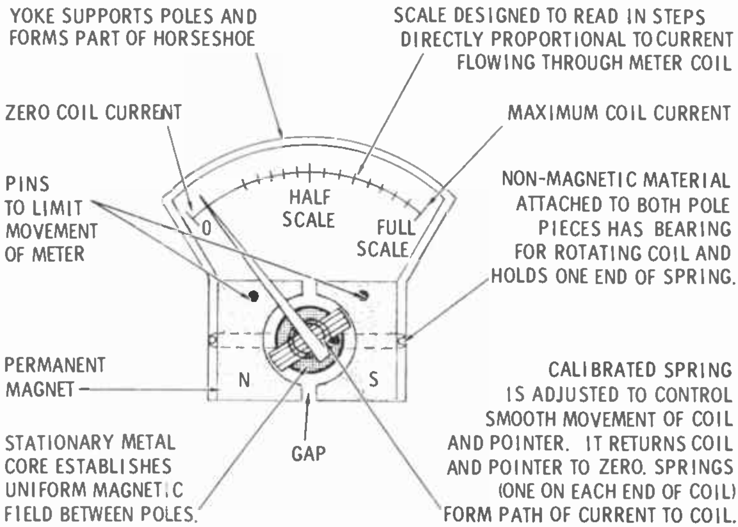
A multimeter can be used to measure voltage, current, and resistance within the limits of several ranges of values. From the technician's point of view, all multimeters consist of three basic sections—meter, circuitry, and front panel.

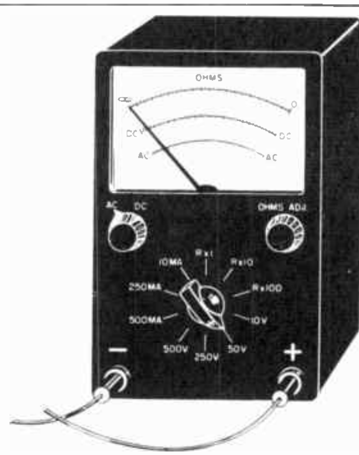
The meter coil moves a pointer across a calibrated scale to a mark that indicates the measurement being taken. The circuitry is a network of components that determines the functions (ohmmeter, ammeter, voltmeter) and ranges. The front panel contains the controls and jacks that permit operation of the instrument.

Most meters have moving-coil movements. As the name implies, the movement has a coil of wire that is free to rotate between the north- and south-seeking poles of a permanent magnet. Current flowing through the coil sets up a magnetic field. This field reacts with the field existing between the poles of the magnet and causes the coil to rotate.

A pointer attached to the coil moves to a position on the meter scale; the position of the pointer depends on the amount of current passing through the coil.

BASIC CONSTRUCTION OF A METER





A Multimeter

Q1. What are the ammeter ranges in the above meter?

Q2. What is the maximum voltage measurement?

Q3. How many ohmmeter ranges does it have?

Q4. What is the maximum resistance reading?

Your Answers Should Be:

A1. **0-10 ma, 0-250 ma,** and **0-500 ma**

A2. **500 volts**

A3. **Three**

A4. **Infinity**

Meter Torque

When a small current passes through the coil, a weak magnetic field is produced. This causes a small turning force (torque) to exist between the coil field and the permanent field. Thus the coil and pointer rotate a small amount. A larger current through the coil produces a stronger magnetic field around the coil, a greater torque, and more rotation of the coil and pointer.

Meter Coil

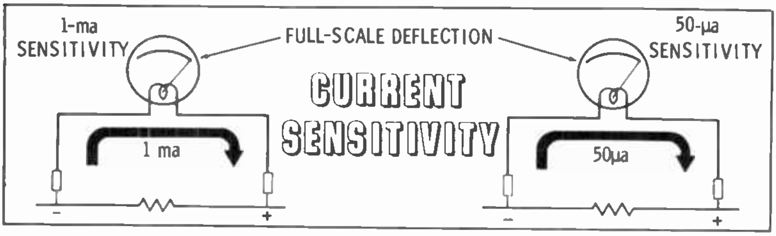
The meter coil is formed of fine wire wrapped on a rectangular aluminum frame. The coil frame is mounted so that it can rotate freely in the gap between the core and the poles. In some meters a screw on the front panel (just above the pointer axis) permits accurate adjustment of the pointer position. The pointer should read zero (ammeter and voltmeter scales) when no current is flowing through the coil.

Meter Sensitivity

Meter sensitivity is expressed in two ways—**current** sensitivity and **ohms-per-volt** sensitivity. Current sensitivity is determined by the amount of current required by the meter movement to cause full-scale deflection of the pointer. Ohms-per-volt sensitivity expresses the amount of resistance (in ohms) that must be in series with the meter when full-scale deflection occurs with 1 volt applied.

Current Sensitivity—Current sensitivity depends on the number of turns in the meter coil. It also depends on the strength of the permanent-magnet field.

Current sensitivity is expressed as the number of milliamps (ma) or microamps (μa) required for full-scale deflection. Typical meter movements have current sensitivities of 1 ma and 50 μa.



Ohms-per-Volt Sensitivity—Ohms-per-volt sensitivity is determined by the total resistance that must be in series in the meter circuit to obtain full-scale deflection when 1 volt is applied. The resistance value can be determined by Ohm's law:

$$R \text{ (ohms/volt)} = \frac{E \text{ (1 volt)}}{I \text{ (current sensitivity)}}$$

For a 50-μa (0.00005 amp) meter, the resistance is 20,000 ohms, resulting in a sensitivity of 20,000 ohms per volt.

OHMS-PER-VOLT SENSITIVITY

$R = \dfrac{1 \text{ VOLT}}{0.001 \text{ AMP}} = 1{,}000\Omega/\text{VOLT}$ $\qquad$ $R = \dfrac{1 \text{ VOLT}}{0.00005 \text{ AMP}} = 20{,}000\Omega/\text{VOLT}$

Q5. What causes the meter pointer to move?

Q6. If the permanent magnetic field between the pole pieces decreases in strength, the meter will give readings that are (more than, less than, the same as) those given before.

Q7. Which meter will have a greater number of turns in its coil, a 40-μa or a 2-ma movement?

Q8. If the coil rotates, how does current get from the meter circuitry to the coil?

Q9. What is the ohms-per-volt sensitivity of a meter with a current sensitivity of 2 ma?

Q10. If the resistance in a DC voltmeter circuit is 10,000 ohms for full-scale deflection at 1 volt, what value of resistance must be substituted to measure 10 volts full scale?

Your Answers Should Be:

A5. **Torque,** resulting from the reaction between the magnetic fields of the coil and the pole pieces, causes the meter pointer to move.

A6. A decrease of the magnetic field strength of the pole pieces will cause the meter to give readings less than those given before.

A7. The 40-μa **meter movement** will have a greater number of turns in its coil.

A8. **Calibrated springs,** one at each end of the coil, form the current path to the coil.

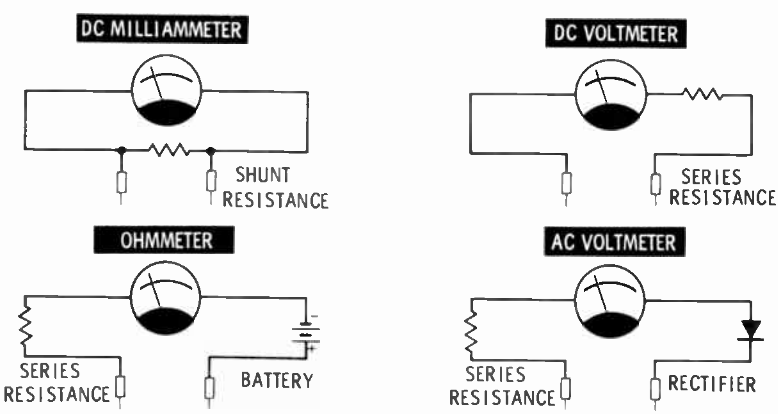
A9. A meter movement of 2 ma has a sensitivity of **500 ohms per volt.**

A10. **100,000 ohms**

Meter Circuitry

A meter is a current-reading device. To provide accurate readings, the electrical values of its circuit components must be fairly precise. The circuit design must provide for all of the types of measurements to be made by the meter.

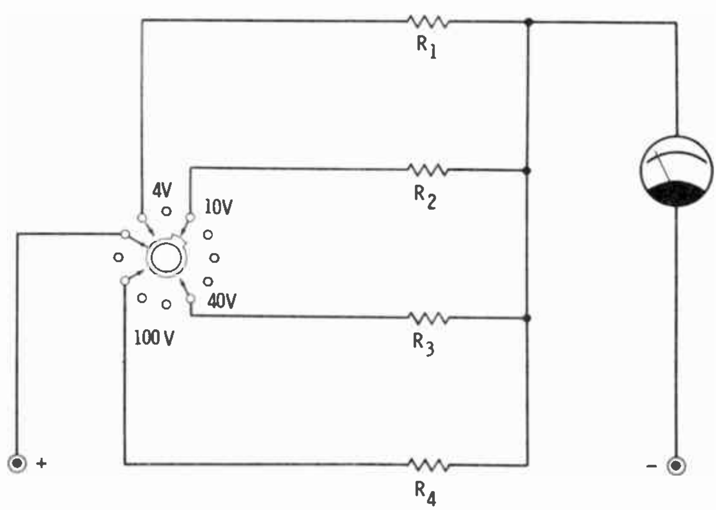
If a meter measured only one characteristic (voltage, current, or resistance) and if it had only a single range (10V, 1 ma, or 1,000 ohms, for example), the design would be relatively simple. Without considering ranges, there are four basic types of circuits found in multimeters.



Meter-Circuit Components—The figure on the opposite page shows that multimeter circuitry requires series and/or shunt resistances, a battery for measuring ohms, and a diode for limiting current direction when measuring AC voltage. To obtain different ranges for volts, amps, or ohms, resistances of selected values must be used in the circuit. The circuits are connected to front-panel controls that provide means of selecting the desired function and range.

Rotary Wafer Switches—These switches are often used to provide range selection. As seen in the schematic diagram below, a metallic wafer can be rotated to one of several positions. The blade of the wafer engages taps, or contacts, that are connected to appropriate parts of the circuit.

CIRCUIT WITH A WAFER SWITCH



A multimeter may have only a single rotary switch with enough wafers to select both the function (ohmmeter, milliammeter, DC voltmeter, or AC voltmeter) and the appropriate range for each function. In a multimeter having two rotary switches, one switch usually selects the meter function, and the other selects the range.

Q11. In the schematic above, to which resistance is the positive test lead connected?

Q12. What multimeter function does the circuit provide?

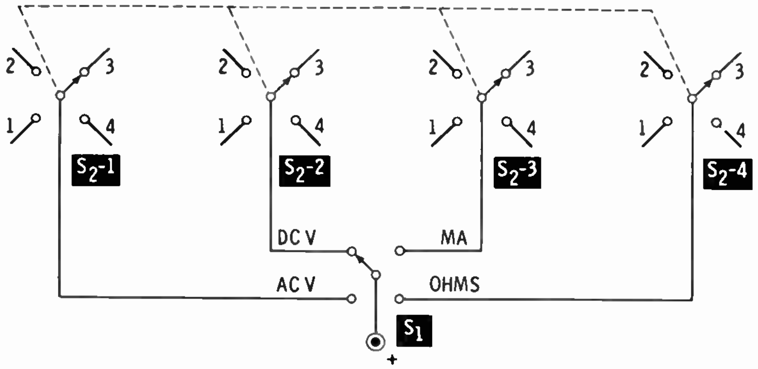
Your Answers Should Be:

A11. The test lead is connected to R_2.

A12. The switch and circuitry indicate that the circuit can be used to measure **DC volts.**

Ganged Rotary Switches—The schematic below shows another method of representing rotary switches. It indicates how a pair of switches (S_1 and S_2) might be used to make all the necessary connections in a multimeter. The dashed line shows that the S_2 switch sections are **ganged.** That is, the wafers are mechanically connected to the same shaft and stacked in decks along the shaft.

GANGED ROTARY SWITCHES



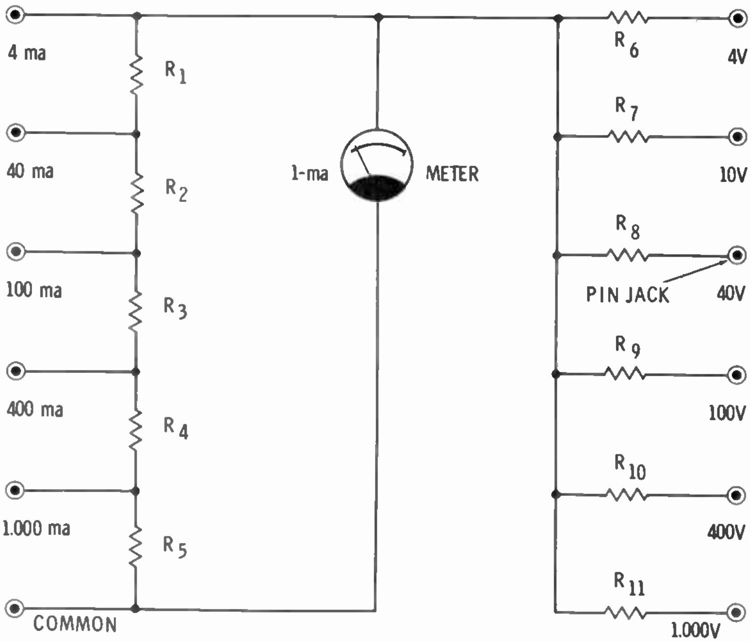
METER FRONT PANEL

The front panel of a multimeter has a scale for reading values, and provision for setting, or adjusting, the position of the pointer. Means for selecting the type of measurement to be taken and the desired ranges are also provided. Jacks for inserting test leads are mounted on the panel.

One means of selecting measurement and range scales was shown above—rotary wafer switches. In some multimeters a combination of a rotary switch and **pin jacks** is used. The switch selects the desired range. The red test lead is inserted in a pin jack marked with the quantity to be measured, and the black test lead is placed in the pin jack marked **COMMON** or **—**.

Another method often used employs a number of pin jacks on the front panel. Test leads are inserted in the desired positions—one in the jack marked **COMMON** and the other in the jack marked with the desired measurement. A schematic diagram of a circuit for DC voltage and current measurement using this arrangement is shown below.

MULTIMETER WITH PIN JACKS



Whatever the arrangement might be, always check the settings before taking a measurement. If the switch is positioned in the wrong function or in too low a range, the meter could be damaged.

Q13. If the test leads were in the COMMON and 400 ma jacks in the above schematic, what resistances would be shunting the meter?

Q14. With the test leads in the COMMON and 1,000V jacks, current will flow through the meter and which resistances?

Q15. With the voltage values shown, which resistance would have the larger value, R_8 or R_9?

Your Answers Should Be:

A13. R_4 and R_5 would be shunted across the meter. R_1, R_2, and R_3 would be in series with the meter.

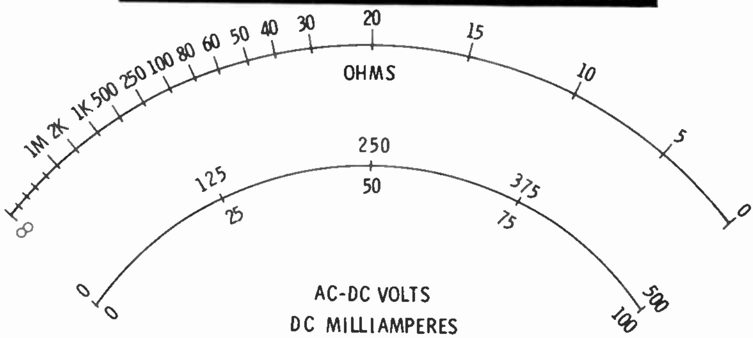
A14. Current will flow through R_1, R_2, R_3, R_4, R_5, and R_{11}.

A15. R_9 would be larger than R_8.

CURRENT AND VOLTAGE SCALES

Scales on a multimeter are usually calibrated to measure the quantities marked on the selection switches or jacks. A single scale can be used for more than one function and range. If a separate scale were used for each type of measurement and each range, the meter face would be cluttered and difficult to read. The types of measurements you have learned about thus far can be made using a meter face with either two or three scales.

METER FACE WITH TWO SCALES



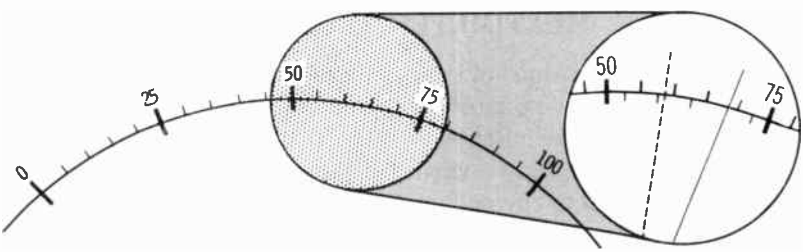
The figure above shows a two-scale meter—one scale for ohms and the other for AC-DC voltage and DC current. The lower scale is calibrated so that each mark has two values. The value to use depends on the selected range. A meter with three scales would probably have separate scales for **OHMS, DC VOLTS and MILLIAMPS,** and **AC VOLTS.** Each of the separate scales for the different functions may have more than one set of numbers for the divisions on the scales. Thus, it is possible to read values on more than one range for each function.

Multimeter scales for reading voltage or current are usually linear. This means that the divisions on the scale are spaced equal distances apart. On a scale that measures from 0 to 100, for example, the halfway mark would be 50. Midway between 0 and 50 is 25. If major divisions are marked off in smaller units, the spaces between subdivisions are also equal.

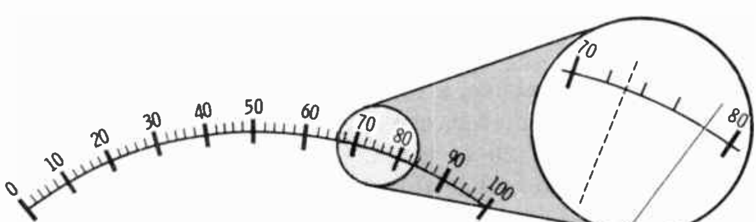
Reading Linear Scales

A linear scale is not difficult to read if care is taken. To keep the scale uncluttered, only the major divisions are numbered. If the pointer rests between numbers or marks, the correct quantity can easily be estimated by determining the units in which the subdivisions are calibrated.

Major divisions are 0, 25, 50, 75, and 100 on the scale below. The magnified portion shows subdivisions of five units each. There are additional marks halfway between these subdivisions.



Q16. The solid pointer in the diagram above is between 65 and 70 and slightly beyond the midmark. The meter reads 68. What is the reading indicated by the dotted pointer?



Q17. The solid pointer reads 78 in the above diagram. What does the dotted pointer read?

Your Answers Should Be:

A16. 58

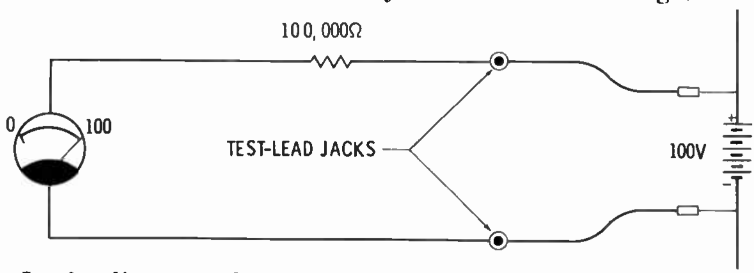
A17. 73

Linear-Scale Markings

There is no standard system for marking linear scales. The left end of the scale is usually zero. On rare occasions, however, zero may be on the right end. This only means the pointer will move from right to left. The other end may be 10, 15, 25, 40, 50, 60, 100, or some other number. To use the scale, determine the quantity contained between numbered markings and the values of the indicated subdivisions. You should have no trouble if you make this determination with care. Estimating readings between markings will be no more difficult than your readings on the previous page.

MULTIMETER ACCURACY

The electrical values of components are never precise. You have learned that resistors vary as much as ±20% of the stated ohmic value. Better resistors have tolerances of 10 and 5%. The tolerance rating of the resistors used in the multimeter affects the accuracy of the meter readings.



In the diagram above, a 100,000-ohm resistor was selected to give a full-scale meter reading of 100 volts. If the resistor had a tolerance of 20%, the full-scale reading could be off about 20 volts in either direction. A 10% resistor could cause readings between the extremes of about 90 volts and 110 volts. A 5% resistor could result in an error of 5 volts above or below 100 volts. None of these readings would be close enough for most purposes.

Most multimeters employ ±1% resistors. In the example given, a 100-volt reading would not be off more than 1 volt, a 1% error. This is close enough for most measurements.

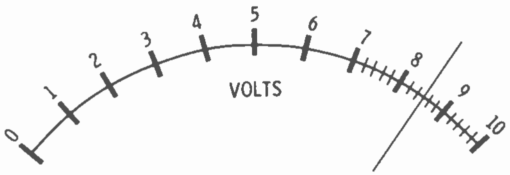
The meter movement itself may give some error. For example, its readings might be off 1 volt throughout the 100-volt scale. One volt off at 100 volts is a 1% error, but a 1-volt difference at 10 volts is a 10% error. For this reason, voltage and current readings should be taken on the upper half of the scale if possible.

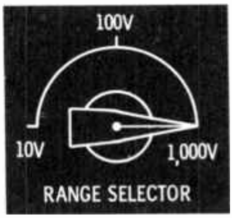
LINEAR-SCALE RANGES

It is sometimes necessary to take measurements as high as 100 volts or even 1,000 volts; at other times a reading of only a few volts will be called for. A 1,000-volt scale would provide any of these readings, but the accuracy of a 6-volt measurement would be very poor. Also, small differences on a 1,000-volt scale would be difficult to read. To overcome these limitations, multimeters have several ranges.

Multiple-Range Scale Reading

The scale below is marked in divisions from 0 through 10. When the range selector is set for 10V, the exact measurement is read directly from the actual scale markings. If the





selector is set on 100V, the scale readings are multiplied by 10 to obtain the measured value. If 10 volts were the measured value, the pointer would show a full-scale reading if the meter were on the 10V range. On the 100V range the pointer would come to rest over the 1 mark—10 times 1 equals 10 volts.

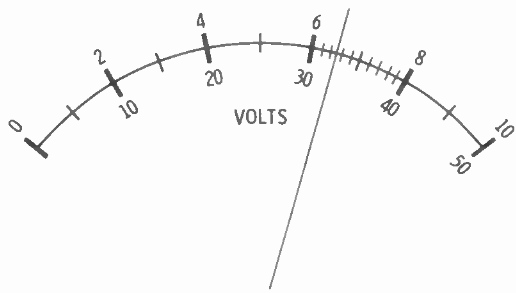
Q18. What voltage is being measured with the pointer and range settings shown in the diagram?

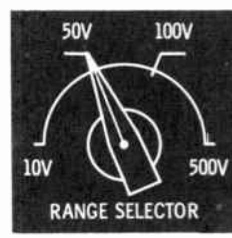
Q19. A multimeter has ranges of 10V, 50V, 100V, and 500V. Which range should be used to read 45V?

Your Answers Should Be:
A18. 850V.
A19. The 50V range.

Dual-Marked Scales

Another example is a single scale having two values for each of its markings. This type is used in multimeters whose ranges are not multiples of ten times a single full-scale quantity. Study the scale and range settings in the diagram below. The principles used in the preceding example still



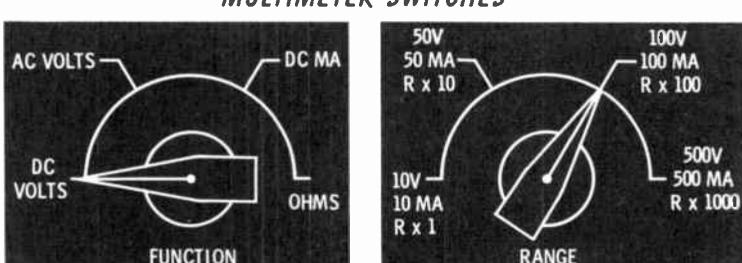


apply. With the range shown, the meter reads 32.5 volts.

Multimeasurement Scales

A linear scale can be used to measure more than one electrical characteristic. The preceding examples used voltage readings. These could have been either AC or DC volts as far as the scale or range settings were concerned. The same scale can also be used to read milliamperes. Appropriate switches on a multimeter might look like the following.

MULTIMETER SWITCHES



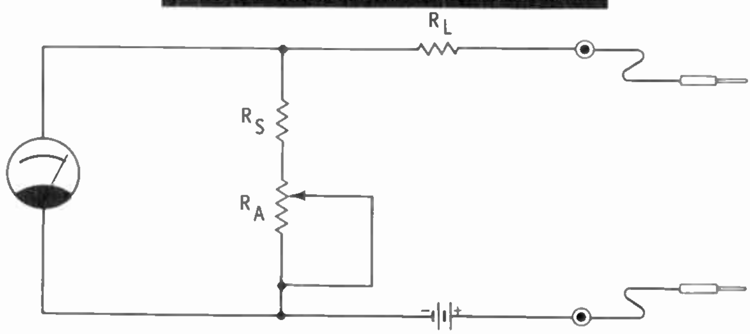
Measurement Precautions

When making a measurement, make a habit of taking the reading first on the highest-value range. Such a precaution prevents damage to the meter. For example, a 500-volt measurement taken at a 10-volt range setting will cause excessive current to pass through the meter coil. This will result in either burning out the coil or bending the pointer against the retarding pin. Therefore, unless you are absolutely certain of what range to use, set the multimeter for the highest-value range to take the first reading.

OHMMETER SCALES

The scale and range selection for the resistance-reading portion of the multimeter are a little different from those already discussed. The scale reads from 0 to infinity (∞) instead of from 0 to some number. Unlike the volt and milliampere scales, the resistance scale is not linear. Range selection is indicated by multipliers ($R \times 1$, $R \times 10$, $R \times 100$, etc.) instead of a quantity indicating full-scale deflection. These differences will become apparent as you examine the basic ohmmeter circuit shown below.

BASIC OHMMETER CIRCUIT



Q20. **On which range should a meter be set when making the first measurement of a circuit quantity?**

Q21. **Your meter has range settings of 10V, 50V, 100V, and 500V. You wish to measure the voltage across a load and suspect a voltage of 90V. To which range should you set your meter to read this voltage?**

Your Answers Should Be:

A20. When taking the first reading, set the meter on the **highest range** for the meter function being used.

A21. The meter should first be set on the **500V range.** This setting will insure against meter damage.

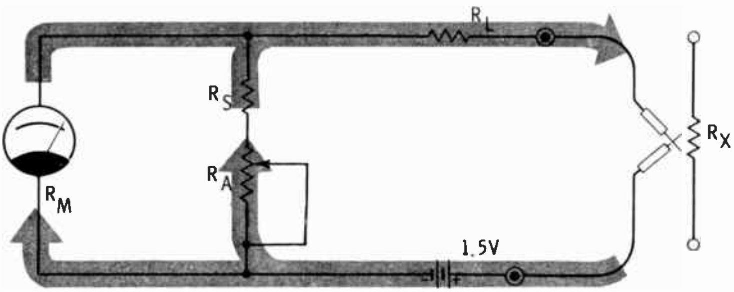
Ohmmeter Circuits

An ohmmeter circuit must supply its own source of current. Usually a self-contained battery is used for this purpose. The voltage of the battery is determined by the sensitivity of the meter, the arrangement of the series and shunt resistors in the circuit, and the size of the external resistance to be measured. Depending on the design of the ohmmeter, the battery might be from 1.5 to 45 volts.

R_L in the circuit on the preceding page is a current-limiting resistance in series with the meter. Its value is determined by the amount of current required to cause full-scale deflection. R_A and R_S form a shunt across the meter. Therefore, only a fraction of the total current in the circuit flows through the meter. The current through the meter is determined by the ratio of the meter resistance to the shunt resistance. R_A, controlled by the zero-ohms-adjust knob on the panel, establishes the value of total shunt resistance that will cause the meter to register accurate readings.

Determining Ohmmeter-Scale Markings

In the diagram below, resistance values in the parallel network—R_M (meter resistance), R_S (shunt resistance), and



R_A (zero ohms adjust)—are such that full-scale pointer deflection will occur when 1 ma enters the network. If the battery voltage is 1.5V and the circuit resistance is 1,500 ohms, 1 ma ($I = E/R$) will flow when the test leads are shorted (touched together). The meter will show full-scale deflection of the pointer, or zero ohms. When the test leads are parted, no current flows, and the pointer returns to its normal position. The ohmic reading becomes infinity (∞). This is the reason for zero being at the right-hand end on most ohmmeter scales.

Using Ohm's law, plot the value of current and resulting scale positions when resistances (R_X) of 500, 1,500, and 4,500 ohms are measured. If R_X is 500Ω and the resistance of the ohmmeter circuit is 1,500Ω, the total resistance is 2,000Ω.

$$I = \frac{1.5V}{2{,}000\Omega} = 0.00075 \text{ amp, or } 0.75 \text{ ma}$$

As far as the meter is concerned, it will receive the same ratio (or fraction) of any current flowing into the parallel network. Since 1 ma is required for full-scale deflection, 0.75 ma will move the pointer to three-fourths of full scale. Calculating current for the other values of resistance, you should be able to plot a chart that looks like this.

R_X	R_L	R_T	I_T	Scale Deflection
0	1,500	1,500	1 ma	Full
500	1,500	2,000	0.75 ma	¾
1,500	1,500	3,000	0.50 ma	½
4,500	1,500	6,000	0.25 ma	¼
Inf.	1,500	Inf.	0.00 ma	Zero

Q22. What factors determine the voltage of an ohmmeter battery?

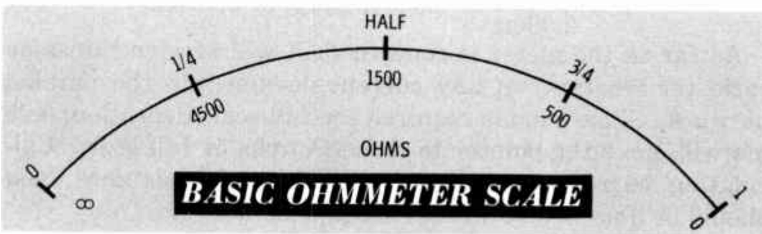
Q23. What factors determine the fraction of the total current that flows through the meter coil in an ohmmeter circuit?

Q24. The zero reading is usually on the ______ end of an ohmmeter scale.

> **Your Answers Should Be:**
>
> A22. The **sensitivity of the meter, arrangement of the shunt and series resistors,** and **size of the external resistance** to be measured.
>
> A23. The **ratio of meter resistance to shunt resistance.**
>
> A24. The zero reading is usually on the **right** end of an ohmmeter scale.

Ohmmeter-Scale Design

Starting at the right, compare deflection and ohmic readings at the quarter points on the ohmmeter scale shown below. The first quarter covers 500 ohms; the second quarter, 1,000 ohms (1,500-500); the third, 3,000; and the fourth, infinity. Such a scale cannot be calibrated in linear divisions.



BASIC OHMMETER SCALE

Reading Accuracy

Because of the nonlinearity of ohmmeter scales, readings should be taken with the pointer in the most readable area of the scale. A rule used by many technicians is to read values in the area of the scale bounded by 1/10 and 10 times the value of the midscale reading.

If only one range is available, such a rule is not practical. For example, if a meter reads 10 ohms at midscale, all desired resistance measurements will not fall between 1 and 100 ohms. Therefore, several ohms ranges are provided in a multimeter.

Resistance Ranges

Typical ohmmeter ranges are R × 1, R × 100, and R × 10K. Some multimeters have multipliers as high as R × 10 million. Using the rule mentioned above, the R × 1 range provides low resistance readings (0 to 100 or 200 ohms).

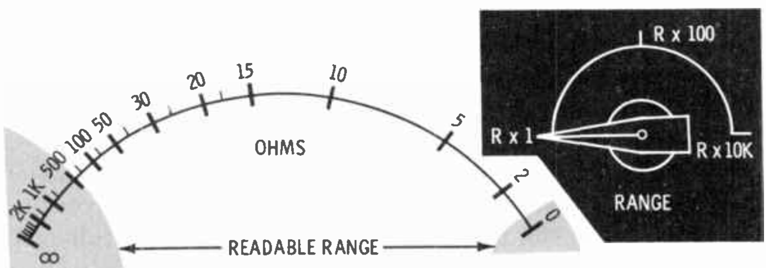
The R × 100 range will give useful readings between 100Ω and 10K, and the R × 10K range will be satisfactory for readings from 10K to 1 megohm. Higher readings may be estimated with fair accuracy. If an R × 1M range is available, resistances up to about 100 megohms can be measured.

USING THE OHMMETER

The basic procedures for measuring resistance are the same for all multimeters. First, set the meter to read **OHMS.** Plug the test leads into the proper jacks. Hold the tips of the test probes together, thus placing a short (zero ohms) across the internal circuit. Turn the **zero ohms adjust** (sometimes labeled **zero adjust**) control until the meter pointer rests at zero on the ohms scale.

Each time the meter is set for reading ohms and each time it is switched to a new range, short the test probes and zero the pointer with the **ohms adjust** control.

> **CAUTION**
>
> Never use an ohmmeter to take a resistance reading across an energized circuit. The internal circuit is designed to carry only the current developed by its own battery. Its voltage is usually between 1.5 and 9 volts. Voltage from an external source will usually be larger than this value and will damage either the meter coil or the pointer.



Q25. Using the above diagram, which range setting should be used to measure an estimated 1,500 ohms?

Your Answer Should Be:
A25. The range selector should be set on R × 100.

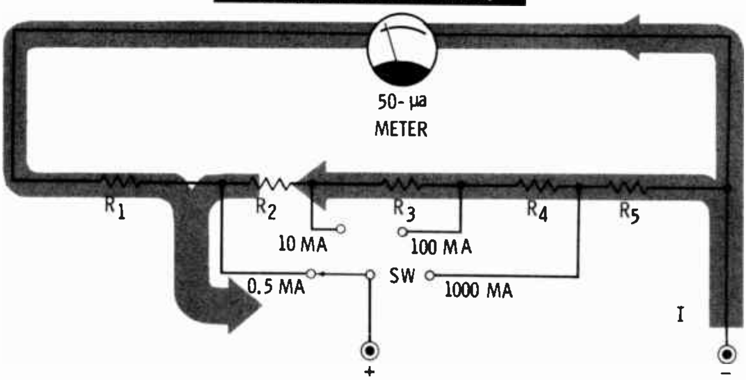
MULTIMETER CIRCUITS

Understanding how function and range circuits work is important in learning how to use a multimeter properly. Studying these circuits will also help develop your skill in analyzing electronic circuits. For these reasons, multimeter circuits will be studied a portion at a time. As each is discussed, it will be added to the preceding portions until a typical multimeter is developed. Each portion will be diagramed first with a rotary range switch, and then as it might appear employing pin jacks.

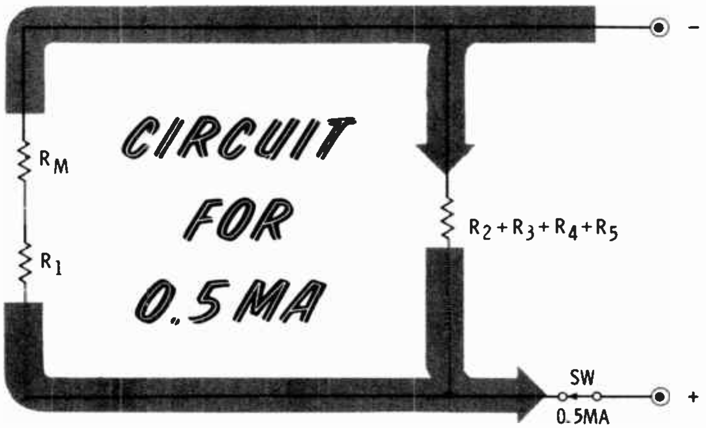
Milliammeters

The following schematic diagram shows a typical DC milliammeter circuit with rotary-switch connections. Resistor values are not shown. They will vary according to the multimeter.

DC MILLIAMMETER

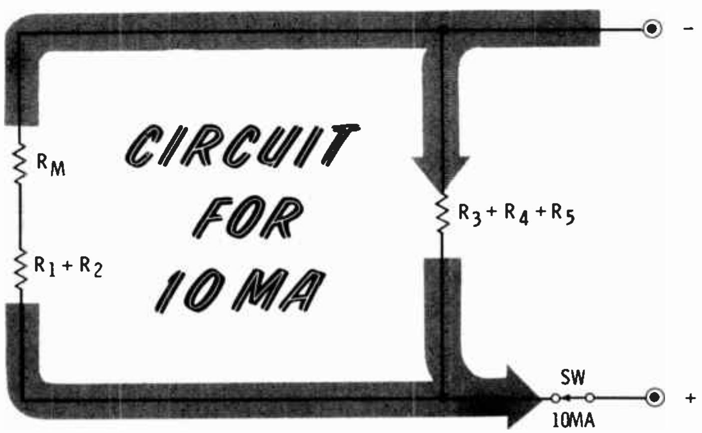


Notice that the arrangement is a parallel circuit in which the resistance can be changed in both branches by rotating a switch. Since the meter has a 50-μa movement (full-scale deflection), the ratio of resistances must be such that 50 μa will be the maximum current flowing in the meter branch at each switch setting. Redrawing the circuit for each switch position may help make this clear.



How much of the total current (0.5 ma) must flow through the shunt? 500 μa (0.5 ma) minus 50 μa (maximum meter current) equals 450 μa. This means that the ratio of shunt current to meter current must be maintained at 9 to 1. Therefore, the shunt resistance must be 1/9 of the resistance in the meter branch. With some meters, resistor R_1 is included as a part of the basic meter movement to increase its resistance. This is sometimes necessary so that the shunt resistance for the high-current ranges will not be unreasonably small.

Q26. What is the ratio of shunt current to meter current in this circuit?



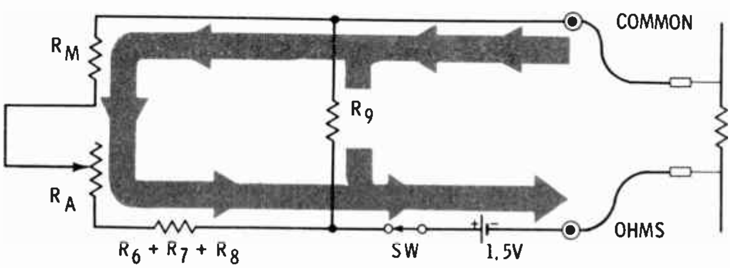
Your Answer Should Be:

A26. $\frac{I \text{ (shunt)}}{I \text{ (meter)}} = \frac{9{,}950\ \mu a}{50\ \mu a} = \frac{199}{1}$

Shunt Ohmmeters

In the illustration below, R_M represents meter resistance. R_A is the **ohms adjust** control and is used to set the pointer to zero reading (full-scale deflection). In the R × 1 range, R_M, R_A, R_6, R_7, and R_8 form one branch of a parallel network; R_9 forms the other.

CIRCUIT FOR R × 1 RANGE



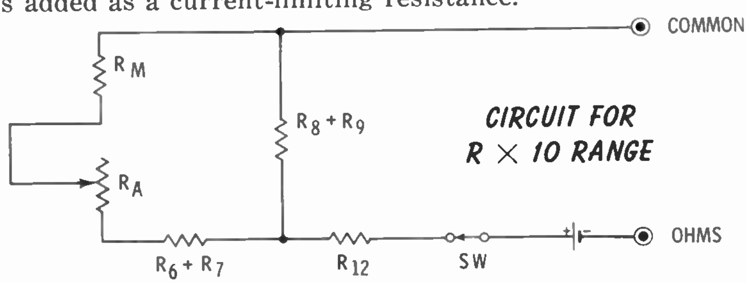
The shunt permits external resistances of low values to be read with reasonable accuracy. Without it, the measured resistance would be in series with the resistance in the meter branch, and the same current would flow through all resistances. The total resistance would thus have to be large to limit current flow to the maximum level of 50 μa. As a consequence, slight changes of current due to small changes in measured resistances would cause only tiny changes in pointer movement. Markings would be very close together.

An external resistance equal to the internal circuit resistance would bring the pointer to midscale. With a 50-μa meter and a 1.5-volt battery, Ohm's law shows that the internal resistance must be 30,000 ohms for full-scale deflection, or zero reading. 30,000 ohms of external resistance would halve the current flow and provide a midscale reading. On the R × 1 range, measurements between 0 and 30,000 ohms would be distributed on one half of the scale and readings would be difficult to estimate with accuracy.

Placing a shunt in the circuit provides a low-resistance current path around the meter branch. Most multimeters using this design have a midscale reading of 10 to 30 ohms, permitting greater accuracy in reading the scale markings.

A typical value for R_9 is 11 or 12 ohms. In round figures, the total resistance of the parallel network would then be about 10 ohms. With the terminals shorted, the 1.5-volt battery will cause a total current (I_T) of 0.15 amp (150,000 μa) to flow. Since maximum current for the meter is 50 μa, one part in 3,000 (50/150,000) of the total current will flow through the meter branch. The remainder (2,999 parts) flows through R_9, the shunt path. R_A is used to adjust the meter branch resistance to produce a 2,999/1 ratio.

When the range-selector switch is moved from R × 1 to R × 10, the resistances in the parallel network are redistributed. Compare the schematic below with the R × 1 circuit on the preceding page. The resistance is increased in the shunt branch and decreased in the meter branch. R_{12} is added as a current-limiting resistance.



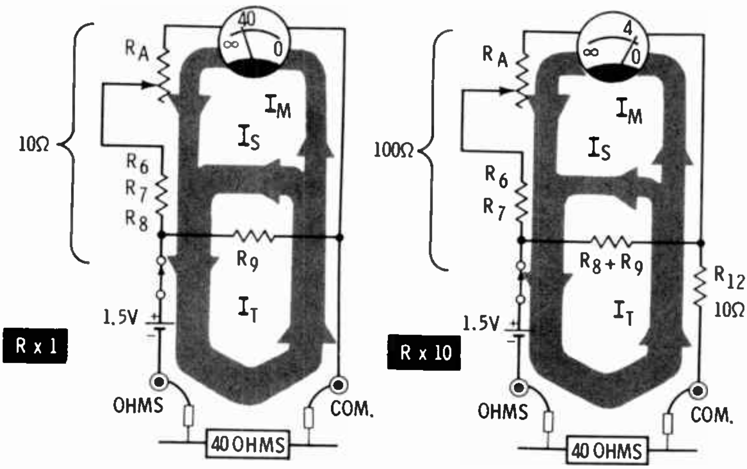
R_{12} in the R × 10 circuit will allow less current to flow than in the R × 1 circuit. You saw that maximum I_T in the R × 1 circuit would be near 150,000 μa if the parallel network had a resistance of 10 ohms. Suppose the resistance of the parallel network in the R × 10 circuit is approximately 100 ohms and R_{12} is 10 ohms. The 1.5-volt battery is then in a circuit having a total resistance (R_T) of 110 ohms. The total current with test leads shorted would approach 15,000 μa. Since I_M must be 50 μa, 50/15,000 or 1/300 of the total current flows through the meter.

Q27. In which circuit (R × 1 or R × 10) will the meter pointer be farther from zero when a given resistance is measured?

Your Answer Should Be:

A27. The R $\times$ 1 circuit.

Redrawing the two circuits with meter scales added will help you understand why the answer above is correct.



R_S is in the meter branch for R $\times$ 1 and in the shunt branch for R $\times$ 10. The ratio of meter-branch to shunt-branch resistance for R $\times$ 10 is smaller than for R $\times$ 1. This means that if I_T were equal in both parallel networks, I_M for R $\times$ 10 would be larger than I_M for R $\times$ 1. Therefore, a larger part of the total current would flow through the meter in the R $\times$ 10 circuit than in the R $\times$ 1 circuit.

R $\times$ 1 Circuit:

Total circuit R = 50 ohms (see figure)
Total circuit I = 30,000 μa (I = E/R)
I_M/I_S = 1/3,000 (meter-branch to shunt-branch ratio)
I_M = 10 μa (1/3,000 of 30,000 μa)

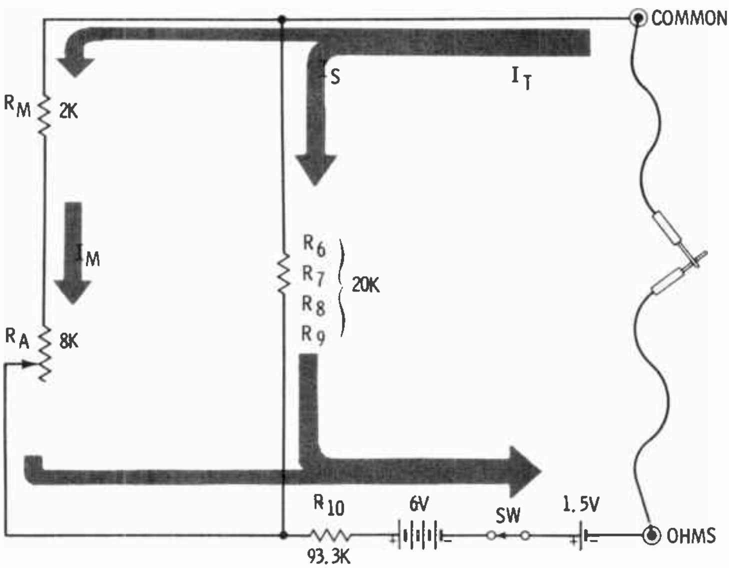
R $\times$ 10 Circuit:

Total circuit R = 150 ohms
Total circuit I = 10,000 μa (I = E/R)
I_M/I_S = 1/300 (meter-branch to shunt-branch ratio)
I_M = 33.3 μa (1/300 of 10,000 μa)

There will be greater deflection (more I_M) in the R × 10 circuit than in the R × 1 circuit when the same value of resistance is measured. The proportions established for the series-parallel resistances in the R × 10 circuit are such that scale readings can be multiplied by 10.

In the R × 100 and R × 1,000 circuits the series-parallel resistive networks are changed in the same manner, and the scale readings are multiplied by factors of 100 and 1,000, respectively. In the R × 1,000 circuit below, you will note that there is an additional battery to permit measurement of large resistances.

CIRCUIT FOR R × 1,000 RANGE



Q28. What is the value of R_T in the circuit above?

Q29. What is the purpose of the additional 6-volt battery in the meter circuit above?

Q30. What is the value of I_T in the circuit above when the test leads are shorted?

Q31. What is the ratio of meter-branch current to shunt-branch current?

Q32. How much of the total current will pass through the meter?

Your Answers Should Be:

A28. R_T is equal to **99.97K.**

$$R_T = \frac{(2K + 8K) \times 20K}{(2K + 8K) + 20K} + 93.3K = 99.97K$$

A29. The additional 6-volt battery **permits large resistances to be measured accurately.**

A30. I_T is equal to **approximately 75 μa.**

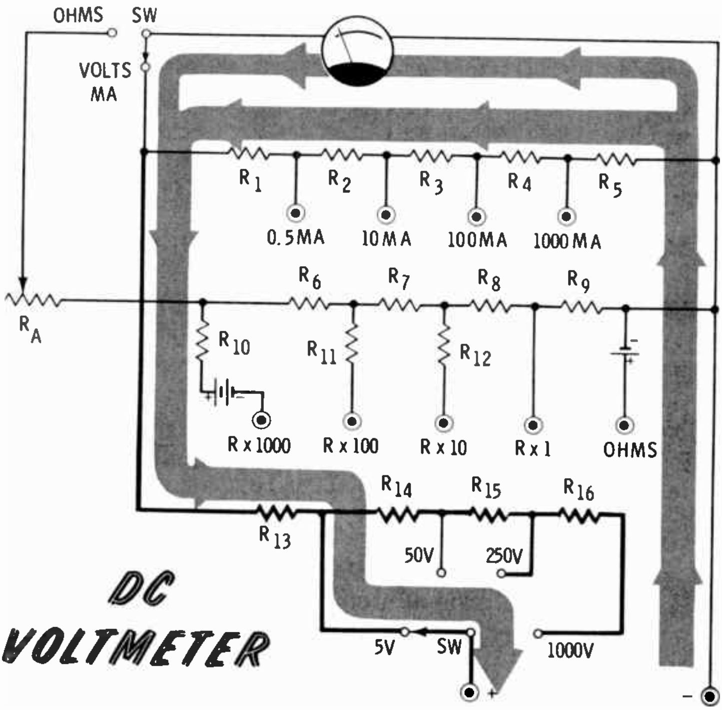
$$I_T = \frac{E}{R_T} = \frac{7.5V}{99.97K} = 75\ \mu a$$

A31. $I_M/I_S = 2/1$

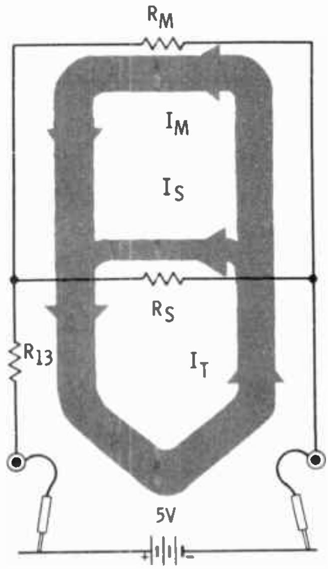
A32. $I_M = 50\ \mu a$ (2/3 of 75 μa)

DC Voltmeter Circuits

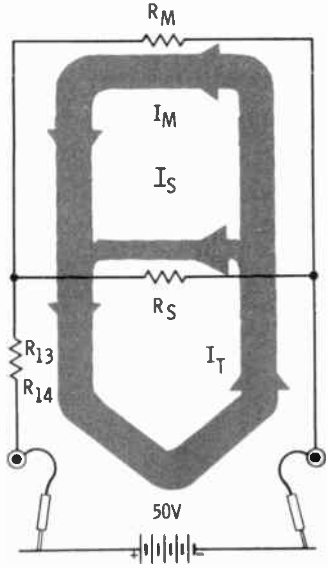
The figure below shows a typical DC voltmeter circuit added to the circuit of the DC milliammeter and ohmmeter.



As you can see, the DC voltmeter circuit is a network of four resistors in series with the meter-shunt resistor combination. Simplified schematics for the 5- and 50-volt positions are shown in the diagrams below.



5V RANGE



50V RANGE

In the 5-volt position, current flows through R_{13} and the meter-shunt network. The 50-μa meter has a coil resistance of 2,000 ohms. Since R_S is very close to the same value, it can be assumed that the total resistance of the parallel network is 1,000 ohms. What must R_{13} be for a full-scale reading of 5 volts? If R_M and R_S are equal, I_M and I_S are also equal. Therefore, for I_M to be 50 μa, I_T must be 100 μa. R_T equals 5V/100 μa, or 50,000 ohms. Subtracting 1,000 ohms, R_{13} is 49,000 ohms. To find the value of R_{14}, apply the same reasoning.

Q33. If 3.7 volts is measured using the 5-volt circuit, how much current will flow through the meter?

Q34. If R_{14} decreases in value, will the 50-volt range read high or low?

Q35. What is the value of R_{15} (250-volt circuit)?

Q36. What is the value of R_{16} (1,000-volt circuit)?

Your Answers Should Be:

A33. 37 μa. $I_M = \frac{1}{2} I_T$ (74 μa)

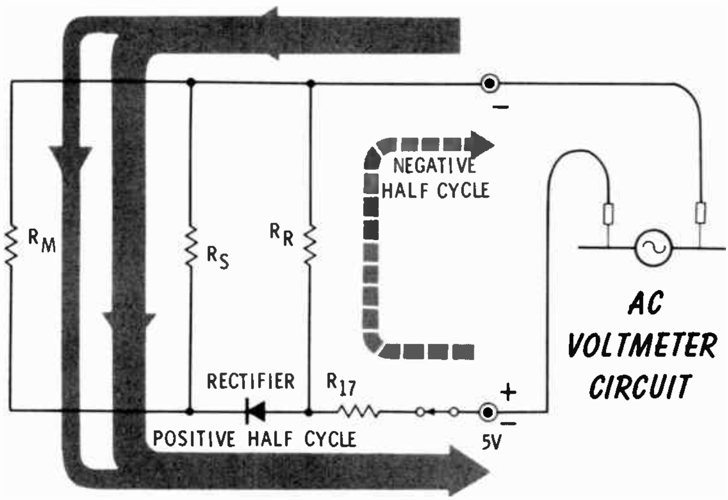
A34. The meter will read **high.**

A35. 2 **megohms**

A36. 7.5 **megohms**

AC Voltmeters

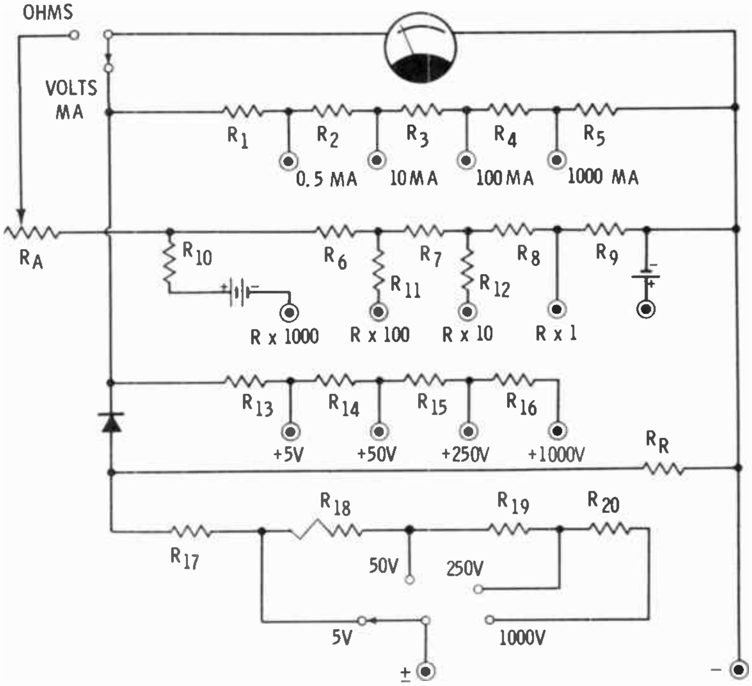
The diagram below shows an AC-voltmeter circuit. The four multiplier resistances are connected as in the DC voltmeter, but there are other differences.



When the polarity of the measured voltage is positive at the plus terminal, current will flow as indicated. It will pass through the rectifier. When the voltage swings in the negative direction, current flow will reverse. The rectifier offers a high resistance to current in this direction. Therefore only a very small amount of current can flow through the meter during this part of the cycle. Consequently, the meter receives a pulsating DC, and the pointer is deflected. If an alternating current passed through the meter in both directions, the pointer would remain at zero.

The rectifier resistance is low in comparison to R_R when the current flows counterclockwise, but it is high with respect to R_R when the current flows in the opposite direction. R_R becomes a path for current during the negative half cycle, thereby preventing a possibly destructive negative voltage from building up across the rectifier.

COMPLETE MULTIMETER CIRCUIT



USING A MULTIMETER

You have learned a great deal about why a multimeter operates as it does. This knowledge should aid you in using one wisely. However, it might be helpful to list the more important **do's** and **don'ts.**

General Precautions

Before using any multimeter, carefully study and apply the information contained in its instruction book. If the book does not contain a schematic diagram of the circuitry, request one from the dealer or manufacturer. Study the diagram and learn how the circuits are connected.

Keep the front panel clean. Dirt or moisture around the jacks may act as a shunt for current. Although it may look rugged, handle the instrument with care.

Always take readings with as much precision as possible. Develop the accuracy habit early. Then, when you need to take precise measurements, you will be able to.

Handle the front-panel controls carefully. Do not try to rotate switches beyond their stops.

Keep your hands away from the metal tips of the test probes. Failure to do so may cause you to receive an electrical shock when measuring current or voltage. The resistance of your body across the probes will make ohmmeter readings inaccurate.

Voltmeter and Milliammeter Functions

Have great respect for an energized circuit. Stand on dry, insulating material, and if you must measure voltage of great amounts, (a) turn the equipment off, (b) discharge any capacitors near the test point, (c) clip the meter leads on the test points, (d) turn the equipment on, (e) take the meter reading, and (f) turn the equipment off before removing the meter test leads.

Never place the milliammeter circuit across a voltage source. Even a small amount of voltage may force an excessive amount of current through the meter coil. To measure current, always connect the milliammeter in **series** with the circuit. Always turn the equipment off before removing the meter from the circuit.

Always connect the voltmeter in parallel with the circuit, voltage source, or circuit component.

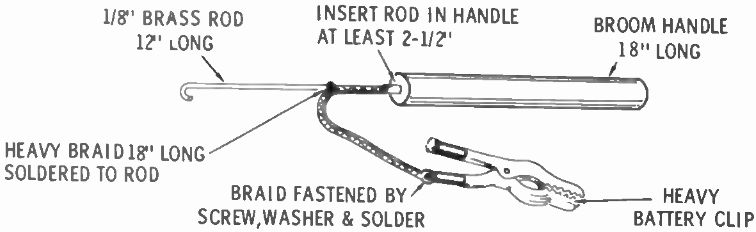
Observe polarity. Place the negative test probe (usually black) on the negative side of the element and the positive probe (usually red) on the positive side.

Ohmmeter Function

Do not measure resistance in an energized circuit. Turn off the appropriate switches, remove the power plug, disconnect the battery terminals, or take any other measure that will remove voltage from the circuit. A very small voltage added to that of the ohmmeter battery may damage the meter coil.

Discharge any capacitors in and around the circuit before making a resistance reading. Remember, capacitors store voltage. The ohmmeter may serve as a discharge path for a capacitor when the meter leads make connection in the circuit. The metal shaft of a screwdriver may be used to discharge low-voltage capacitors. Rub the blade against all leads or terminals of the capacitor while the shaft rests on the chassis. Hold the screwdriver by its handle. For high-voltage capacitors (300V or above) use a grounding tool.

GROUNDING TOOL



Fasten the clip of the grounding tool to the bare metal of the chassis. Touch the terminals or leads of the capacitor with the tip of the rod.

Do not measure the resistance of circuit elements that are still hot. Readings taken on parts above room temperature may be inaccurate.

When taking resistance readings in a circuit, determine if the element being measured is shunted by another component. If it is, the reading may be affected. If such a condition exists, you have two choices; either remove one of the component leads from its terminal before measuring, or use the point-to-point resistance values contained in the instruction book or technical manual for the equipment under test. The resistance values may be shown in chart form. One type of chart is shown below and lists the resistance values between tube pins and chassis ground.

RESISTANCE MEASUREMENTS*

Tube	Pin 1	Pin 2	Pin 3	Pin 4	Pin 5	Pin 6	Pin 7	Pin 8	Pin 9
V_1	Inf	615K	0	0.1	0	6.2K	165K	Inf	0
V_2	10.3K	68	1 meg	100	Inf	16K	1.5K		
V_3	22K	100	920	0	100	100	0	1	
etc.									

*Resistance values are given in ohms.

Another type of chart may be for a single circuit, giving both voltage and resistance readings from tube pin to chassis ground.

TABLE OF VOLTAGES AND RESISTANCES

Element	Pin No.	Voltage	Resistance
Plate	1	320VAC	280
Filament	3	3.15VAC	0
Filament	4	3.15VAC	0
Plate	6	320VAC	280
Cathode	7	+350V	125K

When using these charts, be sure the front-panel controls of the equipment are set as indicated by the manual containing the chart. Also, be sure to use a meter with the same sensitivity as the type used by the manufacturer in developing the chart.

If your measurements are the same or reasonably close, those components included in the reading may be good. You cannot be absolutely sure, however. For example, a normally high-value resistor may be open. If this resistor is in parallel with low-resistive components, such as a coil, the ohmmeter reading may agree with the chart value. A leaky capacitor across a resistor may also produce a normal reading. However, if you suspect this condition or get an abnormal reading, disconnect one of the leads of the suspected component and make another measurement.

The condition of capacitors can be approximated with an ohmmeter. When testing capacitors other than electrolytics, use the highest resistance range of the meter. This range will supply more voltage than the others. If the capacitor is good, the meter pointer will deflect slightly and then return to infinity as the capacitor charges from the ohmmeter battery. If there is no deflection, the capacitor may be open or have too small a value for the size of the ohmmeter battery. Full-scale deflection with no return indicates a shorted capacitor. Leakage is indicated by a steady deflection to some part of the scale.

WHAT YOU HAVE LEARNED

1. A multimeter is an instrument used to measure ohms, AC and DC volts, and DC milliamperes.
2. A combination of switches and jacks on the front panel of a multimeter permits the instrument to measure these electrical characteristics with a single meter.
3. Meters vary in sensitivity. Sensitivity can be stated in two ways—in current and in ohms per volt. Current sensitivity, rated in milliamps or microamps, indicates the amount of current flow through the meter coil necessary to cause full-scale deflection of the meter pointer. Current sensitivity of most multimeters ranges from 2 ma to 50 μa. The smaller current rating means greater sensitivity. Ohms-per-volt sensitivity is determined by the amount of meter-circuit resistance that will result in full-scale deflection when 1 volt is applied to the meter leads. A 2-ma current sensitivity would be rated at 500 ohms per volt ($R = E/I$). A 50-μa meter movement would have a sensitivity of 20,000 ohms per volt. The latter meter is preferred, since it adds less loading effect to a circuit being measured.
4. Most multimeters have a variety of ranges for each of the four meter functions—ohms, DC volts, AC volts, and DC milliamperes. Ranges are obtained by selecting internal circuit arrangements through the use of switches or jacks.
5. These circuit arrangements are parallel or series-parallel resistive networks. Each range circuit sets up a distribution of resistances in the meter and shunt branches of the network. The resistance ratios are such that no more than the maximum meter current will flow through the meter branch of the network. The excess current is diverted through the shunt branch.
6. Full-scale deflection of the pointer occurs when maximum rated current flows through the meter coil.
7. When the instrument is set up as an ohmmeter, full-scale deflection occurs when the test leads are shorted. This indicates zero ohms.

8. Voltmeter and ammeter scales on the meter face are usually linear. Units of scale markings are equal distances apart. The same scale can be used for measuring both volts and milliamps. On some multimeters a separate scale for each is available.
9. The ohmmeter scale is nonlinear—markings are not equal distances apart. The scale reads from zero (usually at the right end) to infinity.
10. For best accuracy, all multimeter readings should be made in the range position where the pointer will be in the upper-half region of the scale. There is some error present in even the best movement. This difference at full scale will be less of a measurement error than near zero. Also, the markings of the ohmmeter scale are less crowded toward the zero end (full-scale deflection).

2

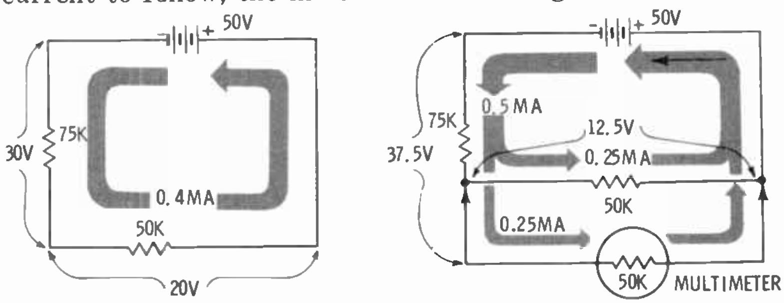
Vacuum-Tube Voltmeters

What You Will Learn

In this chapter you will learn the functions and operations of a vacuum-tube voltmeter (VTVM). You will learn, by comparison, the advantages of the VTVM versus those of the multimeter. After completing this chapter, you will know which type of meter to use for any circuit.

CAPABILITIES

A VTVM, because of its design, has a few advantages not found in multimeters. The primary advantage is that it can be used for measuring voltages without excessively loading a circuit. For example, a 1,000-ohm/volt multimeter set on the 50-volt range will place 50,000 ohms across the circuit being measured. Since this provides another path for circuit current to follow, the multimeter is **loading** the circuit.



A Multimeter Loads a Circuit

According to Ohm's law, you should be able to measure 20 volts across the 50K resistor in the circuit above. A 1,000-ohm/volt meter on the 50-volt range will place 50,000 ohms across the resistor, thus loading the circuit. The voltmeter will, therefore, read 12.5V (0.25 ma × 50K). This is a large error.

A 20,000-ohm/volt multimeter, because of its higher input resistance, causes less circuit loading. A typical VTVM has a 10,000,000-ohm input resistance, regardless of range. Study the chart below, and compare the loading effects of the two meters.

Range	Input Resistance		Loading Effect
	VTVM	Multi*	
5V	10 meg	0.1 meg	VTVM 100 times less
10V	10 meg	0.2 meg	VTVM 50 times less
50V	10 meg	1 meg	VTVM 10 times less
100V	10 meg	2 meg	VTVM 5 times less
500V	10 meg	10 meg	Multimeter equal to VTVM
1,000V	10 meg	20 meg	Multimeter 2 times less

*Multimeter with 20,000-ohm/volt sensitivity

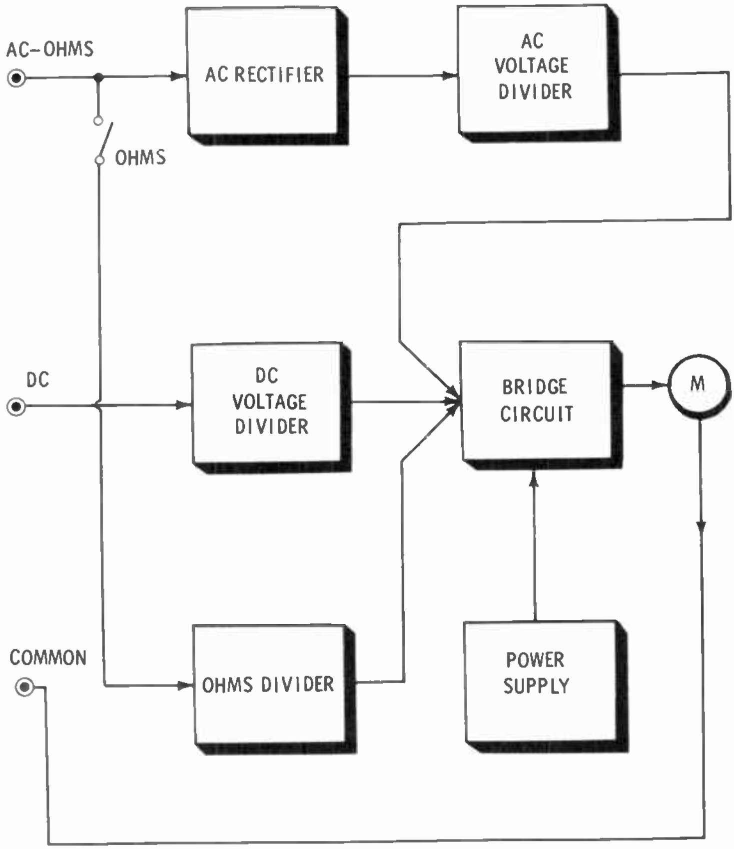
As you can see, a VTVM has less loading effect on circuits at the lower voltages than does a good multimeter. Some circuits are so sensitive to loading effects that a reading can be obtained only with a VTVM.

Another advantage of the VTVM is its wider frequency coverage. The AC voltage-reading error increases at the rate of 0.5 to 1% per 1,000 cycles in a multimeter. At 5,000 cps, for example, a multimeter would read 2.5 to 5% low. At 50,000 cps, readings would be 25 to 50% low. A VTVM, however, will provide AC measurements of reasonable accuracy up to tens of megacycles.

VTVM'S

There are many different designs for constructing a VTVM. Most of them use some type of vacuum-tube bridge circuit to regulate the amount of current that flows through the meter coil. This method not only provides an accurate means of measurement, but it also permits the use of a less sensitive meter. A typical VTVM might use a 200-μa meter movement, whereas a 20,000-ohm/volt multimeter requires a more expensive 50-μa movement.

BLOCK DIAGRAM OF A TYPICAL VTVM



The above block diagram of a VTVM shows three input jacks for test leads. By following the arrows, you can see that when measuring AC, the input current flows through a rectifier, a voltage divider, a bridge circuit, and the meter before it returns through the **COMMON** pin jack. Current, representing DC and ohm readings, flows through the respective divider networks in the circuit to the bridge circuit and the meter. From there it returns to the **COMMON** jack.

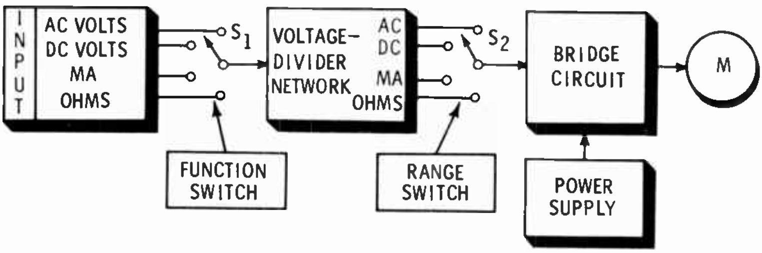
Q1. Why does a VTVM provide more accurate readings than a multimeter when measuring low voltages?

Your Answer Should Be:

A1. A VTVM has a **greater impedance** across its input jacks at lower voltage ranges than a multimeter. Therefore it **draws less current** from the circuit.

VACUUM-TUBE VOLTMETER CIRCUITS

In the diagram below, the inputs are shown in a block rather than as individual jacks. This VTVM would have four jacks on the panel, each labeled with the function titles

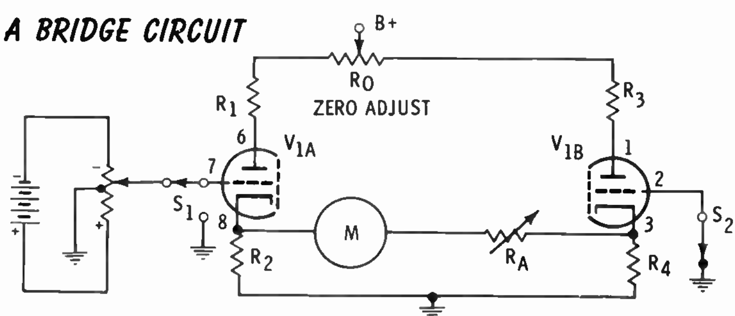


shown. The function switch (S_1) connects the jacks to the proper voltage-dividing networks. The range switch (S_2) selects the proper network, usually resistive, to supply the bridge circuit with the correct voltage. The bridge circuit provides the amount of current that should flow through the meter for the correct pointer deflection. The power supply provides filament and B+ voltage to the vacuum tubes.

Bridge Circuit

The bridge circuit will be described first since it represents the most significant difference between a VTVM and a multimeter. The schematic below shows a typical circuit.

A BRIDGE CIRCUIT

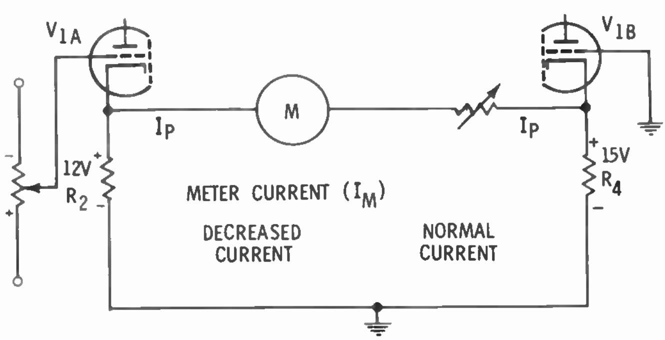


As the schematic shows, V_{1A} and V_{1B} are separate halves of a twin triode. (The A and B designations represent separate groups of elements in the same tube envelope.) The arrangement of the circuit is such that the plate current of V_{1A} can be made equal to the plate current in V_{1B}. The balance in plate currents is brought about by the adjustment of R_0. The control for R_0 is on the VTVM panel and is labeled **ZERO ADJUST.** Before taking a measurement, this control is adjusted until the pointer is resting on zero of the desired scale.

A pointer reading of zero means no current is flowing through the meter. This condition exists when the two cathode voltages are the same with respect to ground. Since cathode resistors R_2 and R_4 are equal in value, the voltages are equal as long as the two plate currents remain the same.

A 200-μa meter is sufficiently sensitive to operate in such a circuit. R_A is a range calibrating resistor. When the range switch is moved to a new position, a different R_A is switched into the meter circuit.

If the switch (S_1) at the grid (pin 7) of V_{1A} is thrown from ground to the battery and resistance circuit, a negative voltage will be applied to the grid. Plate current will decrease by an amount determined by the change in grid voltage. A decrease in plate current will lower the voltage across resistor R_2. Since the voltage across R_4 has not changed, a difference of potential exists across the meter. This potential difference results in a current flow through the meter.



Q2. In which direction will meter current flow in the circuit above?

Your Answer Should Be:

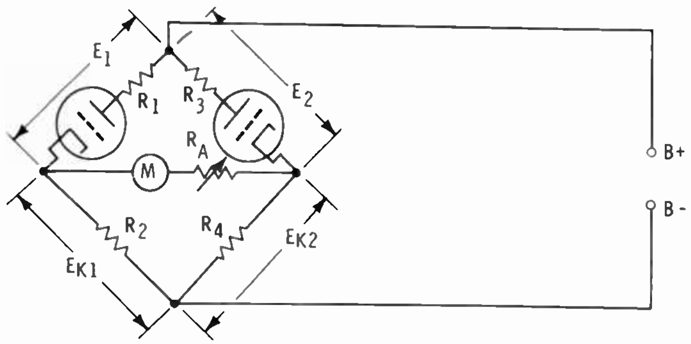
A2. The meter current will flow from **left to right.**

Assume that normal plate current flow through V_{1B} produces a cathode voltage of 15 volts. Also, assume that the decrease in plate current through V_{1A} drops its cathode voltage to 12 volts. Current flows through the meter from the less positive to the more positive side.

If the voltage applied to the grid of V_{1A} represents a full-scale reading at the range setting in use, what should be the value of R_A? A 200-μa meter has a full-scale deflection when a current of 200 μa flows through its coil. If the voltage across the meter is 3 volts, R_A plus the meter resistance must be 15,000 ohms.

$$R = \frac{E}{I} = \frac{3V}{0.0002a} = 15{,}000 \text{ ohms} = 15K$$

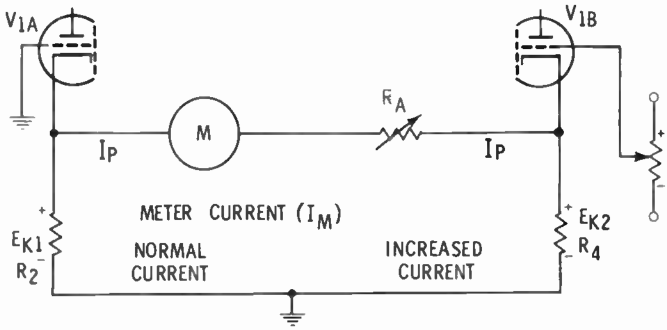
Below is the circuit redrawn in the form of a bridge.



With no voltage applied to the grid of either tube, the current is the same on both sides of the bridge. Cathode voltages E_{K1} and E_{K2} are equal. If a negative voltage appears on the left grid, current through the left leg of the bridge decreases. The voltage drop across resistor R_1 decreases, but the voltage across the tube increases enough that voltage E_1 increases. However, the decrease in current through R_2 lowers the value of E_{K1}, and the sum of E_{K1} and E_1 remains the same. The bridge is unbalanced because E_{K1} is less than E_{K2}. Current flows through the meter from left to right.

If the negative voltage is removed from the grid on the left side, the bridge will return to its normal balanced condition. Voltages on both sides will be equal, and no current will flow through the meter.

POSITIVE VOLTAGE APPLIED TO ONE GRID



Suppose a positive voltage is applied to the grid of V_{1B}. Plate current in V_{1B} will increase, raising the voltage across R_4. E_{K2} will now be a larger positive voltage than E_{K1}. Current will therefore flow from left to right through the meter.

Importance of Chassis Potential

You have seen that a negative voltage applied to one grid or a positive voltage to the other results in the same direction of current flow through the meter. This fact is used to great advantage in a VTVM.

The common, or negative, test-lead jack is grounded to the chassis of a VTVM. In equipment employing electronic circuits, the chassis is usually at zero (ground) potential for safety purposes. If you have to measure a negative voltage in such equipment, the test leads must not be interchanged in order to cause the meter pointer to move up scale. Placing the common, or negative, lead on the negative side of the voltage would connect this voltage directly to the VTVM chassis and case. This could be very dangerous.

Q3. What voltage across the meter leg would produce full-scale deflection of a 200-μa meter? Assume the total leg resistance is 20K.

Q4. What conditions must exist for zero deflection on the meter in the bridge circuit on the opposite page?

Your Answers Should Be:

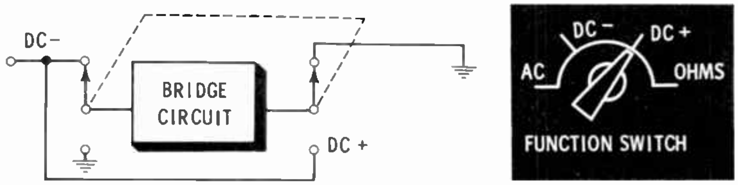
A3. $E = I \times R = 0.0002a \times 20{,}000\Omega =$ **4 volts**

A4. E_{K1} **must equal** E_{K2}. Therefore, R_2 **must equal** R_4, and the **plate currents must be equal.**

Measuring Negative and Positive Voltages

The VTVM eliminates the danger just described by having DC— and DC+ settings on the function switch. The type of bridge circuit about which you have just learned

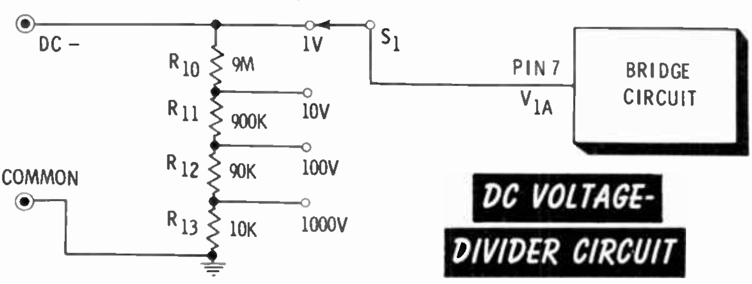
DC REVERSING SWITCH



allows the input voltage to be switched to the grid of the proper tube in the circuit. The same direction of current flow through the meter can thus be maintained regardless of the polarity of the input voltage.

DC Voltage Divider

In a VTVM, the input circuits for the various functions are voltage dividers. A typical DC voltage divider is shown in the diagram below. One end of the string of resistors is attached to the DC pin jack, and the other end is connected

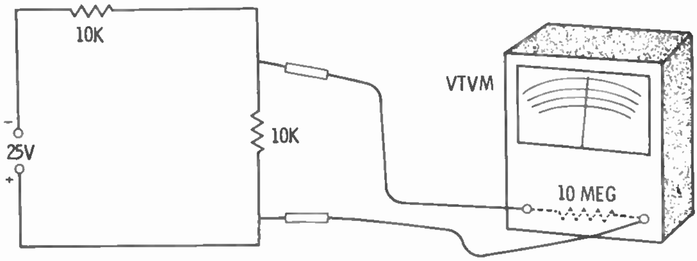


DC VOLTAGE-DIVIDER CIRCUIT

to the **COMMON** jack. A schematic representation of a four-position switch is shown at the right of the voltage divider. Each position represents a tap in the resistor string. Each tap corresponds to a range setting.

The sum of the resistances in the voltage divider is 10 megohms. This large resistance will be in parallel with the measured circuit at any range setting. Loading of the circuit under test is therefore very small.

A VTVM PRODUCES A SMALL LOADING EFFECT

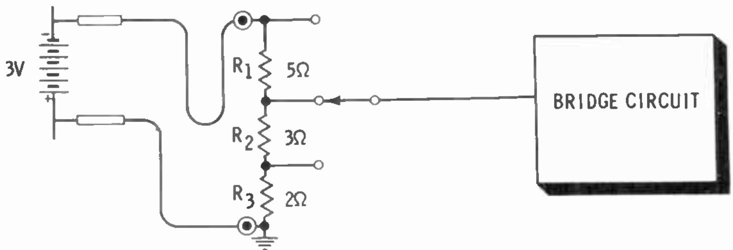


DC Voltmeter Probes

Two different probes for taking measurements are available with a VTVM. The standard probe has a resistor in series with the metal point and the test lead.

DC TEST PROBE

Q5. In the diagram below, how much voltage appears on the grid of the tube in the bridge circuit?



Q6. Refer to the lower illustration on the opposite page. How much voltage is applied to pin 7 of V_{1A} when 1 volt is measured with S_1 positioned as shown?

Q7. How much voltage is applied to pin 7 of V_{1A} when 10 volts is measured with S_1 on the 10-volt tap of the voltage-divider circuit?

Your Answers Should Be:

A5. There is 1.5 volts applied to the grid.

$$I = \frac{E}{R_T} = \frac{3V}{10\Omega} = 0.3 \text{ amp}$$
$$I \times (R_2 + R_3) = 0.3a \times 5\Omega = 1.5V$$

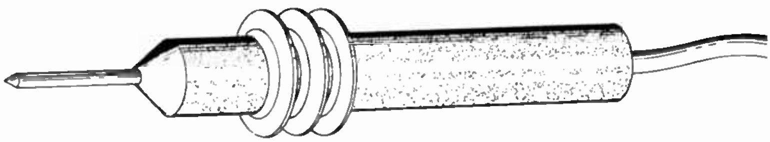
A6. 1 volt.

A7. 1 volt. A voltage of 10 volts is applied across a total resistance (R_T) of 10M. At the 10-volt tap, the resistance to ground is 1M, or 1/10 R_T. Therefore, 1 volt is present at the 10-volt tap.

High-Voltage Probe

A high-voltage probe has an internal series resistor of 25 megohms or more. This probe is used to extend the range of the VTVM above 1,000 volts DC.

HIGH-VOLTAGE DC PROBE



Voltage-Divider Principle

Answers A6 and A7 above illustrate an important point. With the test probes measuring 1 volt, there is 1 volt at the 1-volt tap. When measuring 10 volts there is 1 volt at the 10-volt tap. And, at 100 and 1,000 volts, there is 1 volt at the 100-volt and 1,000-volt taps, respectively. The voltage applied to the bridge circuit must be the same in all ranges to cause the same pointer deflection. Pointer positions are multiplied by the factor indicated by the range setting.

AC Voltage Divider

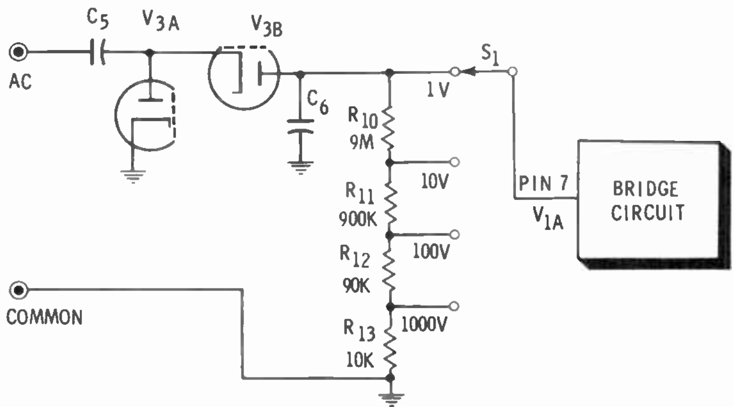
A simplified schematic for an AC voltage divider appears on the next page. It has the same voltage-divider network used in the DC voltmeter circuit.

The main difference between this circuit and the DC circuit is a twin diode for rectifying AC into pulsating DC.

The diode permits measurement of voltages having frequencies from 50 cps to at least 50 kc.

Diodes V_{3A} and V_{3B} and capacitors C_5 and C_6 form a network that converts the AC input voltage into a DC voltage across the voltage divider. Capacitor C_5 also serves to pre-

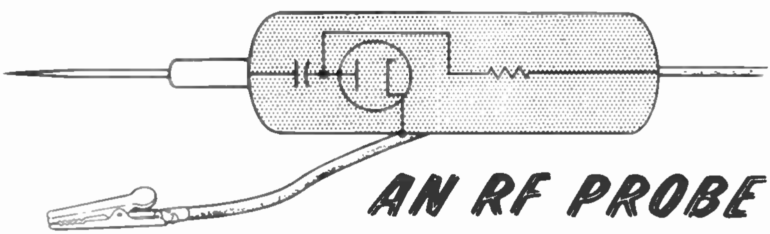
AC VOLTAGE-DIVIDER CIRCUIT



vent the DC that may be present in the input voltage from reaching the bridge circuit. In this arrangement the VTVM actually measures the peak value of the AC voltage. The rms value of a sine wave is 0.707 times the peak value. The scales of most VTVM's are marked to read the rms value.

RF Probe

A special probe for measuring frequencies up to 100 megacycles can be used in the DC jack.



AN RF PROBE

Q8. In addition to being part of the network that converts AC to DC, what is the purpose of capacitor C_5 in the AC voltage-divider circuit above?

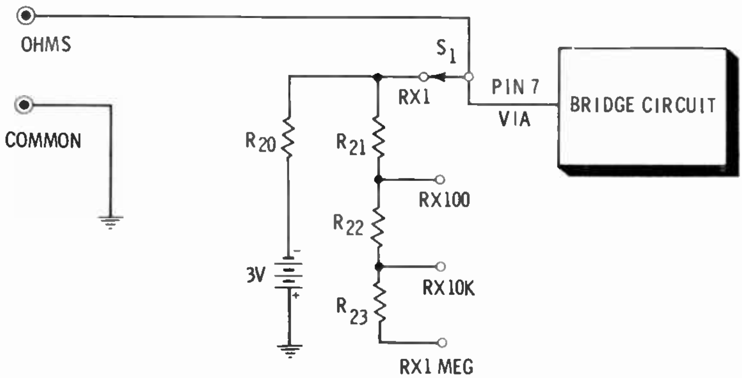
Q9. What is the purpose of the two diodes in the AC voltmeter circuit?

> **Your Answers Should Be:**
>
> **A8.** C_5 is also used as a **blocking** capacitor to prevent a DC component of any measurement from entering the AC measuring circuit.
>
> **A9.** The two diodes **rectify the incoming AC** into pulsating DC.

Ohmmeter Voltage Divider

Some ohmmeter circuits employ a battery as a voltage source. In others a metallic rectifier with a resistor-capacitor filter is used. Whatever the source of voltage, the current normally flows through a voltage-divider network similar to the one below.

AN OHMMETER VOLTAGE DIVIDER



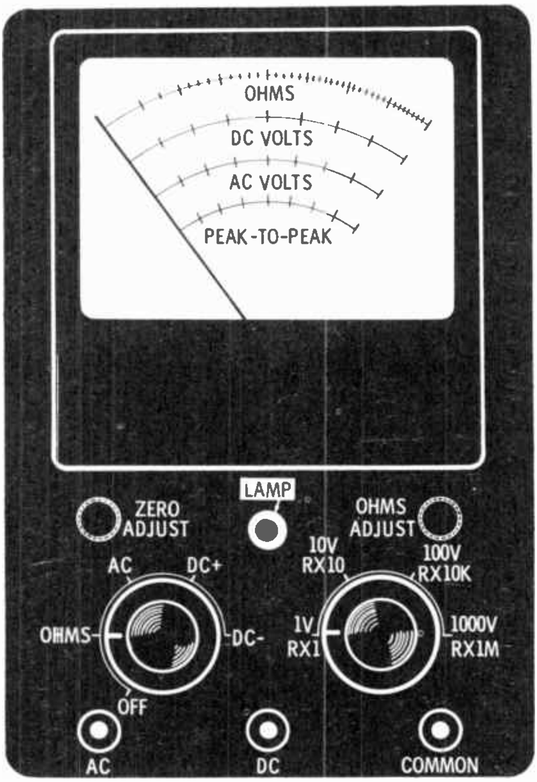
Witn S_1 in the $R \times 1$ position, the voltage applied to the bridge circuit depends on the ratio of the unknown resistance to R_{20}. In the $R \times 100$ position, the voltage depends on the ratio of the unknown resistance to $R_{20} + R_{21}$. The unknown resistances measured on the $R \times 100$ range are 100 times as large as those measured on the $R \times 1$ range. You can see that $R_{20} + R_{21}$ must be 100 times as large as R_{20}. Similar reasoning applies to the $R \times 10K$ and $R \times 1$ MEG ranges.

The ohmmeter scale of a VTVM using this circuit measures 0 to ∞ from left to right—the reverse direction to that of a typical multimeter scale. When the probes are shorted, full-scale deflection will occur. When they are open, the pointer will remain stationary and register ∞. As in the multimeter, the ohmmeter scale is nonlinear.

USING THE VTVM

The same precautions given for the use of multimeters also apply to vacuum-tube voltmeters. Generally, a VTVM is used in the same manner as a multimeter in taking voltage and resistance readings. The illustration below shows how the front panel of a typical VTVM might appear.

A TYPICAL VTVM



Q10. If R_{20} in the circuit on the opposite page is 100 ohms, what is the value of R_{21}?

Your Answer Should Be:

A10. The sum of R_{20} and R_{21} must be 100 times 100Ω, or 10,000Ω. Therefore, R_{21} is 10,000 — 100, or **9,900Ω.**

SPECIAL VTVM PRECAUTIONS

1. Beware of high voltages.
2. When making high-voltage checks, grip the probes well up on the insulated parts of the handles. This reduces the danger of shock and the possibility of adding hand capacitance to the circuit.
3. Always ground the AC test probe after a voltage check. The capacitor in the input circuit may have been charged by a DC voltage.
4. An RF probe can be used to measure voltages having frequencies from about 1 kc and 100 mc. Connect the probe and its ground connection as close together in the circuit as possible.

WHAT YOU HAVE LEARNED

1. A vacuum-tube voltmeter is similar to a multimeter in function, range selection, and use.
2. A VTVM has a higher input impedance (around 10 megohms) than a multimeter. As a result, it has less loading effect on circuits.
3. The range circuits of a VTVM are usually voltage-divider networks. The range switch connects the selected multiplier tap to a vacuum-tube circuit. This circuit regulates the amount of current that will flow through the meter coil.
4. Most VTVM's use some type of bridge circuit. When no measurement is being taken, voltages across the bridge are balanced, and no current flows though the meter. When a measurement is being made, current in one of the tubes increases. This unbalances the voltages across the bridge, causing meter current to flow in proportion to the measurement taken.
5. Safety precautions must be followed when measuring high voltages with a VTVM.

3

The Oscilloscope

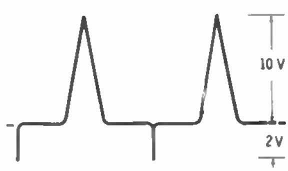
What You Will Learn

An oscilloscope is a test instrument capable of showing the waveforms of sinusoidal and nonsinusoidal signals. You will learn how the oscilloscope performs its various functions to aid the user in gaining valuable knowledge about an electronic circuit. In this chapter you will discover how the oscilloscope can be used to measure the voltage and phase of an applied signal. This chapter will also give you additional information concerning the operation of the cathode-ray tube.

LIMITATIONS OF METERS

You have become acquainted with multimeters and vacuum-tube voltmeters. If asked to describe them in a brief statement, you might say they are instruments capable of measuring the magnitude (size) of certain electrical characteristics. This would be a good description if you added that the characteristics are basically limited to voltage, current, and resistance.

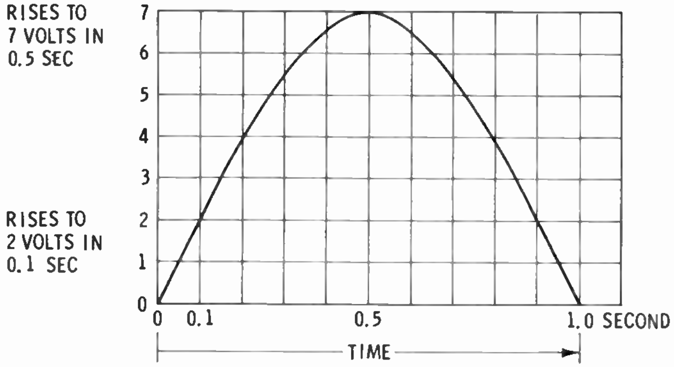
How much information would a multimeter or VTVM tell you about a voltage that varies as shown below?



Your answer might be merely voltage. This would be a good answer, since you did not specify the amount of voltage. A multimeter or a VTVM is designed and has its scales calibrated to measure sinusoidal (sine-wave) AC voltages. It cannot accurately measure a nonsinusoidal voltage. Since the meter pointer is not able to follow the rapid rise and fall of such a voltage, the meter reading, if any, will be only a slight indication.

IMPORTANCE OF WAVEFORMS

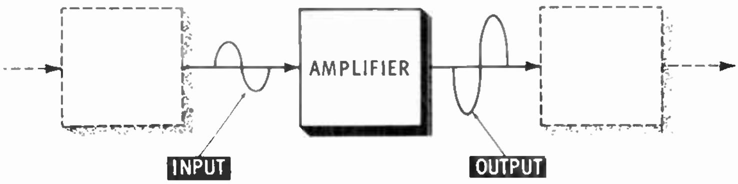
Since a voltage or current can be described in terms of amplitude and time, you can identify and analyze any signal in these terms. A graph or picture of how the amplitude of a signal varies with time is called a **waveform.**



To maintain, troubleshoot, and repair electronic equipment, a technician needs to look at the waveform of a signal passing from one circuit to another. For this, an instrument is needed that will provide a reliable representation of the signal. If the representation matches the desired size and shape of a signal that should occur at the test point, the technician can assume the circuit from which it came is operating as it should. If the representation does not match the signal, the type and amount of difference will help in identifying the cause of the trouble.

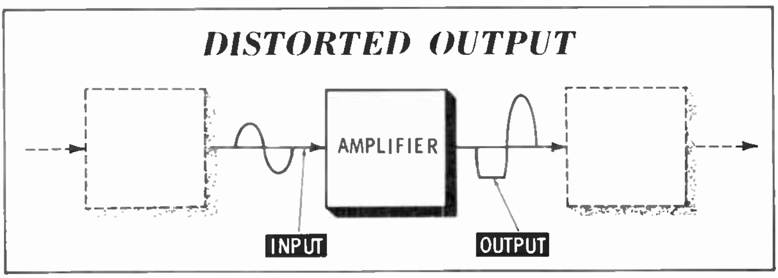
Waveform Characteristics

Each electronic circuit is designed to accomplish a specific purpose. The purpose determines the input and output requirements of the circuit. The input signal of one circuit is normally the output signal of the preceding circuit, or stage. The output signal is the signal required as the input to the next stage. Circuit components are selected and connected in such a way as to convert the input to the required output for each stage.



An amplifier, for example, usually receives a small signal from a preceding stage and converts it to a larger signal. In other words, the stage amplifies the signal.

It is often helpful to be able to determine if the change from input to output signal has been made properly. For example, it is desirable to know if the shape of a signal waveform is changed when the signal passes through an amplifier circuit.



In the figure above, the leading half of the cycle in the output has been distorted. You would, therefore, suspect that the amplifier had gone into saturation and was clipping off that portion of the wave. You could also reasonably conclude that the most probable cause of the trouble was a change in tube bias.

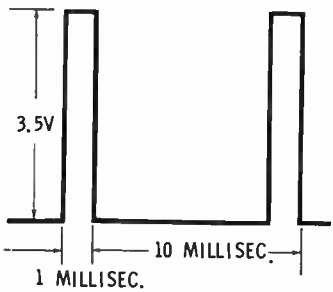
Q1. What determines the input and output requirements of a circuit?

Q2. What signal characteristics are shown by a waveform?

> **Your Answers Should Be:**
>
> **A1.** The input and output requirements of a circuit are determined by the **purpose of the circuit.**
>
> **A2.** The **amplitude and time** of a signal are shown by a waveform.

Waveform Characteristics

Each pulse below has an amplitude of 3.5 volts and a width of 1 millisecond. The pulse repeats itself every 10 millisec-

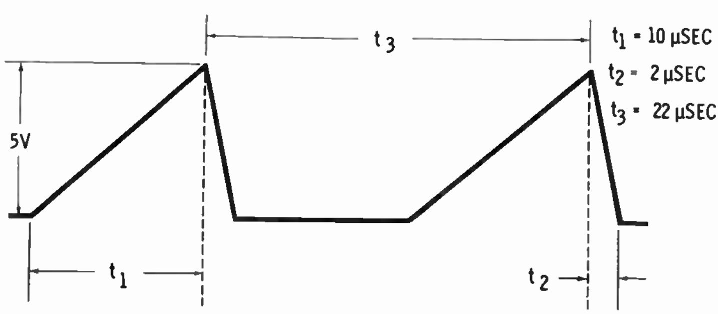


A PULSE WAVEFORM

onds. Since one pulse occurs every 0.01 second, the pulse frequency is 100 pulses per second.

$$\text{Frequency} = \frac{1}{\text{time}}$$

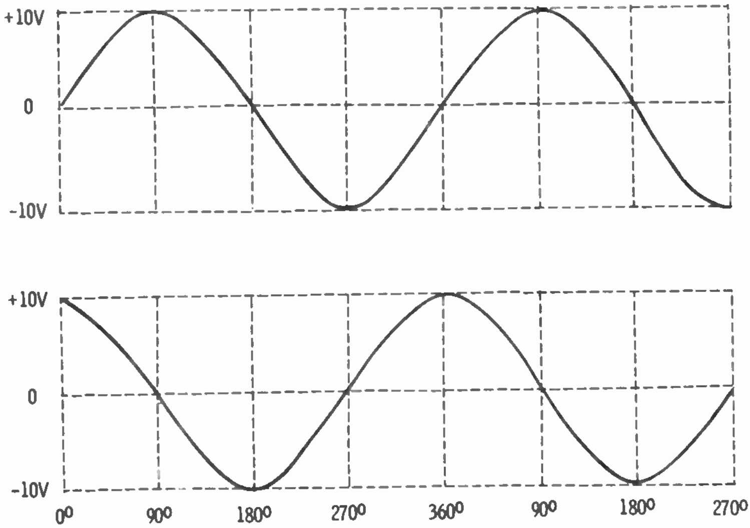
A sine wave is a curved waveform. There are other waves whose increases and decreases appear to be straight lines. The pulse waveform in the above figure is an example. Another example is a **sawtooth** waveform.



A SAWTOOTH WAVEFORM

Another observation that can be made about waveforms is their phase relationship. What is the relationship of their amplitudes at a given instant of time? Observe the two waveforms in the following illustration.

PHASE RELATIONSHIP



The top waveform (sine wave) rises from zero to 10 volts positive in 90° (one-quarter cycle). During the same time period the bottom sine wave decreases from 10 volts to zero. In other words, the two are 90° out of phase.

These and other characteristics of waveforms can be determined by plotting amplitude against time. Even if he had the means of measuring small changes in time, man's vision is too slow to follow the rapid rise and fall of the amplitude. He could not make an accurate plot. The oscilloscope does this for him electronically. It presents a pictorial representation of an amplitude-versus-time plot of the waveform.

Q3. What is one type of waveform that appears to be made up of straight-line segments?

Q4. Why does the electronics troubleshooter need an oscilloscope?

Your Answers Should Be:

A3. A **sawtooth waveform** is one that appears to be made up of straight-line segments.

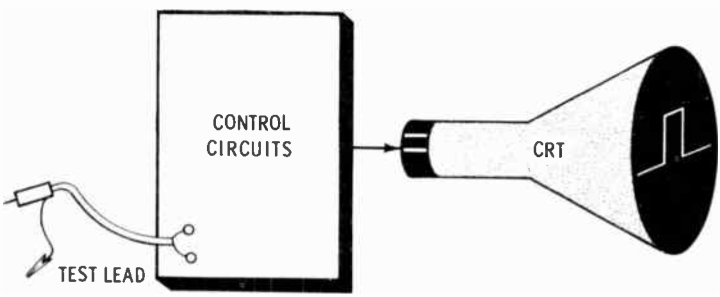
A4. The electronics troubleshooter needs an oscilloscope **to see an accurate representation of** various **circuit signals.**

WHAT IS AN OSCILLOSCOPE?

An oscilloscope is an indicator. It indicates the shape of a signal appearing at a test point. Some oscilloscopes are better at showing a reliable reproduction of waveforms than others. The difference is merely one of design. All oscilloscopes function in accordance with the same set of fundamentals. If you learn how one oscilloscope works and how it can be used, you can easily learn how to operate others.

All oscilloscopes contain a **cathode-ray tube** (CRT) and a group of **control circuits.** The CRT displays the waveform. The control circuits present the signal to the CRT. A set of test leads brings the waveform to the control circuits.

THE OSCILLOSCOPE



A typical oscilloscope will be described in terms of how the cathode-ray tube and the control circuits function. The test leads are only slightly different from those with which you are already familiar. Since the control circuits are designed to operate the CRT, the cathode-ray tube will be studied first.

CATHODE-RAY TUBES

The cathode-ray tube is a vital part of a television set. The CRT operates by moving a controllable beam of electrons across the inside face of the tube. The number of electrons in the beam is determined by the blacks, grays, and whites of the scene the TV camera is viewing. White is produced by a large number of electrons striking a chemical coating on the inside of the tube. The electrons cause the coating to give off light. Black is achieved by stopping the electron flow, and shades of gray are obtained by varying the amount of electrons between the amounts required for black and white.

The picture is "painted" on the screen by the narrow electron beam moving back and forth across the tube many times a second. This movement is due to a varying magnetic field produced by a set of coils around the neck of the CRT.

The principle of putting a picture of a waveform on the screen of an oscilloscope is similar. The movement of an electron beam is controlled **electrostatically** so that the beam traces out the pattern of the waveform being measured. As in the TV tube, electrons illuminate a coating on the inside of the tube.

Electrostatics

To understand how a CRT operates requires a review of what you learned about **electrostatic fields.** As you recall, an electrostatic field is a region in which electric forces are acting.

An electrostatic field can be developed between two charged plates. If one plate is negative with respect to the other, the direction of the electric force can be determined.

Q5. A waveform can be described in terms of its vertical and horizontal dimensions. What are these dimensions?

Q6. A cathode-ray tube can display a picture on its face, or screen. What causes the picture to appear?

Q7. An oscilloscope is made up of a cathode-ray tube and a group of control circuits. What is the function of the control circuits?

Q8. What is an electrostatic field?

Your Answers Should Be:

A5. The vertical and horizontal dimensions of a waveform are **amplitude and time.**

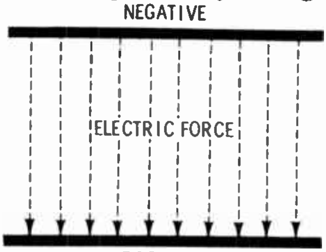
A6. The picture on a CRT is developed by a **moving electron beam** that strikes and illuminates a chemical coating on the inside face of the tube.

A7. The function of the oscilloscope control circuits is to **present a signal to the CRT.**

A8. An electrostatic field is a **region in which electric forces are acting.**

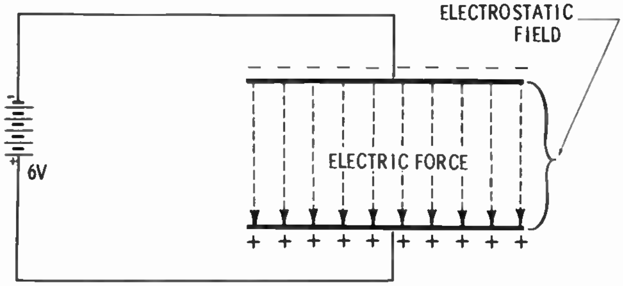
Forces in an Electrostatic Field

In the figure below, lines of electric force take a direction from negative to positive. This means a negatively charged body entering the field would be moved downward (from negative to positive). A positively charged body, however,



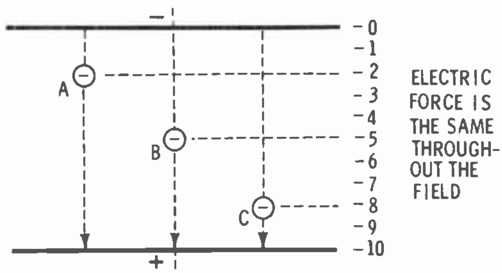
would be moved upward (positive to negative). Like charges repel, and unlike charges attract. Do you recall how an electrostatic field is formed?

An electrostatic field is formed with a voltage source and a pair of metallic plates to hold the charges.



If a 6-volt battery is connected to the plates in the manner shown on the opposite page, the battery will draw electrons from the bottom plate and deposit them on the top plate until the difference in potential between the plates equals the battery voltage. The potential of the plate having an excess of electrons will be negative. The other plate, being deficient in electrons, will be positive.

As indicated in the diagram, an electric force exists in an electrostatic field. This force can act on other charges entering the field.



In the figure above, three electrons are located in an electrostatic field. All three are attracted by the positive plate and repelled by the negative plate. The distance between the plates is marked off in 10 equal units; electron A is 2 units away from the negative plate, electron B is 5 units away, and electron C is 8 units removed.

A uniform electric field is established between the two plates. This means that an electron in one part of the field has the same force acting on it as an electron in another part of the field. Thus electrons A, B, and C all have the same amount of force acting on them, even though each is in a different position relative to the plates. Since the same amount of force is exerted on each electron, the relative time of travel of each electron depends on its distance from the positive plate.

Q9. A positive ion rests in an electrostatic field. Toward which plate will it move?

Q10. What causes an electrostatic field to exist between two metallic plates?

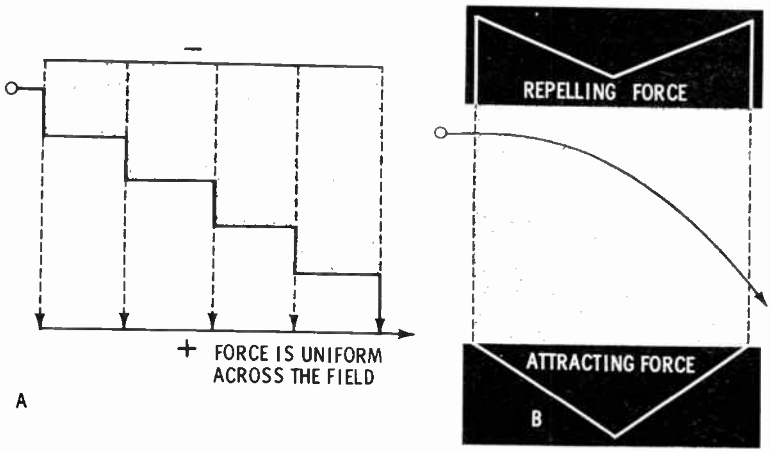
Your Answers Should Be:

A9. The positive ion will move **toward the negative plate.**

A10. An electrostatic field is formed when **one plate has an excess of and the other a deficiency of electrons.**

Distribution of Electric Force

Electrostatic force is conventionally represented by dashed lines with an arrowhead showing the direction in which the force is acting. Is an individual force represented by each

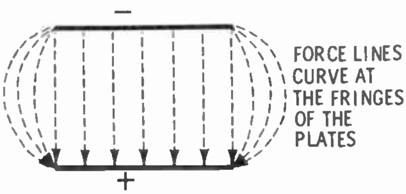


line? If this were true, an electron traveling between the plates with sufficient velocity to pass through the field would cover the distance in a stair-step pattern, as in A above. It is known that the path of an electron through a force field is curved, as in figure B. Force does not exist in distinct beams; it is continuous and uniform across the field. However, it is easier to talk about the field in terms of imaginary lines.

Distribution of Force Lines

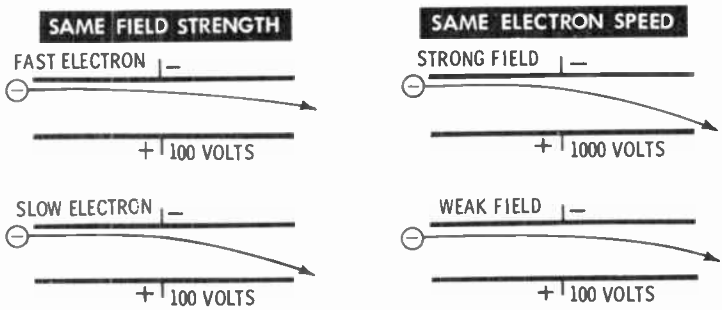
Thus far you have visualized lines of electric force as being straight and parallel to each other. This is not always true. The following diagram shows that part of the lines of force can take a curved direction. Remember, the lines shown are only representative of a continuous field.

Lines directly between the plates are parallel to each other. Because they are equal lines of force, they tend to repel each other in a horizontal direction. The repelling effect is equal



in all directions around a line of force. The lines of force at the edges of the field are bent outward because there are no lines outside the field to repel them inward.

An electron in motion through an electric field will tend to follow the direction of the lines of force. The amount that the electron path will bend in the direction of the lines of force depends on the velocity of the electron and the potential of the electric field. A fast electron may speed through the field with little curvature to its path. The path of a slow electron would curve more. Electrons of equal velocity would curve more when they are passing through a strong rather than a weak field.



Q11. Does an electrostatic field consist of distinct and separate lines of force, or is it continuous?

Q12. Does a moving electron tend to take a path parallel to the direction of force or perpendicular to it?

Q13. Why are the lines of force at the edge of an electrostatic field curved?

Your Answers Should Be:

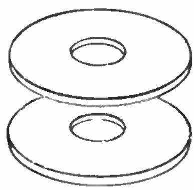
A11. An electrostatic field is **continuous.**

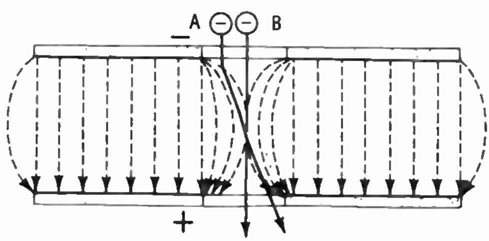
A12. A moving electron will **tend to** take a path **parallel** to the direction of electric force.

A13. The lines of force at the edge of an electrostatic field are curved because **there are no lines of force outside the field to repel them inward.**

Electrostatic Forces Between Circular and Tubular Plates

In the diagram below is shown an electrostatic field between two plates having center holes. Observe the curvature of the force lines under the holes.

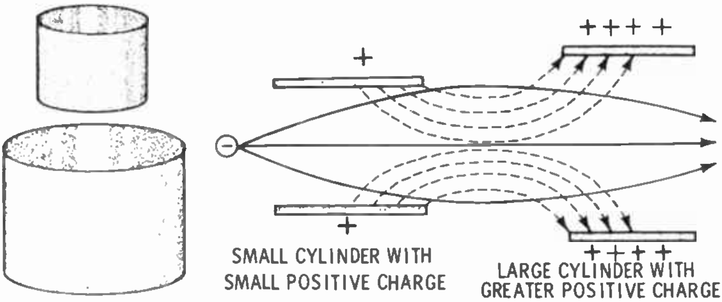




Since its path is parallel to the force lines, electron B will pass straight through the axis (center line) of the holes. Electron A starts in the same direction as electron B. When electron A enters the field, it turns in the direction of the force lines. Just before it leaves the field, it is turned even further and in the direction of the curvature of the force lines.

Suppose a small and a large cylinder, both charged with a positive potential, are placed so the electrons must pass through them. Also suppose the larger cylinder has a more positive charge. The distribution of the lines of force would look like the illustration on the opposite page.

An electron in the space at the left of the small cylinder will be attracted toward the cylinder by the positive charge. If the electron is traveling along the axis of the cylinder, it will pass through without crossing a line of force. As it



approaches the larger, more positively charged cylinder, the velocity of the electron will increase.

An electron entering the small cylinder at an angle will cut the lines of force and be turned in their direction as shown by the top and bottom electron paths in the figure. As it approaches the larger cylinder, the electron will be accelerated by the higher positive potential. Because of the higher electron velocity, the force lines in the larger cylinder will have a smaller turning effect on the electron. If the difference of potential between the cylinders is adjusted properly, the electrons will unite at a given distance after passing through the second cylinder. This action of the electrons as they pass through the influence of the two cylinders provides a convenient method of **focusing** the electron beam.

Q14. As an electron approaches the larger cylinder, the velocity of the electron will ---------.

Q15. Why is the above statement true?

Q16. What path will the electron take if it is on the axis of both cylinders as it enters the first?

Q17. What path will the electron take if the small cylinder is charged positively and the large cylinder is charged negatively?

Your Answers Should Be:

A14. As an electron approaches the larger cylinder, the velocity of the electron will **increase.**

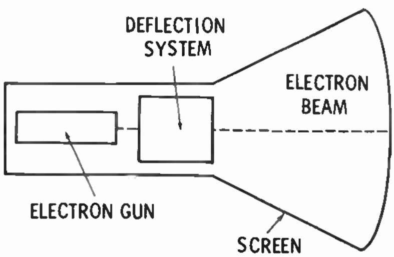
A15. The above statement is true because **the larger cylinder is more positively charged.** It will attract the electron with a greater force, thereby increasing the velocity of the electron.

A16. The electron will move in a **straight path** through both cylinders.

A17. The electron will be **attracted by the small cylinder,** but **repelled by the large cylinder.**

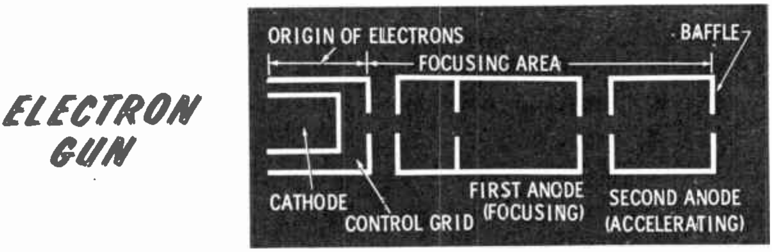
ELECTRON GUN

Cathode-ray tubes used in oscilloscopes consist of an **electron gun,** a **deflection system,** and a **fluorescent screen.** All elements are enclosed in an evacuated container, usually glass. The electron gun generates electrons and focuses them into a narrow beam. The deflection system moves the beam across the screen in the manner desired. The screen is coated with a material that glows when struck by the electrons.



CATHODE-RAY TUBE

An electron gun has a cathode to generate electrons, a grid to control electron flow, and a positive element to accelerate electron movement. The control grid is cylindrical in shape and has a small opening in a **baffle** at one end. The positive element consists of two cylinders, called **anodes.** They also contain baffles (or plates) having small holes in their centers. The main purpose of the first anode is to focus the electrons into a narrow beam on the screen. The second anode speeds up the electrons as they pass.



Cathode and Grid

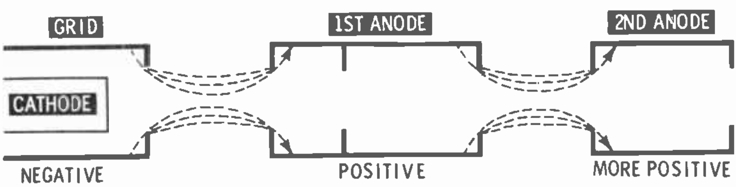
The cathode is indirectly heated and emits a cloud of electrons. The control grid is a hollow metal tube placed over the cathode. A small opening is located in the center of a baffle at the end opposite the cathode. The grid is maintained at a negative potential with respect to the cathode.

A high positive potential on the anodes pulls electrons through the hole in the grid. Since the grid is near the cathode, it can control the number of electrons that are emitted. As in an ordinary vacuum tube, the negative voltage of the grid can be changed to vary electron flow or stop it completely. The brightness of the image on the fluorescent screen is determined by the number of electrons striking the screen. **Intensity** (brightness) can, therefore, be controlled by the voltage on the control grid.

Focus Control

Focusing is accomplished by controlling the electrostatic fields that exist between the grid and first anode and between the first and second anodes. Study the diagram below. See if you can determine the paths of electrons through the gun.

ELECTROSTATIC FIELDS



Q18. Which element controls the number of electrons striking the screen?

Q19. Which element controls the focus of the beam?

Your Answers Should Be:

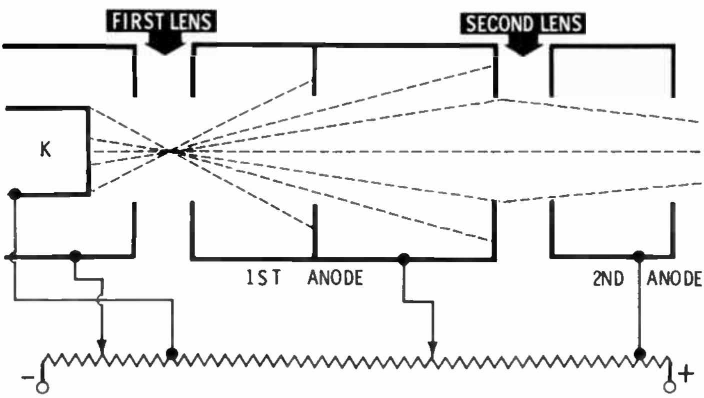
A18. The **control grid** controls the number of electrons striking the screen.

A19. The **first anode** controls the focus of the beam.

Electrostatic Lenses

The diagram below shows electrons moving through the gun. The electrostatic field areas are often referred to as **lenses.** The first electrostatic lens causes the electrons to

FORMATION OF ELECTRON BEAM

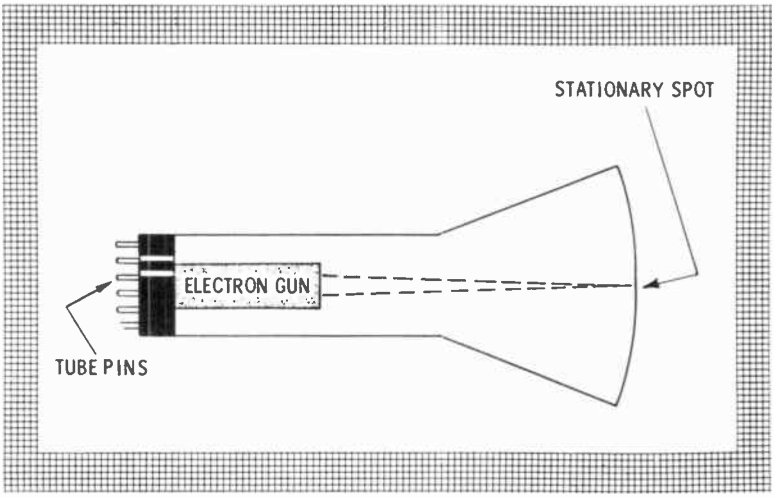


cross at a focal point within the field. The second lens bends the spreading streams and returns them to a new focal point.

The diagram also shows the voltage relationships on the electron-gun elements. The cathode is at a fixed positive voltage with respect to ground. The grid is at a variable negative voltage with respect to the cathode. A fixed positive voltage of several thousand volts is connected to the second (accelerating) anode. The potential of the first (focusing) anode is less positive than the potential of the second anode. It can be varied to place the focal point of the electron beam on the screen of the tube. Control-grid potential is established at the proper level to allow the correct number of electrons through the gun for the desired screen intensity.

ELECTRON-BEAM DEFLECTION SYSTEM

The electron beam is developed, focused, and accelerated by the electron gun. It appears on the screen of the CRT as a small, bright dot. If the beam is left in one position, the electrons will soon burn away the illuminating coating in that one area. To be of any use, the beam must move.



As you have learned, an electrostatic field can bend the path of a moving electron.

Assume the beam of electrons passes through an electrostatic field between two plates. Since electrons are negatively charged, they will be deflected in the direction of the electric force (from negative to positive). The electrons will follow a curved path through the field. When the electrons leave the field, they will take a straight path to the screen at the angle at which they left the field. Although the beam is still wide (the focal point is at the screen), all the electrons will be traveling toward the same spot. This is assuming, of course, that the proper voltages are existing on the anodes which produce the electrostatic field. Changing the voltages changes the focal point of the beam.

Q20. Why are the electrostatic fields between electron-gun elements called lenses?

Q21. What is the function of the second anode?

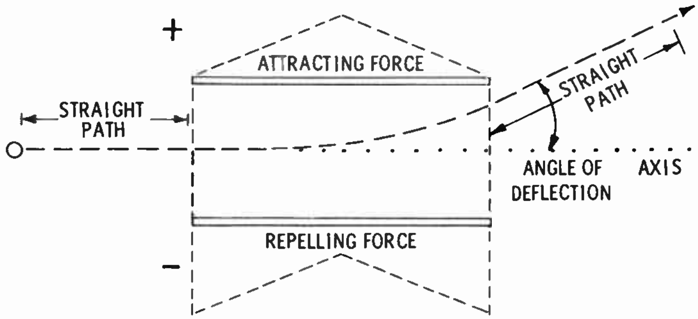
Your Answers Should Be:

A20. They are called lenses because **the fields bend electron streams** in the same manner that optical lenses bend light rays.

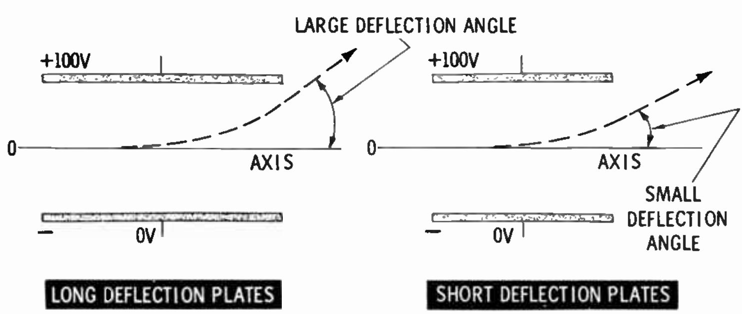
A21. The second anode **accelerates the electrons** emerging from the first anode.

Factors Influencing Deflection

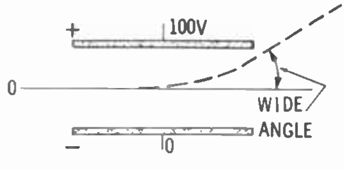
The **angle of deflection** (the angle the outgoing electron beam makes with the axis between the plates) depends on several factors. These factors include the length of the deflection field, spacing between the deflection plates, difference of potential between the plates, and accelerating voltage on the second anode.



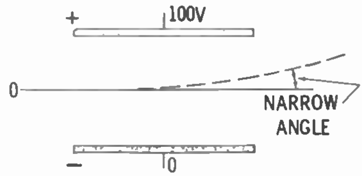
Length of Field—A long field has more time to exert its deflecting forces on an electron beam than a shorter field. Therefore, it bends the beam to a greater deflection angle. This fact assumes that all other factors are equal.



Spacing Between Plates—The closer together the plates, the more effect the electric force has on the electron beam.

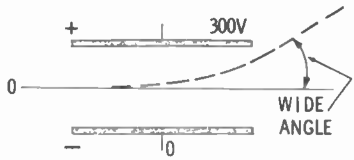


CLOSE SPACING

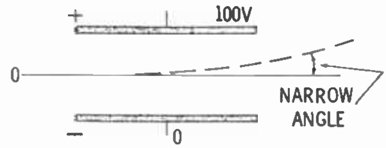


WIDE SPACING

Difference of Potential—Intensity of the electric force can also be varied by the difference of potential on the plates.

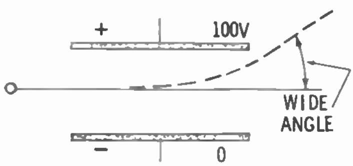


HIGH POTENTIAL

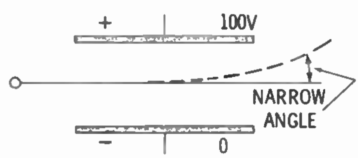


LOW POTENTIAL

Beam Acceleration—The faster the electrons are moving, the smaller their deflection angle will be.



LOW ACCELERATION



HIGH ACCELERATION

Q22. Is the deflection angle in a CRT more easily changed by plate spacing or plate potential?

Q23. Deflection angle is more with (long, short) plates.

Q24. Is the deflection angle greater with close or wide spacing of plates?

Q25. Is the deflection angle greater with high or low potential on the plates?

Q26. Is the deflection angle greater when the beam is moving fast or slow?

Q27. Which of the above methods would be used in a CRT to change the deflection angle?

Your Answers Should Be:

A22. **Plate potential** is more convenient to control.

A23. Deflection angle is more with **long** plates.

A24. It is greater with **close spacing.**

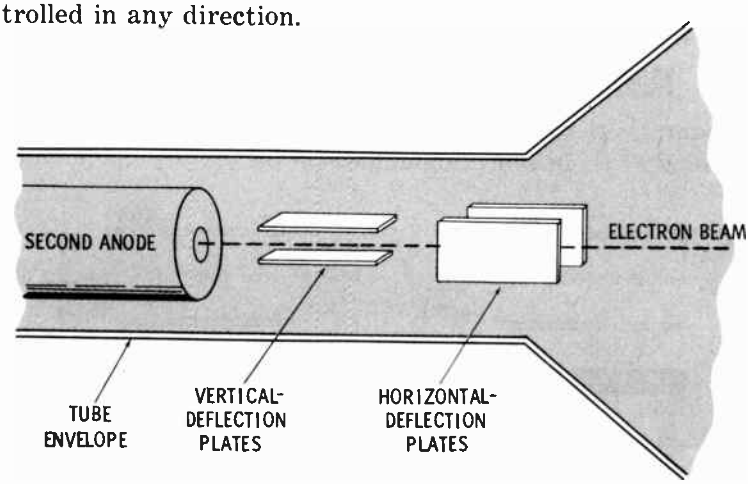
A25. It is greater with **high potential.**

A26. It is greater with a slow **beam.**

A27. **Varying the potential on the deflecting plates** would be the method used to change deflection angle in a CRT.

Vertical and Horizontal Plates

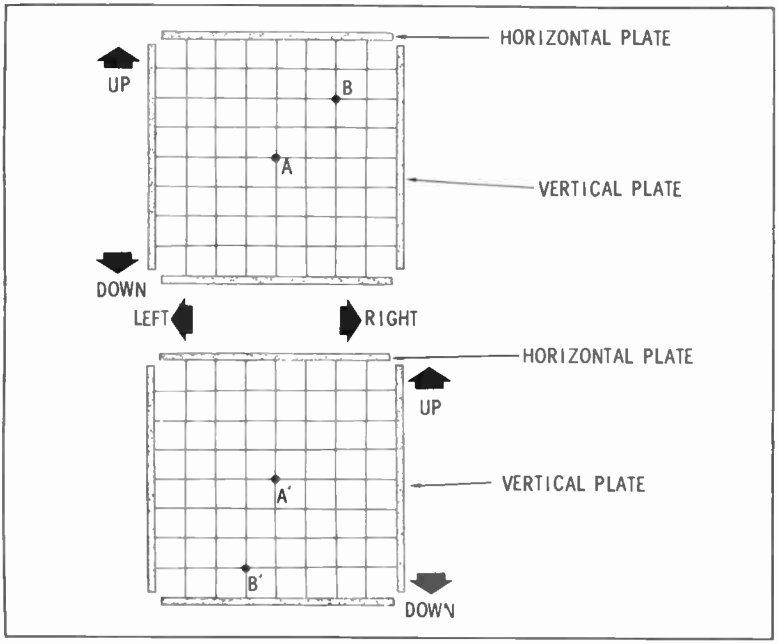
If two sets of deflection plates are placed at right angles to each other inside a CRT, the electron beam can be controlled in any direction.



DEFLECTION-PLATE ARRANGEMENT

By varying the potential of the vertical-deflection plates, the spot on the face of the tube can be made to move up and down. The distance will be proportional to the change in potential between the plates. Changing the potential difference between the horizontal-deflection plates will cause the beam to move a given distance from one side to the other. There are directions other than up-down and left-right. The beam must be deflected in all directions.

Study the two diagrams below. You should be able to see that the beam can be moved to any position on the screen simply by moving it both vertically and horizontally.



In the top diagram above, position A of the beam is in the center. It can be moved to position B by going up two units and then right two units. Movement of the beam is the result of the simultaneous action of both sets of deflection plates. The electrostatic field between the vertical plates moves the electrons up an amount proportional to two units at the screen. As the beam passes between the horizontal plates, it is moved to the right an amount proportional to two units at the screen.

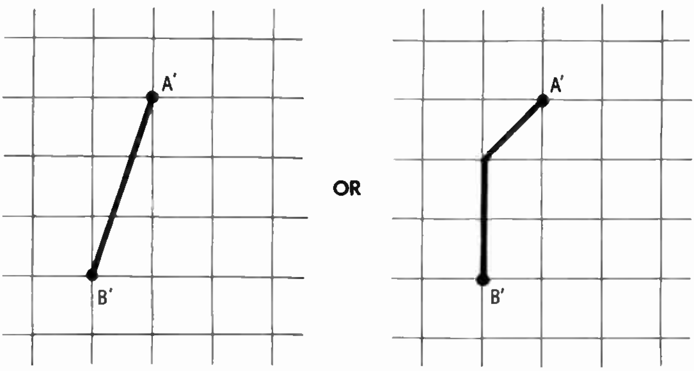
Q28. In the bottom figure, how many units and in which direction will each set of deflection plates move the beam from A′ to B′?

Q29. Draw a line on a rough graph to represent the picture seen on the screen as the spot moves from A′ to B′ in the bottom figure in the above illustration.

Your Answers Should Be:

A28. The vertical plates will move the beam **down three units.** The horizontal plates will move the spot **one unit to the left.**

A29. The picture on the screen will look like:



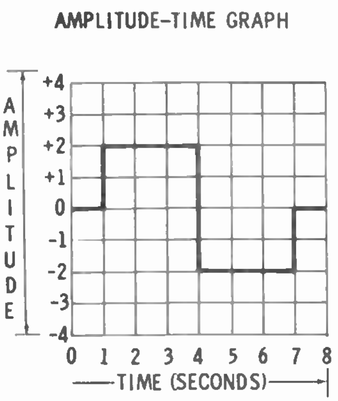
If the amount of deflection (in A29 above) to the left and down occurred so that each set of plates acted at the same time, the picture would be like the one on the left above. For example, if the vertical plates moved the beam downward at the rate of 1 unit per second and the horizontal plates moved it to the left at the rate of ⅓ unit per second, both movements would have been completed in 3 seconds at point B′. The result would be a straight line.

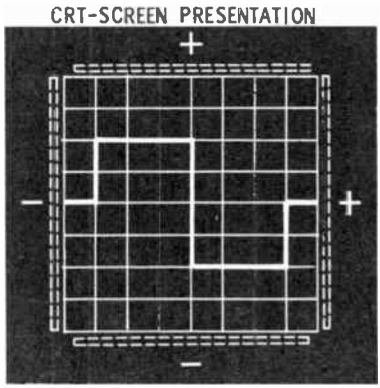
In the example on the right, the potential on the vertical and horizontal plates changes at the same rate. In the same time period, say 1 second, both plates move the beam 1 unit. The horizontal plates have completed their task at the end of 1 second, but the vertical plates have moved the beam only ⅓ of the required distance. If this were true, the picture on the right would appear on the screen.

Amplitude Versus Time

Do you recall the statement made earlier that waveforms could be described in terms of amplitude and time? You have just seen how the movement of the CRT beam depends on both potential (amplitude) and time.

From zero time to 1 second the waveform in the diagram below is at zero volts. In the CRT the vertical plates remain at the same potential difference while the potential difference between the horizontal plates increases 1 unit in the direction necessary to move the beam toward the right.





When time is equal to 1 second the waveform rises to +2 volts. The potential difference between the vertical plates increases enough to move the electron beam 2 units in the positive direction. From 1 to 4 seconds, the waveform remains at +2 volts and then decreases to —2 volts. As the horizontal-plate potential difference increases by 3 units, the vertical potential remains the same (+2 units) and then drops sharply 4 units. For the next 3 seconds the waveform remains at —2 volts. In the CRT, the potential difference between the vertical plates remains unchanged as the horizontal potential increases uniformly by 3 units.

The vertical-plate potential difference follows the **voltage** of the waveform. The horizontal-plate potential follows the passage of **time**. Together they determine the **trace** (image produced on the screen by the moving beam).

Q30. Waveforms can be described in terms of ---------- and ----.

Q31. The horizontal-deflection plates are used to reproduce the ---- ----------.

Q32. The vertical-deflection plates are used to reproduce the ---------- ----------.

Your Answers Should Be:

A30. Waveforms can be described in terms of **amplitude** and **time.**

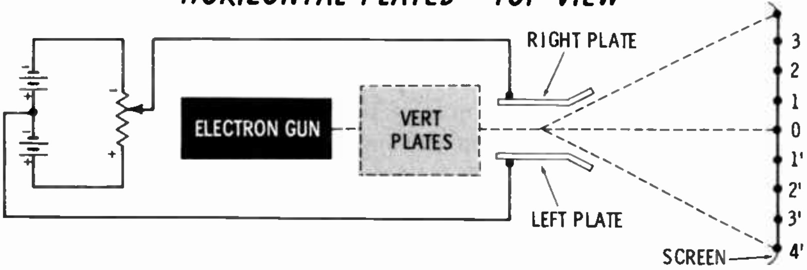
A31. The horizontal-deflection plates are used to reproduce the **time component.**

A32. The vertical-deflection plates are used to reproduce the **amplitude component.**

Voltage Control of Horizontal Plates

Assume that the resistance of the potentiometer in the figure below is spread evenly along its length. When the arm of the potentiometer is at the middle position, there is the same potential on each plate. Since there is zero potential

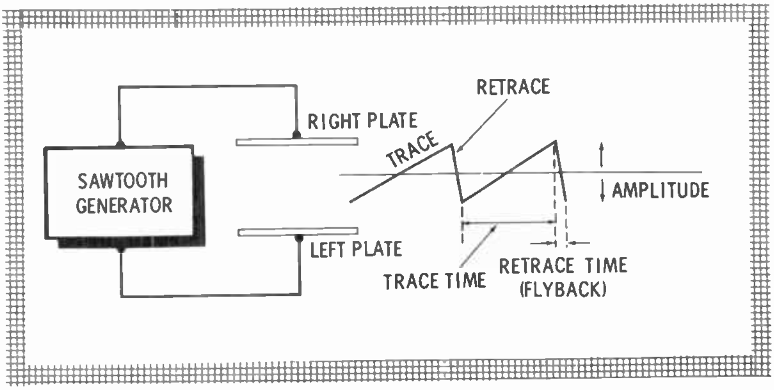
HORIZONTAL PLATES—TOP VIEW



difference between the plates, an electrostatic field is not produced. The beam will be at zero on the screen. If the arm is moved downward at a uniform rate, the right plate will become more positive than the left. The electron beam will move from 0 through 1, 2, 3, and 4 in equal time intervals. If the potentiometer arm is moved at the same rate in the opposite direction, the right plate will decrease in positive potential. The beam returns to the zero position when the potential difference between the plates again become zero. Moving the arm toward the other end of the resistance will cause the left plate to become more positive than the right. The direction of the electric force reverses, and the beam moves from 0 through 4′. If the movement of the potentiometer arm is at a linear (uniform) rate, the beam will move at a steady rate.

The ends of the deflection plates are bent outward to permit wide-angle deflection of the beam. The vertical plates are bent in the same manner.

Moving a potentiometer arm is satisfactory for purposes of illustration, but in real oscilloscopes this is not a practical way to vary the horizontal-deflection voltage. Nearly all oscilloscopes with electrostatic deflection use a sawtooth waveform applied to the horizontal plates to produce horizontal deflection of the beam.



At the reference line, the potential on both plates is equal. Below the line the waveform makes the left plate more positive, and above the line the right plate is made more positive than the other. The waveform amplitude causes a uniform movement of the beam across the screen. The retrace line (trailing edge of the waveform) brings the beam quickly back to the starting point.

Q33. How do most oscilloscopes obtain a linear rate of deflection for use as a time base?

Q34. Why are the ends of the deflection plates bent outward?

Q35. In the illustration on the opposite page, what is the potential difference between the deflection plates when the potentiometer is centered?

Q36. What is the positive-going section of the sawtooth waveform called?

Q37. What is the negative-going section of the sawtooth waveform called?

Your Answers Should Be:

A33. Most oscilloscopes use a **sawtooth waveform** applied to the horizontal plates of the CRT.

A34. They are bent outward to **permit wide-angle deflection** of the beam.

A35. The potential difference is **zero.**

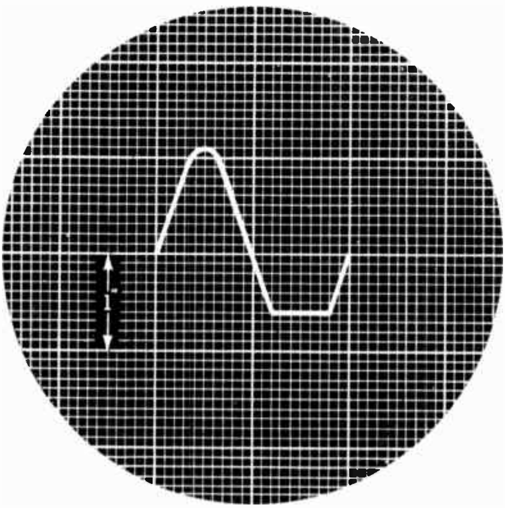
A36. It is called the **trace portion.**

A37. It is called the **retrace portion.**

CRT Graticule

It is possible to cover the face of the CRT with a sheet of plastic on which are scribed horizontal and vertical lines. This marked plastic sheet is called a **graticule.**

CATHODE-RAY TUBE SCREEN



The graticule can be used to determine the voltage of waveforms because the **deflection sensitivity** of a CRT is uniform throughout the vertical plane of the screen. Deflection sensitivity is a constant which is dependent on the construction of the tube. It states the number of inches, centimeters, or millimeters the beam will be deflected for each volt of potential difference applied to the deflection plates. Deflection sensitivity is directly proportional to the physical length of the deflection plates and their distance from the screen. It is inversely proportional to the distance between the plates and to the second-anode voltage.

Deflection sensitivity for a given CRT might be 0.2 millimeter (mm) per volt. This means the spot on the screen will be deflected 0.2 mm (about 0.008 inch) when a difference of one volt exists between the plates. Sometimes the reciprocal of deflection sensitivity (called **deflection factor**) is given. The deflection factor for the example given would be 1/0.008, or 125 volts per inch. Sensitivity is usually measured in inches per volt and deflection factor in volts per inch.

In the above example, 125 volts applied between one set of plates would deflect the beam one inch on the screen. This means that the deflection caused by small signals could not be observed. For this reason, the deflection plates are connected to amplifiers that magnify the signals.

Assume that a peak-to-peak value of a known voltage applied to the oscilloscope indicates that each inch marking on the graticule is equal to 60 volts. Each of the ten subdivisions will therefore have a value of 6 volts. Most oscilloscopes have controls to **attenuate** (decrease) or increase the strength of a signal before the signal is placed on the deflection plates. **Attenuator** and **gain-control** settings must not be disturbed after the calibration has been made. For maximum accuracy, recalibrate the graticule each time a voltage is to be measured.

Q38. If the graticule in the figure on the opposite page has been calibrated to 50 volts per inch, what are the values of the positive and negative peaks of the waveform?

Q39. What is deflection sensitivity?

Q40. In what units is deflection sensitivity measured?

Q41. What is the reciprocal of deflection sensitivity called?

Q42. Deflection sensitivity is inversely proportional to what? It is directly proportional to what?

Q43. How is a signal magnified for screen presentation?

Q44. What must be done for maximum accuracy each time a voltage is to be measured with a graticule?

Your Answers Should Be:

A38. The values are **55 volts** for the positive peak and **30 volts** for the negative peak.

A39. Deflection sensitivity states **the distance that the spot on the screen will be deflected for each volt of potential difference applied to the deflection plates.**

A40. Deflection sensitivity is measured in **inches per volt.**

A41. **Deflection factor** is the reciprocal of deflection sensitivity.

A42. Deflection sensitivity is inversely proportional to the **distance between the plates and the accelerating voltage on the second anode.** It is directly proportional to the **length of the deflection plates and the distance from the plates to the screen.**

A43. **Amplifiers** magnify the signal.

A44. **The graticule must be recalibrated.**

CRT Designation

Cathode-ray tubes are designated by a tube number, such as 2AP1, 2BP4, 5AP1A, etc. The first number identifies the diameter of the tube face. Typical diameters are 2 inches, 5 inches, and 7 inches. Tubes can have diameters up to 24 inches or more. The first letter designates the order in which a tube of a given diameter was registered. The letter-digit combination indicates the type of phosphor (glowing material) used on the screen. Phosphor P1, which is used in most oscilloscopes, produces a green light at medium **persistence.** P4 provides a white light and has a short persistence. Persistence refers to the length of time the phosphor glows after the electron beam is removed. If a letter appears at the end, it signifies the number of the modification after the original design.

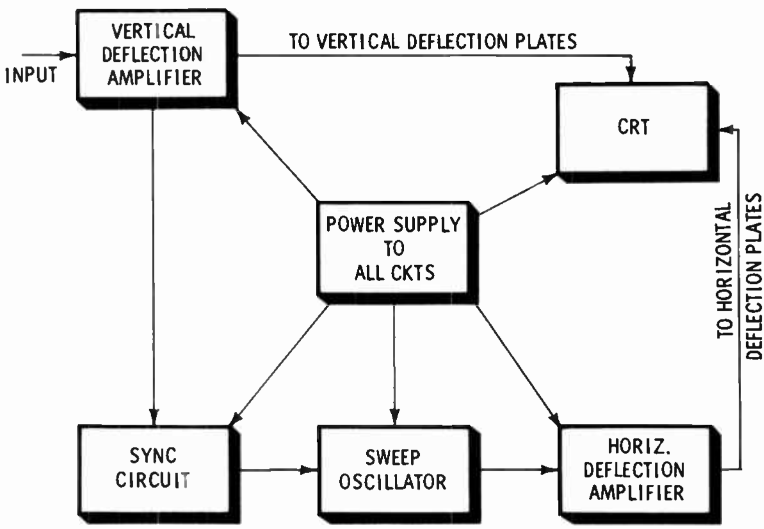
CRT Safety

Handle the cathode-ray tube with a great deal of care. Because of its size and air-evacuated condition, a tremendous amount of pressure is exerted inward over all its surface. A bump or even a scratch may weaken the glass, causing it to **implode** (opposite of explode but with the same results). Pieces of glass and parts will fly in all directions. When replacing a CRT, store the old tube in the box which the new one came in for safely disposing of it later.

CONTROL CIRCUITS

Although the cathode-ray tube is a highly versatile device, it cannot operate without control circuits. Naturally, the type of control circuits required depends on the purpose of the equipment in which the CRT is used.

There are many different types of oscilloscopes. They vary in purpose and cost; from relatively simple test instruments to highly accurate laboratory models. However, all have two things in common; they must have some type of CRT, and they must have a group of control circuits to feed a waveform to the CRT. Although there are other types of circuits, most test oscilloscopes can be divided into the basic sections shown below.



Q45. What does a 3AP1B CRT number designate?

Q46. What must all oscilloscopes have in common?

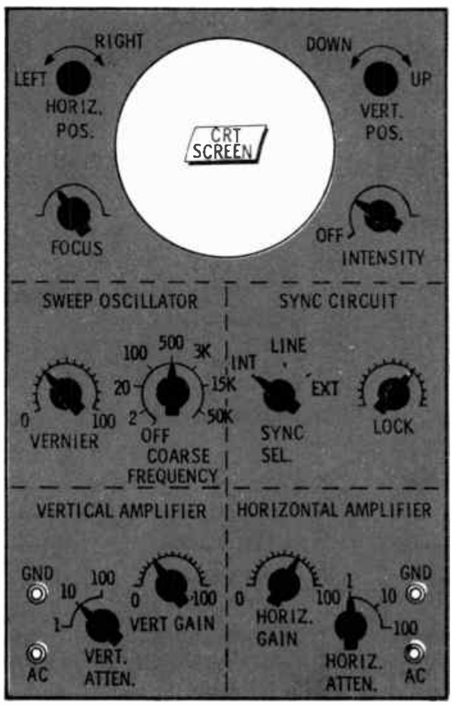
Your Answers Should Be:

A45. 3AP1B designates a CRT that is **3 inches in diameter** and the **first of its diameter registered.** Its trace is **green with medium persistence,** and the CRT is the **second modification** of the original.

A46. All oscilloscopes have in common a **CRT and a group of control circuits.**

Front-Panel Controls

There are several front-panel controls used to adjust the oscilloscope circuits for proper operation. The type and number of controls vary with the purpose of the **scope** (an accepted name for oscilloscope). The following pages will discuss these controls in conjunction with the circuits identified on page 93. Typical controls are shown below.

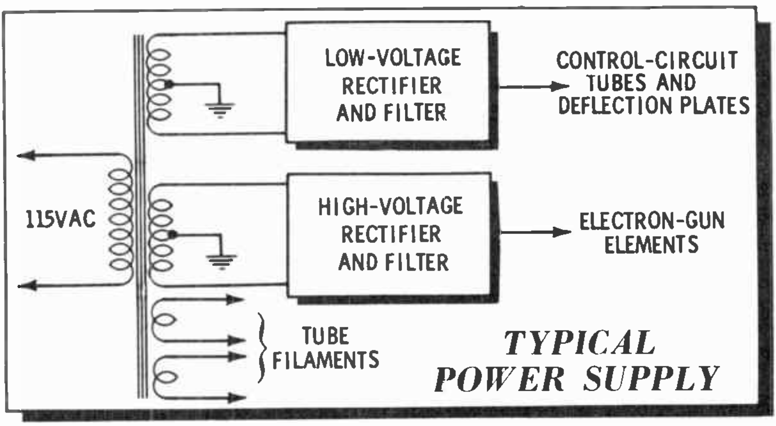


OSCILLOSCOPE PANEL

All of the circuits in the block diagram are represented on the front panel. (The power-supply switch is on the intensity control.) The four controls surrounding the screen regulate voltages being fed to the CRT. The four areas in the lower half of the panel carry titles similar to those in the block diagram.

Power Supply

Power-supply requirements for oscilloscopes vary considerably. Certain cathode-ray tubes require accelerating (second anode) voltages as high as 15 to 30KV (15,000 to 30,000V). The type used with the general-purpose scope, on the other hand, uses 1 to 3KV. Most power supplies employ a transformer, half- or full-wave rectifiers, filters, a load resistance, and, in some cases, voltage regulation.



Most test scopes have both high-voltage and low-voltage power-supply sections fed by a single transformer. The high-voltage, low-current section takes care of the electron-gun requirements. Voltage needs for the remainder of the circuits are supplied by the low-voltage section. This section may provide potentials as high as 300 or 400V. A third or fourth winding on the transformer provides voltage and current for the vacuum-tube heaters.

Q47. To which element of the cathode-ray tube is the INTENSITY control connected?

Q48. To which element of the CRT is the FOCUS control connected?

Your Answers Should Be:

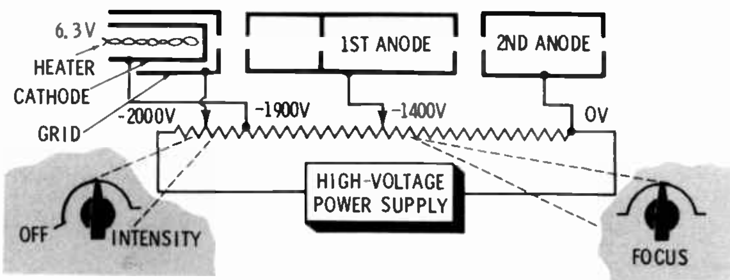
A47. The INTENSITY control is connected to the **control grid** of the CRT.

A48. The FOCUS control is connected to the **first anode.**

CRT Controls

In the circuit below, the second anode (accelerator) is at ground potential. To obtain the high accelerating potential

ELECTRON GUN

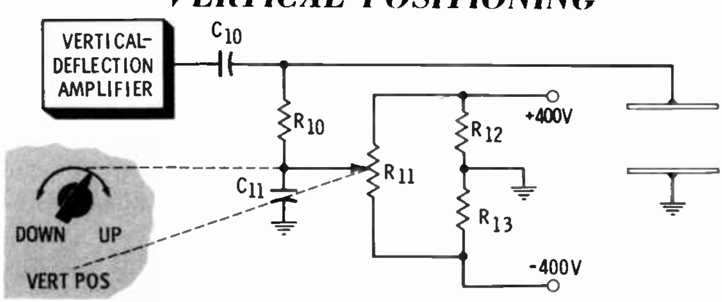


required, the other electron-gun elements are operated at negative potentials. The control grid normally operates near 2,000V negative, 90 to 100V more negative than the cathode. The first anode (focusing) can be maintained between —1,200 and —1,600V. These voltages are typical but vary among instruments.

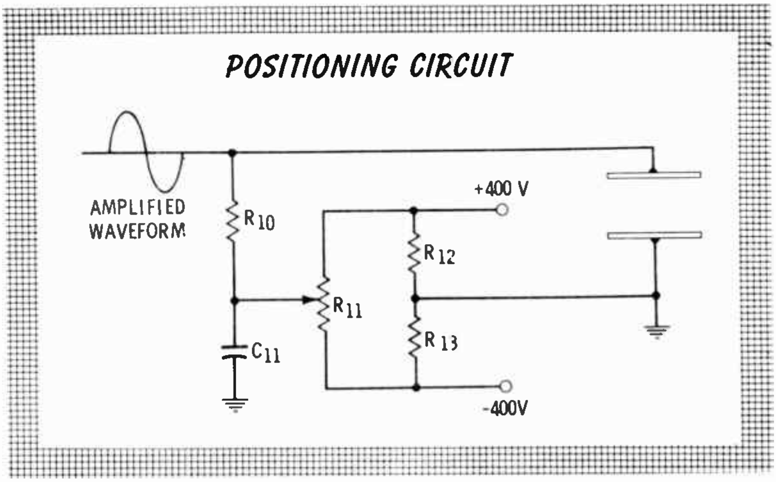
Deflection-Plate Controls

The following method of adjusting the deflection-plate voltage is only one of several possible ways.

VERTICAL POSITIONING



In addition to centering the beam vertically on the screen, there are times when it is desirable to move the entire waveform up or down. VERT POS (vertical positioning) is a front-panel control that permits this. A circuit used to vary the potentials on the plates for positioning purposes is shown on the opposite page. Voltage from the last stage of the amplifier, varying in the same way as the original waveform, is impressed across R_{10}. C_{11} returns the AC signal to ground and blocks DC.



When R_{11} (VERT POS control) is centered, there is no difference of potential between the two plates. When the arm is moved down, the lower plate becomes more positive than the upper plate, and the electron beam moves downward. When the arm is moved up, the upper plate becomes more positive. If there is a waveform being applied across R_{10}, the difference of potential from this positioning network is added to or subtracted from it. This arrangement makes it possible to shift the entire waveform up or down on the CRT screen.

Q49. If one deflection plate is at +124V and the other is +18V, in which direction will the electron beam bend?

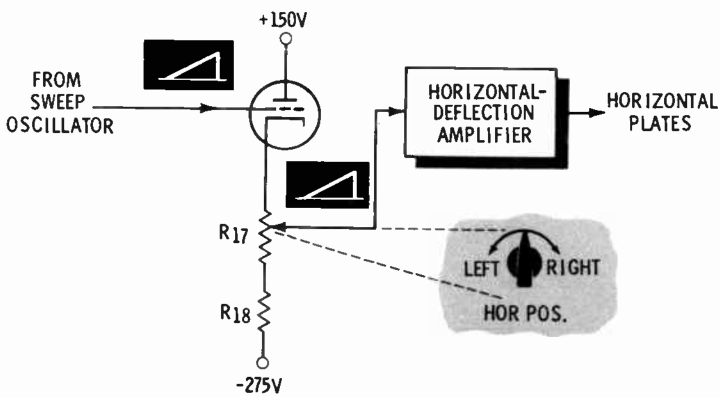
Q50. Why are the deflection plates of a CRT bent outward at the end?

> **Your Answers Should Be:**
>
> **A49.** The electron beam will bend **toward the +124V plate.**
>
> **A50.** The ends of the plates are bent to **allow larger angles of electron-beam deflection** than would be permitted by straight plates.

Horizontal Positioning

One type of horizontal-positioning circuit used in a deflection system is shown below.

HORIZONTAL POSITIONING

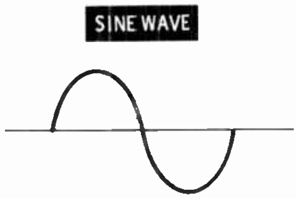


The positioning tube operates as a cathode follower. Its input signal is a sawtooth sweep voltage from the sweep-oscillator circuit. The sizes of the resistors are such that the center position of R_{17} (HOR POS control) is at zero (ground) potential. The horizontal-deflection amplifier is made up of two tubes operating in push-pull. Each tube controls the potential on one of the plates. With the arm of R_{17} at ground potential and no sawtooth signal present, the plate currents in the amplifier tubes are identical. No difference in voltage exists between the deflection plates. When the arm is moved up (more positive) or down (more negative), the plate currents are no longer equal. The potential on one amplifier plate is then more positive or less positive than the other. In this manner the beam can be moved left or right. Vertical positioning can be done similarly.

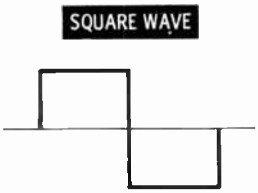
Vertical Amplifier

Since the vertical amplifier receives the waveform to be observed, its input impedance should be very high to prevent loading of the external circuit from which the waveform is obtained and the resultant distortion of the signal. The amplifiers of most scopes have input impedances of several megohms. Some other requirements for good vertical amplifiers are listed below.

Frequency Response—Frequency response is a measure of the ability of an amplifier to pass the frequency components of a waveform. A pure sine wave, as you know, has only one frequency component—the fundamental.



THE FUNDAMENTAL FREQUENCY



FUNDAMENTAL FREQUENCY PLUS ODD HARMONICS

A square wave, however, consists of the fundamental sine wave plus many odd-numbered **harmonics.** A harmonic is a sine wave having a frequency that is a whole-number multiple of the fundamental frequency. A perfect square wave has an infinite number of odd-numbered harmonics. Its tops and bottoms are perfectly flat, and the rise and decay of its sides occur in zero time. Since there must be some time to allow voltages to rise and fall, there is no practical circuit that can produce a perfect square wave. However, a conventional square wave contains several hundred odd-numbered harmonics.

A good general-purpose scope should have a frequency response extending up to 2 megacycles. For practical maintenance work, a scope should be able to pass the tenth odd harmonic of a square wave. Since this is 21 times the fundamental frequency, a 2-megacycle scope should be able to display square waves having a fundamental frequency as high as 100 kc.

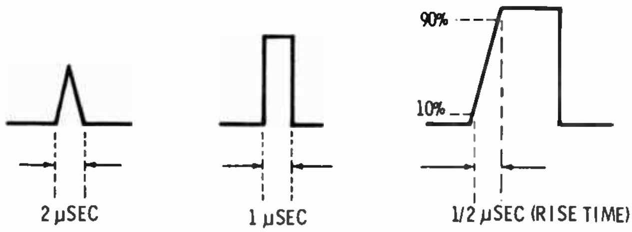
Q51. What makes a square wave different from a sine wave?

Your Answer Should Be:

A51. A sine wave is made up of a single fundamental frequency; a square wave consists of the **fundamental plus many odd harmonics** of the fundamental.

Each of the pulse waveforms shown below consists of a different combination of fundamental and harmonic frequencies. In order to display such waveforms accurately, a scope must have good high-frequency response. This is so that the higher harmonics will be amplified the same amount as the fundamental and the lower harmonics.

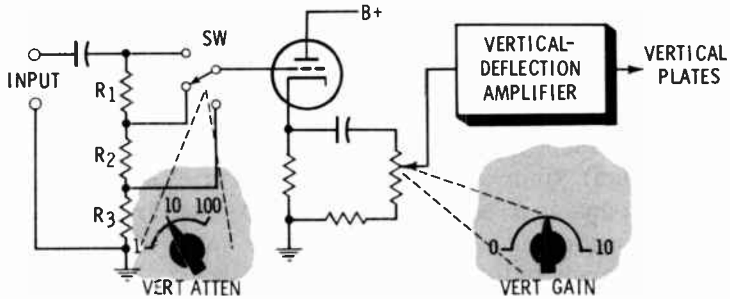
PULSE DURATION



Another way to examine the response of a scope is in terms of **rise time.** The rise time is the time between the 10% and 90% amplitude points on the leading edge of a pulse. The minimum rise time that a scope can reproduce is determined mainly by the charge time of certain capacitances in the scope.

Gain—The gain of a vertical amplifier determines how well a small signal can be expanded for observation on the screen. If the CRT, for example, has a deflection factor of 0.8V per inch and no means of amplification, a waveform having 0.2V amplitude would be very difficult to examine. However, if an amplifier were used, all large signals would be amplified so much they would extend off the screen. Therefore, instead of having several channels of amplification (each with its set of linear, good frequency-response amplifiers), a method must be used to attenuate (reduce) waveform amplitudes before they arrive at a single channel of amplification.

The diagram below shows one method often used for attenuation. The **VERT ATTEN** (vertical attenuator) switch has three positions, 1, 10, and 100, which are factors of attenuation. The attenuation equals unity in position one; there is no attenuation of signal. This corresponds with the



top tap of the switch in the schematic. The full voltage of the input is fed to the grid of the cathode follower. Attenuation equals 1/10 in position 10. R_1, R_2, and R_3 are selected so that 1/10 of the input voltage will arrive at the grid. Position 100 provides an attenuation of 1/100.

Since attenuation values between these broad settings may be desired, a finer attenuation control is provided. This is the **VERT GAIN** (vertical gain) control. As you can see, it selects a voltage from R_4, part of the cathode resistance, and applies this voltage to the vertical amplifier. Through the use of the VERT ATTEN and VERT GAIN controls, the vertical size of the waveform can be regulated on the screen.

The vertical-deflection amplifier stage in a good scope is usually a push-pull amplifier having a constant gain and a frequency response up to 2 mc. The output of the amplifier is fed to the vertical-deflection plates.

Q52. Constant gain refers to the ability of an amplifier to equally amplify all signals within its capability. Why is this necessary in an oscilloscope?

Q53. Is the frequency response of a scope a good measure of its capabilities?

Q54. In the schematic above would the switch be connected to the tap at the bottom of R_2 or the top of R_1 if the VERT ATTEN were set at 100?

Your Answers Should Be:

A52. Constant gain is required so **all waveforms,** regardless of their amplitude (within the voltage range of the amplifier), **are amplified the same amount.** Variations in gain would make the presentations inaccurate.

A53. **Yes,** frequency response is a good measure of the capability of a scope. A scope with good frequency response will reproduce waveforms over a wider frequency range more faithfully (with less distortion) than a scope with a poorer frequency response. A scope with good frequency response responds more quickly to the rapid changes of narrow pulses and steep wave slopes.

A54. The switch would be connected to the **bottom tap,** thus providing the grid with a less negative voltage than at the other two taps.

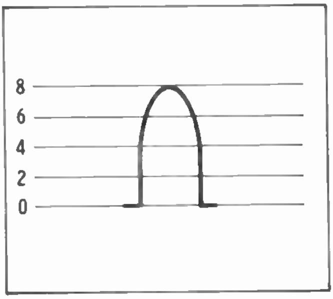
Other Vertical-Amplifier Requirements

Inputs to the Scope—The illustration of the front panel of the oscilloscope shows GND and AC connections for the vertical-deflection amplifier. Test leads with probes attached are inserted into these connections for test purposes. On some oscilloscopes there is a third jack that is marked DC. This provides the possibility of observing a DC voltage or a waveform that varies its amplitude at a very slow rate. The DC connection feeds the signal directly to a DC amplifier and then to the deflection plates. The normal vertical amplifiers cause distortion of very low-frequency signals.

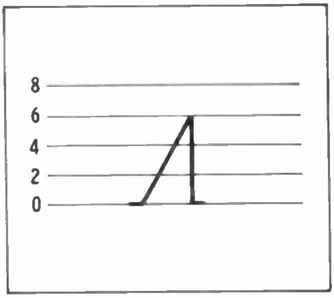
Y-Axis Amplifier—On some scopes the vertical-deflection amplifier is called a **Y-axis amplifier.** The Y axis corresponds to the Y coordinate (up-and-down reference line) on a graph. Since a scope presents a graph of amplitude (plotted on the Y axis) and time (plotted on the X axis), these terms are sometimes used instead of vertical and horizontal.

If the vertical amplifier and its associated circuits are properly designed according to the requirements you have just studied, the amplitude of a waveform will be faithfully reproduced on the screen.

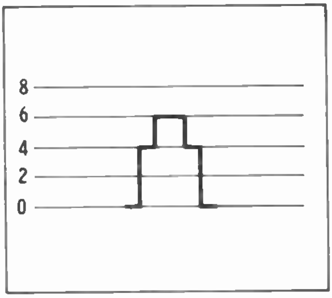
An amplifier is required to increase signal voltages so that the full size of the screen can be used. It is easier and more accurate to study an enlarged reproduction of a waveform. Large waveforms can be attenuated to 1/10 or 1/100 of the amplified size, and any waveform can be made larger or smaller by varying the amplifier gain.



A



B



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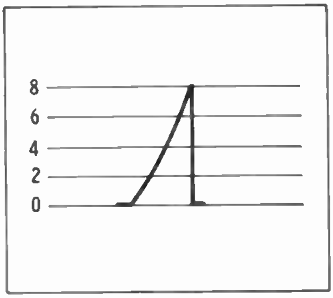


D

Q55. Assume your oscilloscope had only a CRT, vertical-deflection amplifier, and the right type of power supply. Draw a picture of each of the above waveforms, showing how they might appear on the screen.

Q56. What are the two characteristics of a waveform an oscilloscope is able to reproduce?

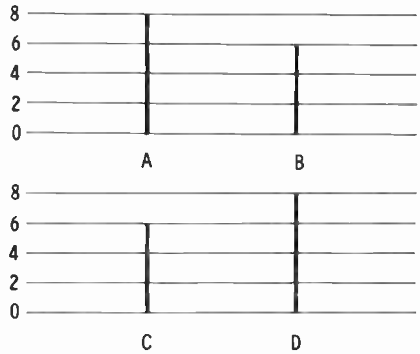
Q57. ____ is plotted on the X axis, and _________ is plotted on the Y axis.

Q58. Why is a DC jack included on some oscilloscopes?

Q59. What other vertical-amplifier inputs are used in an oscilloscope?

Your Answers Should Be:

A55. Your drawing should look something like this:



A56. The two waveform characteristics an oscilloscope can reproduce are **amplitude** and **time.**

A57. **Time** is plotted on the X axis, and **amplitude** is plotted on the Y axis.

A58. The DC jack is used to **observe a DC voltage or a waveform that varies in amplitude at a low rate.**

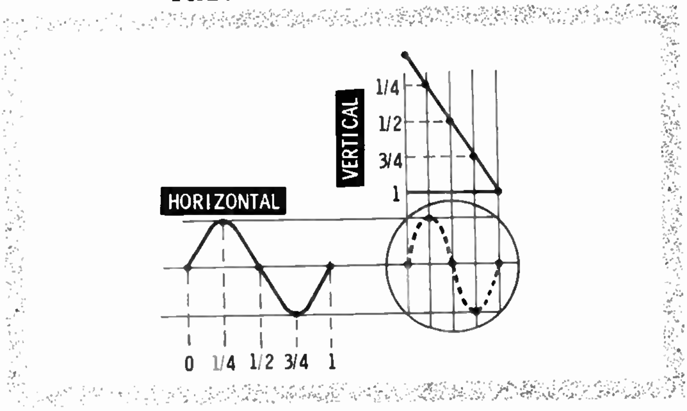
A59. **AC** and **GND** (ground) connections are the other two inputs.

Horizontal Time Base

As you can see in Answer 55, a scope with only a vertical-deflection amplifier in its control circuits will present only a vertical line; the horizontal dimension is missing.

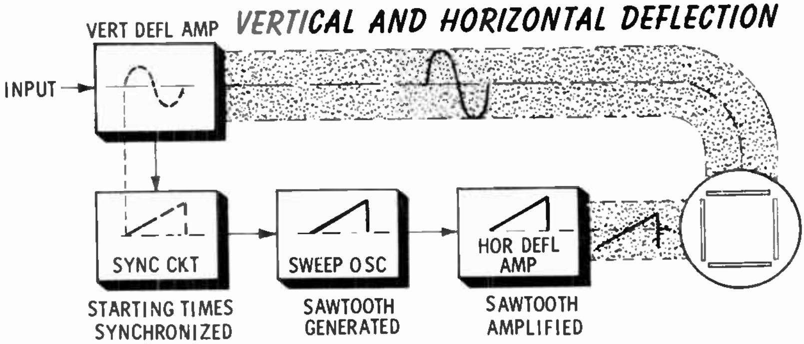
Time as a Reference—Since waveforms change their amplitude in accordance with time, it becomes a useful means of measurement for the horizontal direction on the screen.

Look at the figure at the top of the opposite page. If the two waveforms span the same period of time, each could be divided into corresponding increments (small intervals) of time. If a sawtooth waveform were applied to the horizontal plates and a sine wave applied to the vertical plates, the former would move the electron beam sideways, and the latter would move it up or down in corresponding increments of time. Notice how the vertical and horizontal deflections combine at each instant of time to produce the waveform.



Characteristics of a Sawtooth Waveform—You have probably identified the necessary characteristics of a sawtooth waveform. Voltage must rise uniformly to be constantly proportional to time. It must be capable of starting its rise at the same instant the waveform to be observed starts. The time duration of the sawtooth waveform must be equal to that of the other waveform if one complete cycle is to be observed. The sawtooth must decay quickly to zero so that both waveforms can complete their cycles at the same time.

VERTICAL AND HORIZONTAL DEFLECTION



Q60. The ________ waveform moves the electron beam from side to side, and the __________ waveform moves the beam up and down.

Q61. What part of the control circuits of a scope produces all the characteristics of the sawtooth waveform?

Your Answers Should Be:

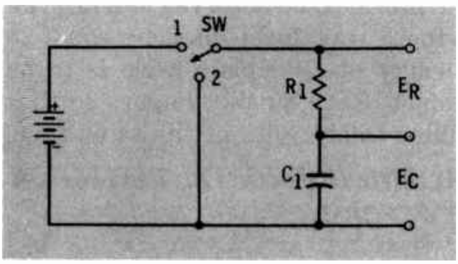
A60. The **sawtooth** waveform moves the electron beam from side to side, and the **sinusoidal** waveform moves the beam up and down.

A61. The horizontal-deflection circuits produce all the characteristics of the sawtooth waveform.

Sweep-Oscillator Circuits

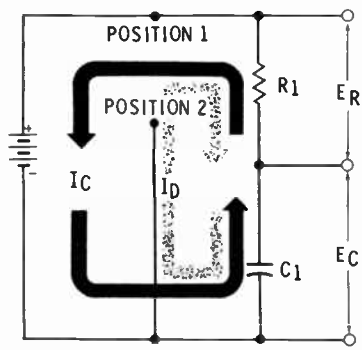
The sawtooth waveform is generated by the sweep oscillator. Sweep refers to the steady rise of sawtooth voltage that moves the waveform horizontally across the screen in a desired period of time. An oscillator is a circuit capable of repeating the waveform it generates at some specific frequency.

In AC fundamentals you learned about the simple RC circuit shown below. The circuit contains a resistor and a

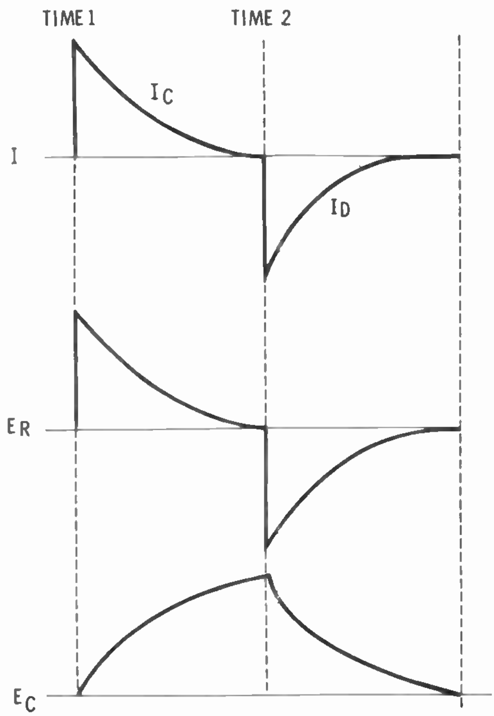


SIMPLE RC CIRCUIT

capacitor in series with a battery. A switch capable of disconnecting the battery and placing a short circuit across R_1 and C_1 is also connected in this circuit.



At the instant the switch is placed in position 1, I_C (charge current) rises to maximum, and E_R rises to the value of the battery voltage. As C_1 charges (E_C) at an exponential rate, I_C and E_R decrease at the same rate. At the end of a period of time determined by the values of R_1 and C_1, the capacitor will reach its maximum charge. Current will stop flowing, and E_R will become 0. At time 2, when the switch is in position 2, the capacitor begins to discharge. I_D (discharge current) is maximum negative (reverses direction), and E_R is also maximum in the negative direction. The discharge decreases exponentially until all values reach 0. E_C resembles the sawtooth, but its rise is not linear.



Q62. Refer to the top figure on the facing page. At the instant the switch is placed in position 1, is E_R equal to, greater than, or less than E_C?

Q63. Assume C_1 has been charged. At the instant the switch is placed in position 2, is E_R equal to, greater than, or less than E_C?

Your Answers Should Be:

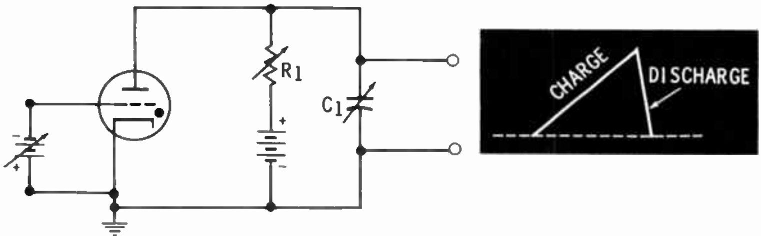
A62. **E_R is greater than E_C** at the instant the switch is closed. E_R is at maximum voltage, and E_C is at zero.

A63. **E_R is less than E_C** at the instant the switch is placed in position 2. When C_1 is fully charged, there will be zero volts across the resistor, and the voltage across C_1 will be at its maximum.

Developing a Sawtooth Waveform

There are several types of sawtooth generating circuits—neon-tube, thyratron, multivibrator, etc. The **thyratron sawtooth generator** is representative of how all of these circuits operate.

A THYRATRON CIRCUIT

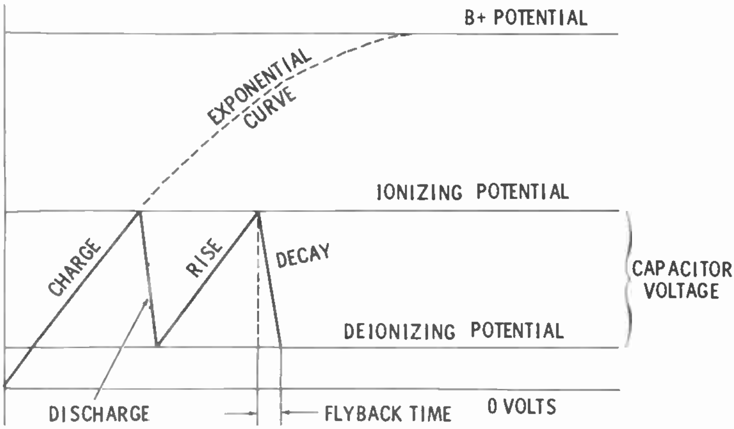


A thyratron is a triode containing an ionizing gas. B+ current flows through R_1 and charges C_1. When the voltage across C_1 reaches a certain potential, the gas ionizes.

When this happens, the thyratron conducts and rapidly discharges the capacitor. The voltage across C_1 has a waveform that depends on the charge and discharge times. Charge time can be lengthened by increasing the value of R_1, C_1, or both. The bias on the grid also controls the time at which the tube conducts. A larger negative grid-to-cathode potential, making it more difficult for the tube to conduct, will require a larger ionizing potential on the plate. It will take the RC circuit longer to reach this potential, and the charge time of the sawtooth will be longer. When the tube conducts, the capacitor discharges until a voltage across the tube is reached that no longer supports ionization. C_1 then recharges and the cycle repeats.

As can be seen in the figure below, the capacitor will charge until it accumulates a voltage equal to the ionizing potential of the thyratron. The tube conducts current and discharges the capacitor. Since the thyratron acts as a short

THYRATRON LINEARITY



across the capacitor, the capacitor discharges rapidly. When the capacitor voltage falls to the **deionizing potential** of the tube, the thyratron stops conducting and acts as an open switch. Then the cycle repeats. The charge of the capacitor corresponds to the rise of the sawtooth, and the discharge corresponds to its decay.

The linearity of the sawtooth voltage across the capacitor is determined by the ionizing and deionizing action of the thyratron. The tube discharges the capacitor while its charge voltage is in the lower, more linear part of the exponential curve. The thyratron is also capable of discharging the capacitor rapidly, keeping decay time of the waveform to a minimum. If decay, or **flyback time** as it is most often called, is long, horizontal deflection will not return to the starting point before the waveform on the vertical plates has started its next cycle.

Q64. What are some types of sawtooth-generating circuits used in electronics?

Q65. What is a thyratron?

Q66. How can the charge time of the thyratron circuit be controlled?

Your Answers Should Be:

A64. **Neon-tube, thyratron,** and **multivibrator** circuits.

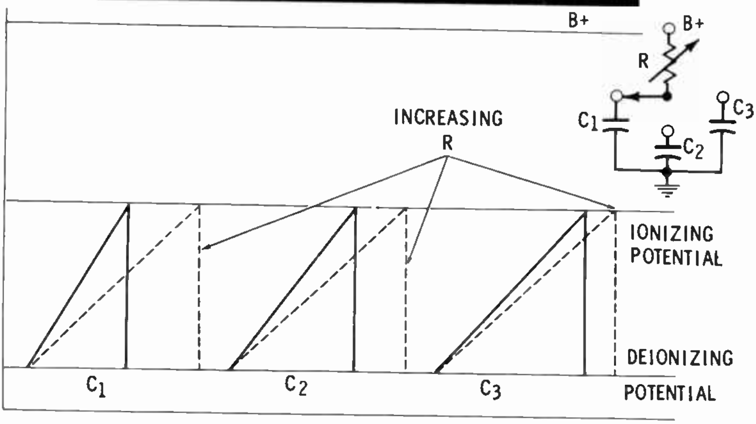
A65. A thyratron is a **triode containing an ionizing gas.**

A66. It can be controlled by varying the **grid bias** of the tube or the values of R_1 and C_1.

A Typical Sawtooth Generator

Since the frequencies, or time durations, of waveforms are not all the same, a sawtooth waveform with only a single rise time is not suitable. The most frequent method for varying the length of the sawtooth waveform is to change the values of the RC charging circuit.

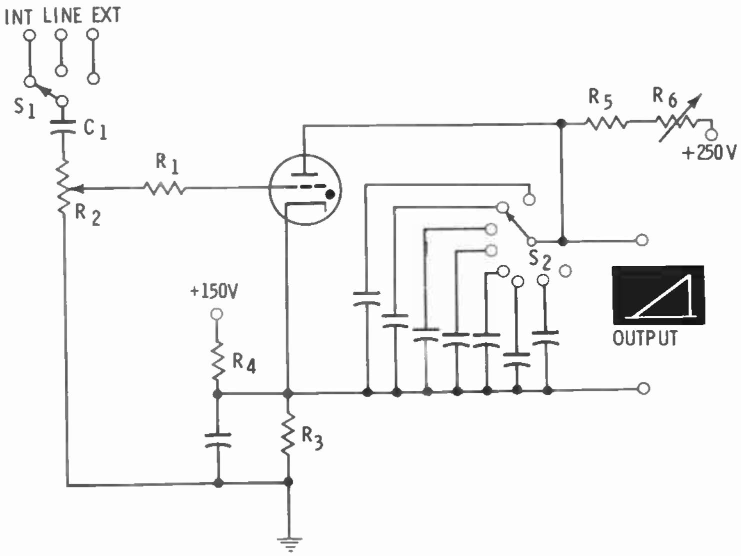
CHANGING LENGTH OF SAWTOOTH



By changing capacitors in the RC circuit, the RC time constant can be increased in coarse increments, as shown by the solid lines in the figure above. C_1 has a smaller capacitance than C_2, which is smaller than C_3. If R remains the same, a larger capacitance will take longer to charge than a smaller one. Consequently, the rise time of the sawtooth waveform generated by the capacitor would increase. If R were a variable resistor, fine variations of the basic sawtooth waveform for each value of C could be controlled. This is shown above in dashed lines. In each case, the firing potential (which determines the time at which the capacitor discharges) would remain the same.

The figure below shows one version of the thyratron sawtooth generator used in oscilloscopes. The cathode is main-

THYRATRON SAWTOOTH GENERATOR



tained at a small positive voltage (about 3V) by the voltage divider made up of R_3 and R_4. The grid is thereby maintained at a desired negative bias, since it is grounded through R_1 and R_2. The bank of capacitors across the tube represents the individual coarse settings for sawtooth rise time. The selected capacitor is charged by the B+ source through R_5 and R_6. R_6 can be adjusted for the precise rise time desired. Because of its established ionizing and deionizing potentials, the thyratron acts like a stable, rapid switch in charging and discharging the chosen capacitor. The sawtooth waveforms developed across the capacitor are fed to the next stage, the horizontal amplifier.

Q67. What is meant by the deionizing potential of a thyratron?

Q68. The cathode of the thyratron is kept at a ––– potential.

Q69. What factors make the thyratron useful in a sawtooth-generating circuit?

Your Answers Should Be:

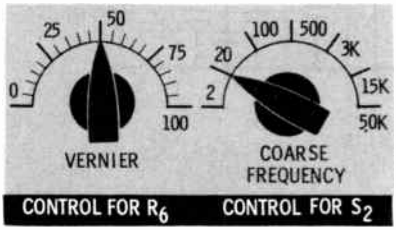
A67. The plate voltage at which the thyratron **stops conducting** is known as the deionizing potential.

A68. The cathode of the thyratron is kept at a **low** potential.

A69. Ionization and **deionization.**

Controlling Frequency and Timing of the Sawtooth

Two controls for the **sweep-oscillator** (sawtooth-generator) circuit are on the front panel of the scope. COARSE FREQUENCY selects one of seven capacitors (in this case) in the circuit. Numbers on the switch specify the frequency

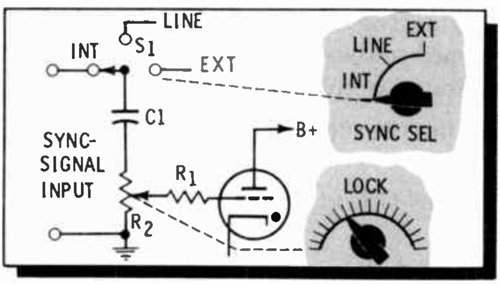


SWEEP-OSCILLATOR CONTROLS

(cps) of the sawtooth. **VERNIER** makes the fine setting of R_6 to obtain frequencies between coarse settings. To place a 60-cycle waveform on the screen, for example, COARSE FREQUENCY is set on 20 and the VERNIER is adjusted until a single cycle is presented.

Sync Circuits

You may have noted the three-position switch (S_1) in the thyratron circuit just discussed. This part is shown below.

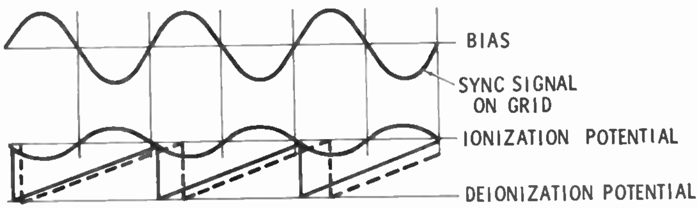


SYNC CIRCUIT

The purpose of the sync circuit is to cause the sawtooth waveform to remain in **synchronization** with the waveform to be placed on the screen. That is, both waveforms must start at the same time. The origin of the waveform to which the sawtooth is to be synchronized determines the setting of the **SYNC SEL** (sync-selector) switch on the front panel. **EXT** (external) is the setting used when the sync signal is to be obtained from an external circuit or source. **LINE** obtains the sync signal from the oscilloscope power line. **INT** (internal) samples the waveform in the vertical-deflection amplifier channel.

The principle is identical for all three settings. Assume the switch is on INT. The waveform (appearing on the screen) is fed through C_1 and R_2 (RC coupling circuit). The grid voltage will rise and fall with the amplitude of the signal, thereby decreasing and increasing the time interval before the tube ionizes and conducts current.

SYNCHRONIZING SEQUENCE



A sync signal on the grid will cause a fall and rise in ionization potential, as shown in the figure above. Without the sync signal, the ionization potential is steady, and the sawtooth waveform is as shown by the dashed line in the figure above. When the sync voltage is added, the sawtooth voltage reaches the ionization potential sooner in each cycle. The rise time of the sawtooth is shortened, and its frequency is increased. This is shown by the solid waveform.

The **LOCK** control varies the amplitude of the signal appearing on the grid. The control is necessary since sync signals vary widely in amplitude. A steady, uniform sync can be obtained by adjusting for proper ionization variation with the LOCK control.

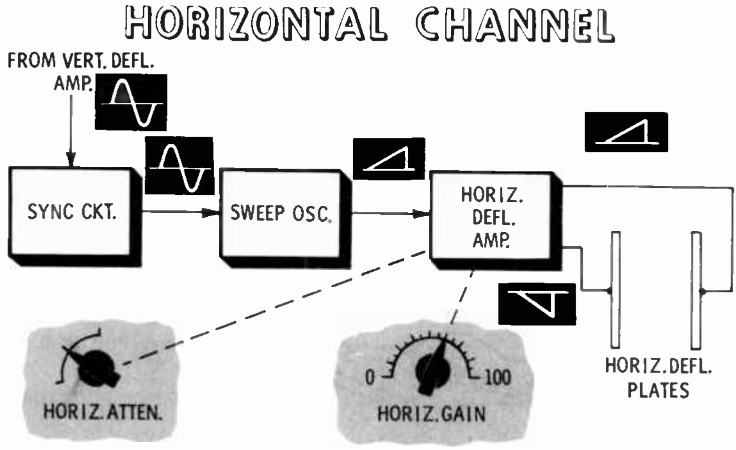
Q70. Explain the three settings on the SYNC SEL switch.

Your Answer Should Be:

A70. The three settings are INT (**samples the internal signal** in the vertical-deflection circuit); **EXT** (used when the sync signal is to be obtained **from an external source**); **LINE** (used when the sync signal is obtain from the scope **power line**).

Horizontal Channels

The sync circuit, sweep oscillator, and horizontal-deflection amplifier make up the horizontal channel.

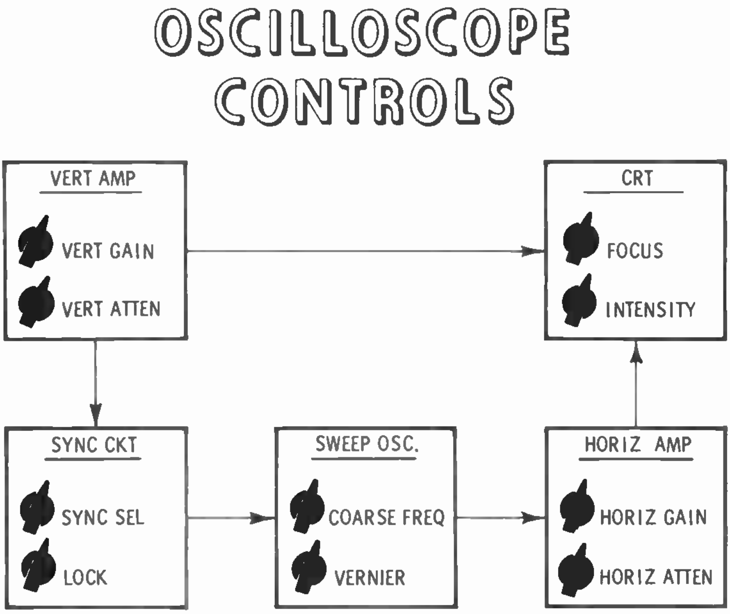


The **sync circuit** sends a sample of the observed waveform to the **sweep oscillator** for synchronization with the generated sawtooth wave. The sawtooth is then amplified by the **horizontal-deflection amplifier** and applied to the horizontal plates.

Vertical and horizontal amplifiers are similar and perform identical functions. Each has a gain control to develop the desired size of the pattern. Each also has an attenuation control to decrease the amplitude of large waveforms so that they will be retained within the area of the screen. The **HOR ATTEN** control is used when an external waveform is to be applied to the horizontal-deflection plates through the amplifier. AC and ground jacks are available on the front panel for this purpose. When a waveform is to be applied directly to the horizontal-deflection plates, the sweep oscillator is disconnected from the horizontal amplifier and neither is used for the scope display.

The Whole Oscilloscope

You have studied the circuits of a typical oscilloscope and have learned they were not difficult to understand, if you were able to recall the fundamentals you studied in preceding volumes. You are now ready to combine all of these circuits into a complete unit. This combination of circuits make up the whole oscilloscope. You will learn how to adjust the numerous controls on the front panel and how they influence the pattern on the screen. Recall now the purpose of some of the oscilloscope controls shown below.



Q71. State the purpose and how it is accomplished for each of the following controls:

Focus control
Intensity control
Coarse-frequency control
Vertical-attenuation control

Your Answers Should Be:

A71. The focus control **establishes the correct potential differences** between the grid and the first anode and between the first and second anode **for focusing.**

The intensity control **varies the brightness of the beam** displayed on the screen by controlling the negative bias on the grid.

The coarse-frequency control **determines the basic frequency of the sawtooth** by selecting the proper value of capacitance for the RC charging circuit.

The vertical-attenuation control **decreases the amplitude of large waveforms** that might be amplified off the screen. This is accomplished by selecting the correct ratio of the waveform voltage from a voltage divider.

Similarity Among Oscilloscopes

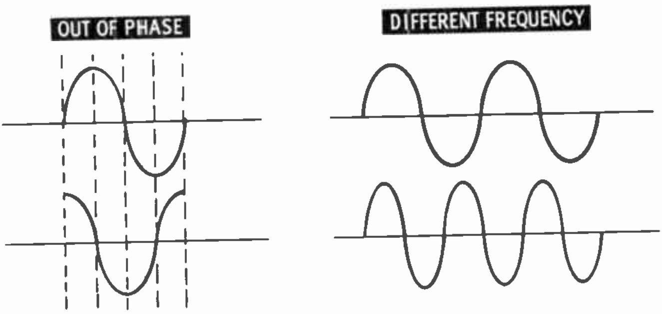
The oscilloscope you use may differ in some respects from the one you have just studied. Controls and circuits may be identified by different titles, and many of the circuits may be designed differently. However, all of the functions will be fundamentally the same. Before using an oscilloscope, it is wise to carefully study the manual that comes with it. Descriptions may not be in detail, but the information you have learned so far will help fill in the missing points. Develop a habit of taking all readings with the greatest accuracy possible.

USING THE OSCILLOSCOPE

An oscilloscope can be used for several different types of measurements. Earlier in the chapter you learned it was most often used to study the shape of a waveform when checking the performance of equipment. The pattern on the scope is compared with the signal that should appear at a test point, and a judgment is then made as to whether the operation of the equipment is good or bad.

You were introduced to the graticule, a plastic sheet scored with calibrated horizontal and vertical lines, that can be fitted on the screen of the CRT. By recording the height of a known voltage on the graticule, you can estimate the value of an unknown voltage placed on the screen.

Other applications for which an oscilloscope can be used include determining phase relationships and measuring frequencies, as shown below. These will be explained later in this chapter.



Turning the Scope On

First, make sure the scope is plugged into an electrical outlet. Many people have turned all knobs on the front panel out of adjustment before they noticed that the power cord was not plugged in. On most scopes the power switch is part of the INTENSITY control. Turn the knob until a click is heard or a panel light comes on. Let the scope warm up for a few minutes so that voltages in all of the circuits become stabilized.

Getting a Pattern on the Screen

When putting a pattern on the screen, adjust the INTENSITY and FOCUS controls for a bright, sharp line. If other control settings are such that a dot instead of a line appears, turn down the intensity to prevent burning a hole in the screen coating. Brightness and sharpness will vary at various frequency settings, because of the different speeds at which the beam travels across the screen. For this reason, it may be necessary to adjust the INTENSITY and FOCUS controls occasionally while taking readings.

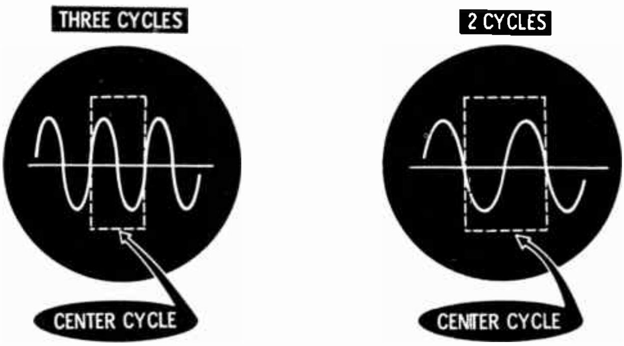
Q72. What should you do before you turn on the oscilloscope?

Your Answer Should Be:

A72. You should carefully **study the manual** that comes with the scope before turning the scope on.

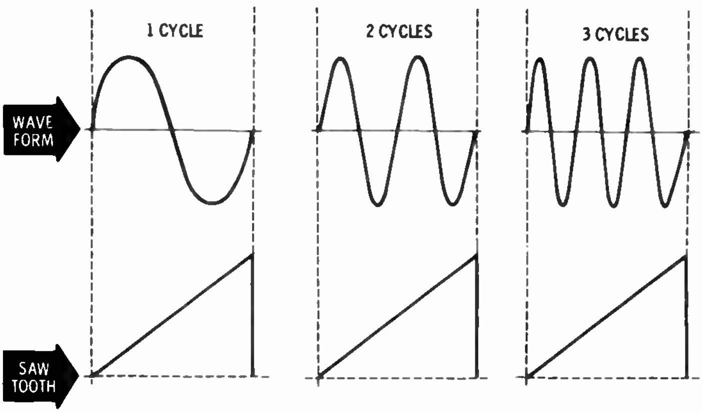
Number of Cycles on the Screen

Because distortion may exist at the beginning and end of a sweep, it is best to put two or three cycles of the waveform on the screen instead of only one.



The center cycle of three cycles gives you an undistorted waveform in its correct phase. The center of a two-cycle presentation will appear inverted, but will be undistorted.

The relationship between the frequencies of the waveform on the vertical plates and the sawtooth on the horizontal plates determines the number of cycles on the screen.

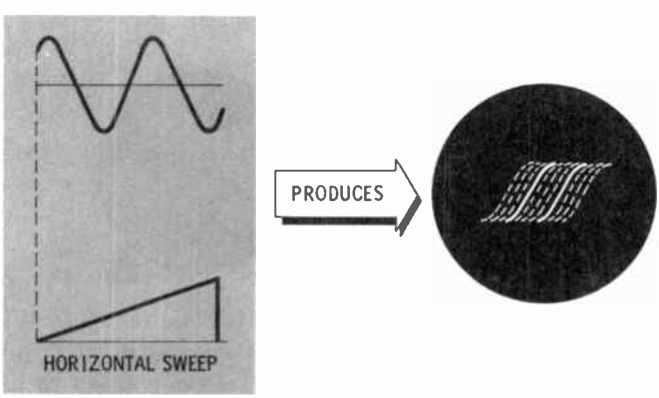


The sweep frequency should always be kept lower than or equal to the waveform frequency; it should never be higher. If the sweep frequency were higher, only a portion of the waveform would be presented on the scope.

As the preceding figure demonstrated, three cycles of the waveform will be on the screen when the sweep frequency is set to ⅓ the frequency of the input signal. If the input frequency is 12,000 cps, the sweep frequency must be 4,000 cps for a three-cycle scope presentation. For two cycles, the sweep frequency must be set at 6,000 cps. If a single cycle is desired, the setting is the same as the input frequency, i.e., 12,000 cps.

The sawtooth frequency is selected by settings on the COARSE FREQ and VERNIER controls on the front panel. If the exact frequency number is not found on the coarse-frequency markings, set the coarse control to the closest number and adjust the vernier control for a stationary pattern on the screen.

The ratio of waveform to sawtooth frequencies should be such that it is on the order of 1/1, 2/1, 3/1, 4/1, etc. When the ratio leaves a quotient that is not a whole number (3/2 for example), the display will be a series of lines moving across the screen. If the pattern appears to be incorrect, adjust the proper control (COARSE or VERNIER).



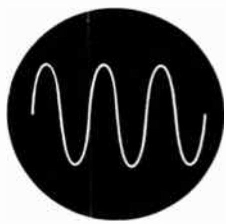
Q73. Why is there only one sawtooth cycle in each example at the bottom of the opposite page?

Your Answer Should Be:

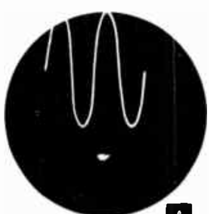
A73. There can be only one sawtooth wave per sweep of the scope, regardless of the number of waveform cycles. The sawtooth will move the electron beam horizontally across the scope during its rise time. When the sawtooth decays, the beam immediately returns to the starting point on the left.

Other Make-Ready Settings

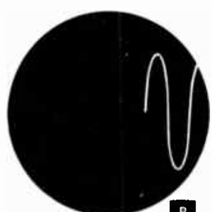
So far you have learned how to set the INTENSITY and FOCUS controls for proper brightness and sharpness of the waveform on the screen. A steady pattern has been obtained by setting the COARSE FREQ and VERNIER controls of the sweep-oscillator stage for a steady, uniform pattern. If the pattern looks like either of the following, you are ready to proceed with an analysis of the waveform.



However, you may obtain patterns that appear similar to the following:



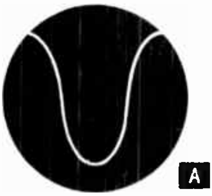
A

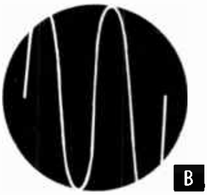


B

Which control would you adjust for figure A? Which would you adjust for figure B? The waveform in figure A can be adjusted by turning the **VERT POS** control to bring the waveform to the center of the screen. The waveform in figure B can be adjusted by turning the **HOR POS** control to bring the waveform to the center of the screen.

The two positioning controls above and to either side of the screen are used to center the waveform. Suppose the display for two cycles appeared like either one of the pictures below. Which controls would you adjust?





It is evident that portions of the waveform are being deflected off the screen in both cases. The figure on the left has too much horizontal expansion, so you would reduce the HOR GAIN (horizontal gain) setting. Reduction in VERT GAIN (vertical gain) would bring the waveform on the right back on the screen. For normal viewing purposes the height and width of a waveform pattern should be about equal and should cover about 60 to 70% of the screen. On a 5-inch scope this would be a little over 3 inches. The pattern should be about 2 inches for a 3-inch CRT. Adjustments of the vertical-gain control not only change the amplitude of the signal fed to the vertical-deflection plates, but they also increase or decrease the amplitude of the signal fed to the sync circuit. Quite frequently the change will affect the ionizing potential of the thyratron sufficiently to cause distortion in the presentation. To remedy this, adjust the LOCK control in the sync circuit.

Occasionally a waveform frequency will be encountered that is so high that the frequency of the sweep oscillator cannot be made high enough to give a screen presentation of 2 or 3 cycles. If the upper limit of the COARSE FREQ control were 50 kc and the frequency of the waveform were 1 mc, the vertical-to-horizontal ratio would be 1,000,000/50,000 or 20/1. Twenty cycles of the waveform would appear on the screen at this setting. The VERNIER adjustment might eliminate a few cycles, but the remaining cycles would be too close together to permit observation.

Q74. To observe three cycles of a 45,000-cps signal, to what setting(s) would you adjust which controls?

Your Answer Should Be:

A74. Set the **COARSE FREQ control to 15 kc** and adjust the **VERNIER control for a stable display.**

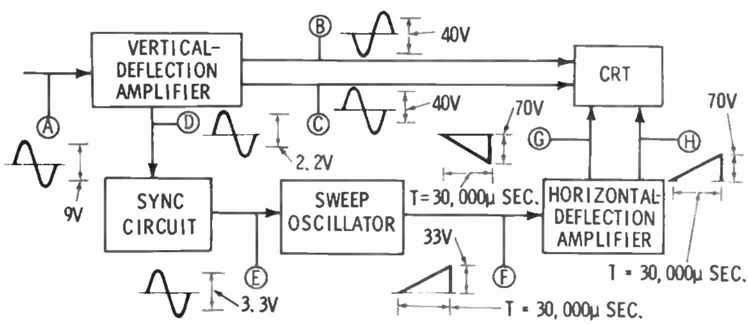
When there are too many cycles for easy viewing, expanding the presentation with the horizontal-gain control will separate the cycles for better viewing.

MULTICYCLE PRESENTATIONS

Reading Waveforms

Earlier in this chapter you learned that signals (waveforms) are modified, or changed, as they pass from circuit to circuit until the signal from the final stage contains the desired characteristics. With an oscilloscope you can test each of the signals in a piece of equipment to determine whether the circuits are operating properly and/or which one might be the cause of a trouble.

SERVICING BLOCK DIAGRAM



The above illustration is representative of a **servicing block diagram.** The letters in circles identify significant test points. The waveforms beside them show the shape, voltage, and time duration (where applicable) that should be observed at these points. Arrows on block-connecting lines show the direction of signal flow. This diagram would be used when matching the characteristics of the waveforms to those shown on an oscilloscope. By using a graticule whose lines have been given voltage values in accordance with the amplitude of a known voltage, the voltage at each of the test points could be checked.

Lissajous Figures

The phase relationship between two waveforms and the frequency of a signal can be measured on an oscilloscope. Patterns placed on the screen to accomplish this are called **Lissajous figures.** A Lissajous figure is the pattern obtained when AC signals are applied simultaneously to both sets of deflection plates. The following procedures are typical of most oscilloscopes.

Phase Measurement—When you are measuring the phase difference between two signals, one signal is applied to the vertical and the other to the horizontal input. Turn the sweep off so that there will be no sawtooth voltage to interfere with the signal in the horizontal channel. For greatest accuracy, the amplitudes of the two signals should be equal. Adjust the gain controls to obtain a pattern that is as high as it is wide. When measuring for phase difference, the two signals must, of course, be the same frequency.

Q75. If test points H, G, and F in the diagram on the opposite page provide faulty indications and test point E does not, in which circuit is the trouble located?

Q76. Patterns placed on the screen to show phase relationship are called _________ _______.

Q77. Why would you want to enlarge a waveform presentation on an oscilloscope?

Q78. What is meant by the output stage in electronic equipment?

Q79. How can the phase relationship between two waveforms be measured using the oscilloscope?

Q80. When measuring the phase difference of two signals, their frequencies must be _____.

Your Answers Should Be:

A75. The trouble is in the **sweep-oscillator circuit.** This circuit has a good input, but it has a faulty output.

A76. Patterns placed on the screen to show phase relationship are called **Lissajous figures.**

A77. The presentation is expanded for **better accuracy** when viewing a waveform.

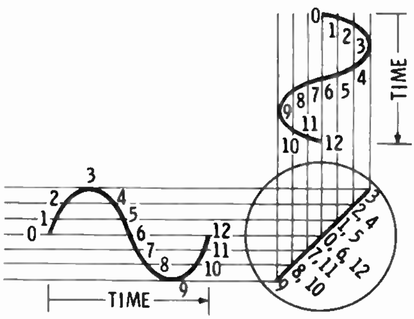
A78. The output stage feeds the desired signal **to the load** of the equipment.

A79. **AC signals are simultaneously applied to each set of deflection plates** when comparing their phase.

A80. When measuring the phase difference of two signals, their frequencies must be **equal.**

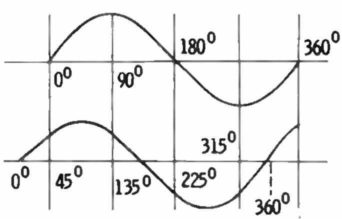
Analyzing a Lissajous Figure

The figure below shows a Lissajous pattern for two sine waves. Numbers are assigned to corresponding voltage points on the two signals. Extensions of these points are brought to the screen. The intersection of corresponding numbered lines is the position of the electron beam at that instant of time. In this case the two sine waves are in phase.

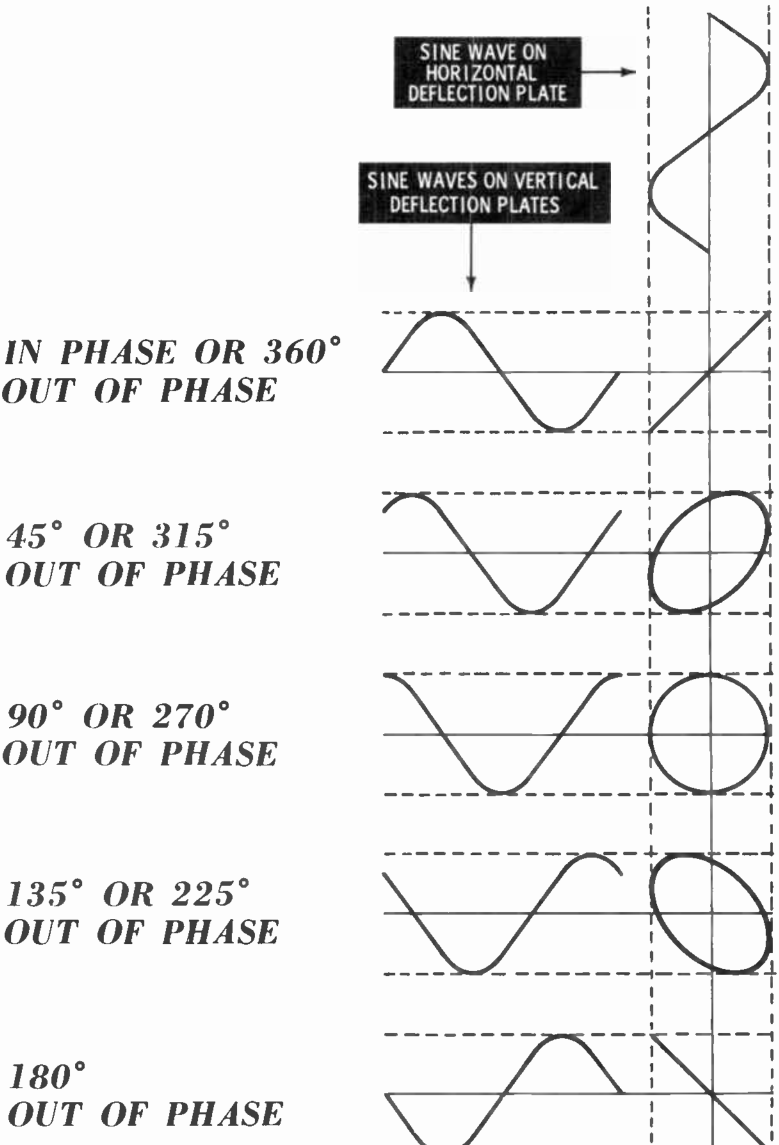


LISSAJOUS FIGURE—WAVEFORMS IN PHASE

In the figure at the right, voltage/time relationships are different; corresponding voltage points are 45° apart. Therefore the waveforms are 45° out of phase.

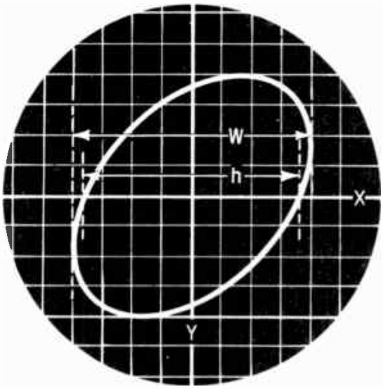


LISSAJOUS PATTERN - SAMPLE PHASE MEASUREMENT



The Lissajous figures on the preceding page are examples of a few out-of-phase relationships. An estimate of the phase difference of two signals can be made by observing the direction and amount of angle and the width of the ellipse. This will be close enough for most checks.

However, if you desire to make the measurement more precisely and can locate values in a sine (trigonometry) table, there is another method available. In this case, the amplitudes of the two signals must be near the same size.



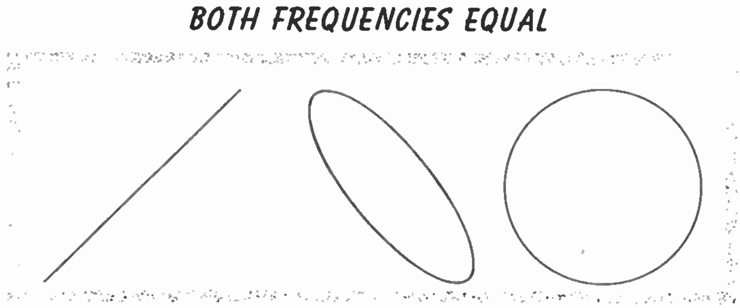
The graticule is placed on the CRT, and the Lissajous figure is centered. The overall height and width of the ellipse should be equal in length. The distances h and W are shown in the figure above. The ratio h/W is the sine of the angular phase difference. For example, if h were equal to 7 units and W equal to 8, then:

$$\frac{h}{W} = \frac{7}{8} = 0.875$$

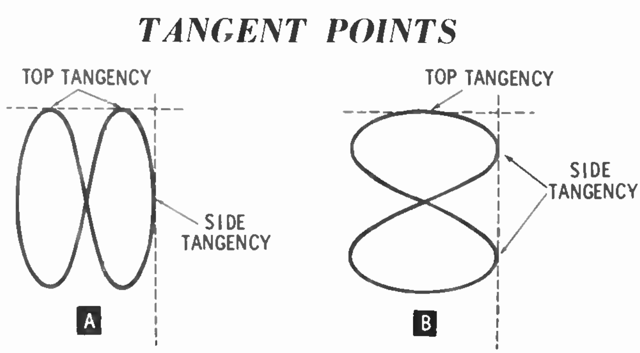
This ratio is approximately the sine of 60°. Therefore, the two signals are 60° or 300° (360° — 60°) out of phase.

Frequency Measurement—Frequency of an unknown sine wave is determined in a manner similar to phase measurement. A known frequency is applied to the horizontal plates while an unknown waveform appears on the vertical plates. The resulting Lissajous figure will reveal the difference in frequency between the two. The reference frequency could be taken from a calibrated signal generator or from the 60-cycle AC supply.

The electron beam will follow the voltage amplitudes placed on the deflection plates. If the waveforms are of the same frequency, the Lissajous figure will resemble those obtained in measuring phase relationships.



Frequency relationships can be determined by the number of loops or points that touch the top (or bottom) and one of the sides of the pattern. In the figures you have seen so far, there is one point of tangency at the top and one at the side. The frequency ratio is 1/1; the unknown has the same frequency as the standard.



In figure A (above) one cycle of standard frequency appears on the horizontal plates at the same time that two cycles of the unknown are on the vertical plates. There are two points (loops) of top tangency and one point of side tangency. Frequency ratios should be expressed in terms of vertical (unknown) to horizontal (standard). The frequency ratio of figure A is 2/1.

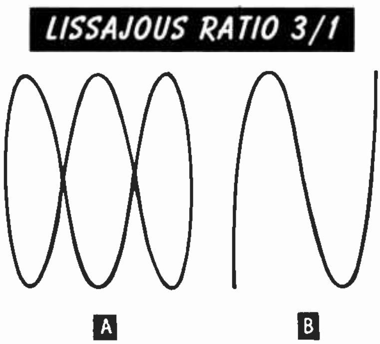
Q81. What circuits must be bypassed in the horizontal channel to obtain a Lissajous figure on the screen?

Your Answer Should Be:

A81. The sync and sweep-oscillator circuits must be bypassed. If a sawtooth wave and an external signal were fed to the horizontal-deflection amplifier at the same time, a Lissajous figure could not be developed. The sweep oscillator would also be highly erratic.

Additional Samples of Lissajous Figures

Both figures provide a vertical/horizontal (unknown/standard) ratio of 3/1. But they do not look alike. Figure A is known as a **closed** pattern. If you will start at any point in the figure and follow the line, you will return to



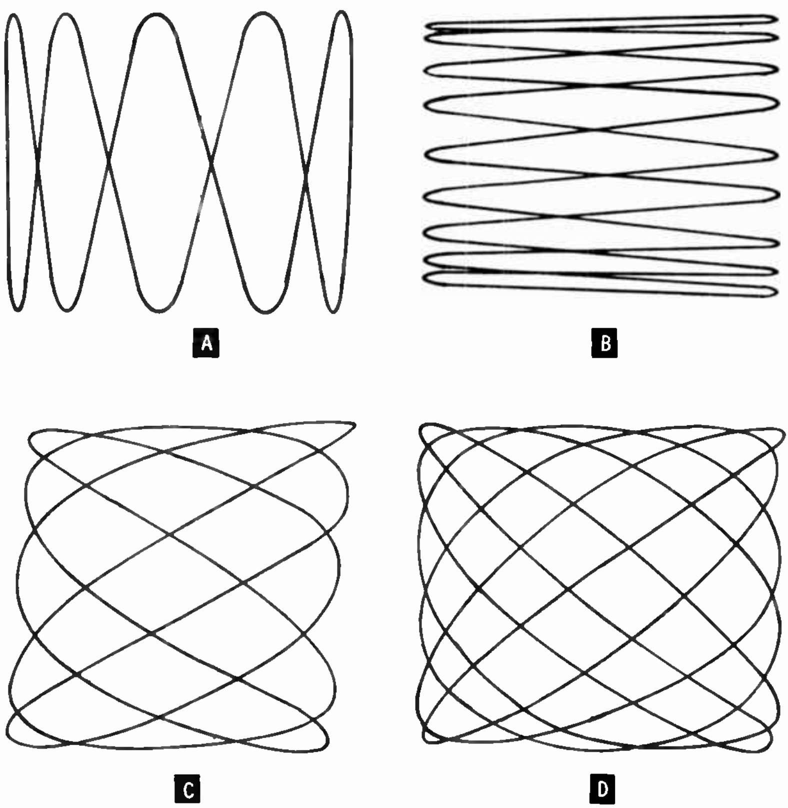
the starting point. The figure is continuous; it has no beginning or end. Figure B, however, is not continuous; it has a beginning and an end. Its pattern is **open.**

The three points of tangency at the top and one point of tangency at the side are easy to count in figure A. But the three tangent points do not appear in figure B. The problem is resolved by counting tangency points in halves instead of units in an open pattern. Each line that terminates at the top or side is a one-half point of tangency. Each loop is considered to be two ends or two one-half points. Counting at the top, there is one loop (two halves) plus one end (one half) for a total of three halves. At the side there is a single end for one half. The vertical/horizontal ratio is three halves divided by one half, or 3/1.

A continually shifting Lissajous pattern results when the phase relationship between the two input signals is constantly changing. The more complex the pattern (resulting from a frequency ratio having large numbers, such as 17/13) the harder it is to interpret. It is better, then, to simplify the ratio, if possible, by changing the known frequency.

Other samples of frequency measurements in Lissajous figures are shown below.

LISSAJOUS FIGURES



Q82. If the standard frequency is 180 cps, what is the frequency of the unknown in each of the above Lissajous patterns?

Your Answers Should Be:

A82. Values of unknown frequencies are:

(A) 900 cps; vertical/horizontal ratio is 5/1.

(B) 20 cps; 1/9 ratio.

(C) 108 cps; 3/5 ratio.

(D) 150 cps; 5/6 ratio.

WHAT YOU HAVE LEARNED

1. You obtained additional practice in analyzing the way in which circuits operate.
2. You also gained experience in reading schematic and block diagrams by tracing signals (waveforms) from stage to stage through the diagrams. A servicing block diagram was introduced. Waveform information contained in such diagrams was found useful in checking circuit operation.
3. An oscilloscope is a test instrument capable of presenting waveforms. An oscilloscope reproduces the amplitude and time characteristics of a waveform. You can use this capability to check the condition of waveforms at selected test points in many kinds of electronic equipment. The information you obtain will tell you the operating status of a circuit or help you to isolate trouble to a single circuit.
4. A scope can be used for other tests in addition to checking the shape of a waveform. Voltage measuring is one test. Since an oscilloscope has a relatively uniform deflection sensitivity (inches per volt) or sensitivity factor (volts per inch) across its screen, this feature can be used to estimate the peak-to-peak voltage of a waveform placed on the screen. A graticule (plastic sheet containing horizontal and vertical lines) and a voltage standard are required. The graticule is placed on the face of the scope, and the standard voltage is applied to the vertical plates.
5. Phase measurement is another test. The standard signal is applied to the horizontal amplifier, and the un-

known is applied to the vertical amplifier. The resulting Lissajous pattern determines the phase relationship of the two signals.

6. Lissajous patterns can also be used in measuring frequency. A known frequency is applied to the horizontal amplifier; the unknown is applied to the vertical amplifier. By counting the number of tangency points at the top and at one side, a ratio of unknown to known frequency can be obtained. After multiplying the ratio times the known frequency, you have the frequency of the unknown.
7. An oscilloscope contains two basic sections—the CRT and control circuitry. The CRT is designed to place a controllable beam of electrons on the face of the tube. The circuitry controls the movement of the beam.
8. An electron gun contains a cathode (to emit electrons), a control grid (to control the intensity of the trace on the screen), a first anode (to develop the electric lenses that focus the beam on the screen), and a second anode (to accelerate the electrons toward the screen). Deflection plates in vertical and horizontal pairs are used to position the beam on the screen. If a waveform is applied to the scope, the plates deflect the beam according to the amplitude and time characteristics of the waveform. The screen is made of fluorescent materials that give off light when struck by fast-moving electrons. The picture seen on the screen is formed by the illumination of these materials.
9. The control circuitry has two channels—vertical and horizontal. A constant-gain amplifier places the waveform to be measured on the vertical-deflection plates of the CRT. The beam follows the differences of potential between the two plates and, therefore, the amplitude of the waveform.
10. The horizontal channel contains a sync circuit, a sweep oscillator, and an amplifier similar to that used in the vertical channel. The sync circuit obtains a synchronizing signal from the vertical amplifier, power line of the scope, or external source. The sync signal is applied to the sweep oscillator to synchronize its frequency in

phase with the waveform in the vertical channel. The shape of the sawtooth is such that when it is amplified, it will be the precise time base required to place one, two, three, or more waveforms on the screen at one time. The horizontal channel can be used for bringing an external signal into the scope.

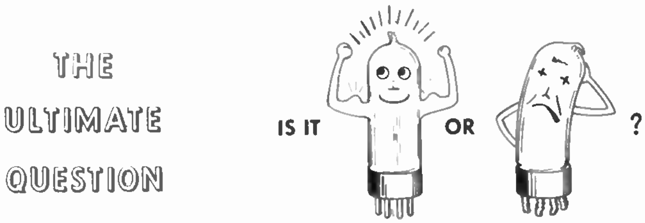
11. Controls are available to adjust the position of a waveform up and down or left and right on the screen.
12. Intensity and focus controls vary the brightness and sharpness of the picture.
13. Sync-circuit controls are two in number. The sync-selector switch is used for selecting the correct sync signal. A lock control stabilizes the screen presentation.
14. To obtain the correct time base for a wide selection of input frequencies, a coarse-frequency switch and a vernier control are used. The coarse-frequency switch selects the approximate frequency setting; the vernier permits making fine adjustments to obtain a stable waveform.
15. Controls for the vertical and horizontal amplifiers are identical. In this section of the front panel, jacks (or posts) are located to which test leads are connected. These jacks enable external signals to be brought into the amplifier sections.
16. You are advised to study the manual that accompanies an oscilloscope before using it. Different scopes are designed differently. The manual will provide the information necessary to operate and use the scope properly.

4

Vacuum-Tube and Semiconductor Testers

What You Will Learn

On completion of this chapter you will be able to use a tube tester, within its capabilities and limitations, to check the quality of a vacuum tube. You will learn how to test tubes for emission, mutual conductance, shorts, noise, and gas. You will be able to explain how these tests are conducted in a tube tester, and thereby judge the validity of the readings. You will also learn how typical semiconductor tests can be made. If you study this chapter thoroughly, you will be able to make simple tests on tubes and semiconductors to determine their operating quality without the use of special instruments.



TUBE-TESTER APPLICATIONS

Claims have been made by many technicians that 50 to 80% of all circuit troubles are caused by bad tubes. Since there are frequently six or seven components in a vacuum-tube circuit, you might think that the component to be tested first would be the tube. Even the lower percentage figure suggests that the law of averages is on your side.

Although it is true that vacuum tubes fail more frequently than most other electronic components, an experienced technician would not grab at this statistical fact as the sole reason for putting a tube into a tube tester. As you will discover in this chapter, there are many reasons why tubes fail, and a tube tester will not always reveal all of them.

A tube which checks out as good on the tester may not function correctly in a particular circuit. A tube may appear bad during the tube test and still perform its function in the circuit. Also, a tube may have gone bad as the result of a faulty resistor, capacitor, coil, connector, or switch. For example, if a cathode capacitor shorts, the resulting increase in plate current could damage the tube. In this case, replacing the bad tube with a good one will not correct the trouble. Sooner or later excess current will damage the new tube.

These and other limitations of a tube tester, as well as its capabilities, will be described. The point to remember while studying and using a tube tester is the need for common sense and technical judgment in interpreting the readings it may give. Reserve your conclusion that a tube must be bad until it has been technically proved.

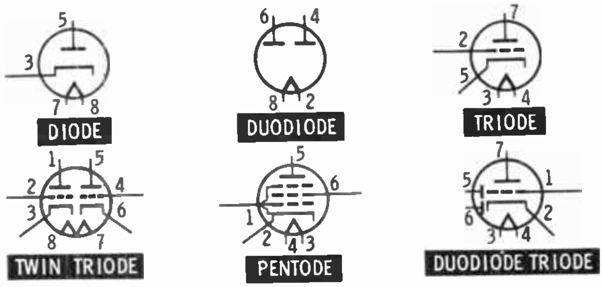
VACUUM-TUBE CHARACTERISTICS

As in previous chapters, some underlying fundamentals will be reviewed before the test instrument itself is explained. For a tube tester, the fundamentals are the basic characteristics of a vacuum tube.

Tube Types

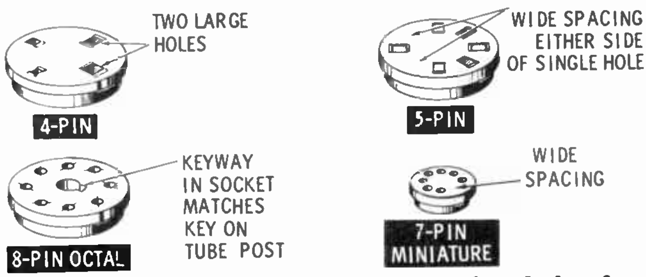
A vacuum tube consists of several elements inserted in a glass or metal container that has been evacuated (most of the air removed). Electrons move more readily in a vacuum than in air. An exception to the literal meaning of the term **vacuum tube** is a gas tube in which air has been replaced by an ionizing gas that supports electron flow.

All vacuum tubes contain elements that aid or control the flow of current through the tube. A tube may have a heater, cathode, plate, and one or more grids. The combinations determine the type of tube and how it can be used in a circuit. If the circuit is to act as a rectifier or detector, for example, a diode would be used. An amplifier or oscillator circuit would require a triode, tetrode, pentode, or other multielement tube. A circuit that detects and amplifies might use a duodiode triode.



The tubes shown above are just a few of many combinations of tube elements. To conserve space, equipment manufacturers use multipurpose tubes as much as possible. The duodiode, twin triode, and duodiode triode are just three of many examples. A number next to an element indicates the number of the pin to which it is connected. This is normal practice in most schematic diagrams.

There are several different types of tube sockets required to accommodate the number and spacing of pins in the tube base. Samples of four different sockets are shown below.



Q1. When numbering tube pins and socket holes for an 8-pin tube, is the same number always assigned for each element?

Q2. Electrons move more readily in a ______ than in ___.

Q3. What are the names of the elements that may be contained in a vacuum tube?

Your Answers Should Be:

A1. No. There is no standard numbering system for tube elements.

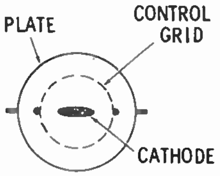
A2. Electrons move more readily in a **vacuum** than in air.

A3. A **heater, cathode, plate,** and one or more **grids** may be contained in a vacuum tube.

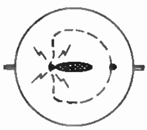
Tube Defects

Tube elements are mounted very close to one another. Periodic heating and cooling of the tube can cause the metal in the elements to weaken and bend. If there is sufficient bending, neighboring elements could touch and cause a condition of arcing or shorting. Such a tube must be replaced to restore proper circuit operation.

TOP VIEW OF TUBE ELEMENTS



Normal Condition

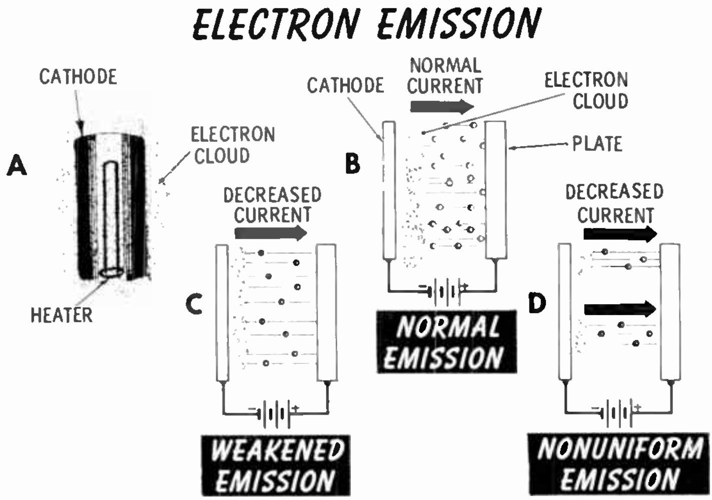


Grid Shorted to Cathode

Modern manufacturing techniques are capable of producing a tube that is ruggedly constructed. Under normal operations, a heating element may operate for 2,000 hours before it weakens and opens. Its life is shorter under abnormal conditions, such as operating the heater at too high a temperature or operating the tube continuously at its maximum ratings. When the heater or any other element opens, the tube will no longer conduct current properly.

A decrease in the emitting capability of the cathode is another tube defect that frequently occurs. The cathode, when heated, will emit electrons into a cloud surrounding the element. When the plate becomes positive with respect to the cathode, the plate will attract a quantity of electrons that depends on the difference in potential between the two elements.

Figure A (below) shows how an electron cloud surrounds the heated cathode. Figure B represents normal current flow between cathode and plate. In figure C the emitting



capability of the cathode has decreased after many hours of operation. A smaller quantity of electrons in the cloud causes a reduction in plate current. In figure D the cathode has weakened more in some areas than in others, resulting in a reduced number of electrons available for plate current.

There are other tube defects that occur quite frequently. **Leakage** between the cathode and heater occurs when electrons travel from the cathode to the heater after the two have become shorted or partially shorted. This leakage flow reduces the quantity of electrons available for full plate current. If leakage is intermittent, it could add noise to the signal in the circuit.

Vibration or overheating may loosen the elements or their supporting wires, causing **microphonics.** The tube picks up vibrations and acts something like a microphone. This happens when the vibrations cause changes in the capacitance that normally exists between tube elements.

Tubes can become gassy when gas that was trapped in the metal of the tube elements is released. This gas interferes with the normal operation of the tube.

Q4. List some of the common tube defects.

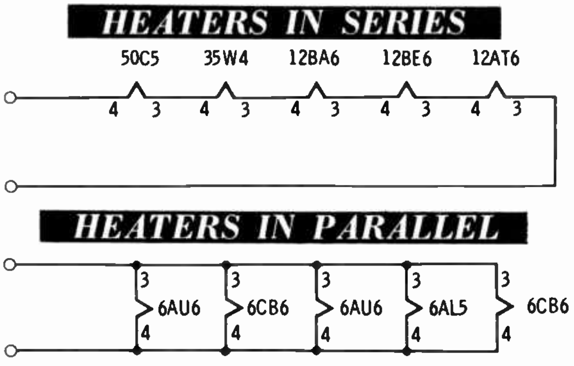
Your Answer Should Be:

A4. Some of the common tube defects are: **shorting, arcing, open element, decrease of cathode-emitting capability, leakage current flow, loose elements, and gas inside the envelope.**

Defect Check

Many times a defective tube can be located without using a tube tester. Some of these checks are described below.

Sight Check—If the tube is in the equipment with voltage applied, there are visual checks you can make. Look down toward the base of the tube. A small, red glow indicates that the heater is still operating.



If one heater in a series string opens, none of the other heaters will receive current. If you are using a sight check, look for the red glow in neighboring tubes. If the glow is missing, a heater may be open in any one of the tubes in the string. Figure A shows the way in which a series string of heaters is shown on a schematic diagram. From the schematic you can also identify the pin numbers of the tube. With an ohmmeter you can determine whether or not the heater has opened. With the tube out of the socket, place the probes of the meter on the heater pins. If the heater is open, the pointer will not deflect (infinite resistance).

Also check the plates of the tubes. If any are glowing red, the tube could be drawing excessive current. If this is so, the trouble could be in the tube itself or in its circuit. Some tubes are designed to operate at a red-hot temperature; these are usually found only in circuits that operate at periodic intervals instead of continuously.

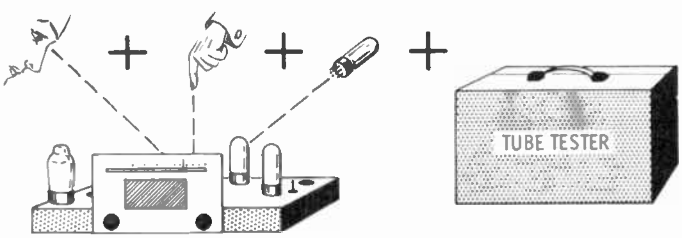
Another visual check can be made. A blue glow inside the envelope indicates a gassy tube. Gas molecules in the tube are being bombarded by plate-current electrons and some of the energy is being released in the form of a blue light. Of course, it is normal for tubes that contain an ionizing gas to glow when they operate. A sight check for gas may not always be conclusive. There may not be enough molecules to cause a glow, but there may be a sufficient number to disrupt the plate current.

Touch Checks—Most tubes are warm or hot when plate current is flowing. Touch the tubes only momentarily, since many tubes operate at extremely high temperatures. A hot metal or glass tube usually indicates that the heater is operating.

Tubes with loose elements can be detected when they are being used in a radio receiver or other equipment having an audible output. Sharply tap the tube and listen for noise (called microphonics) in the speaker.

Substitution Test—Substituting a tube known to be good for one suspected of being bad is another test that can be made without a tube tester. Try to isolate the faulty circuit or group of circuits, and then substitute one tube at a time, listening or watching for a change in equipment operation. If no improvement is noted, replace the old tube and go to the next suspected stage.

TUBE-TESTING METHODS



Q5. Which of the above methods (in addition to a tube tester) can be used to determine whether the heater of a glass vacuum tube is operating?

Your Answer Should Be:

A5. All three—sight, touch, and substitution—can be used.

TUBE TESTERS

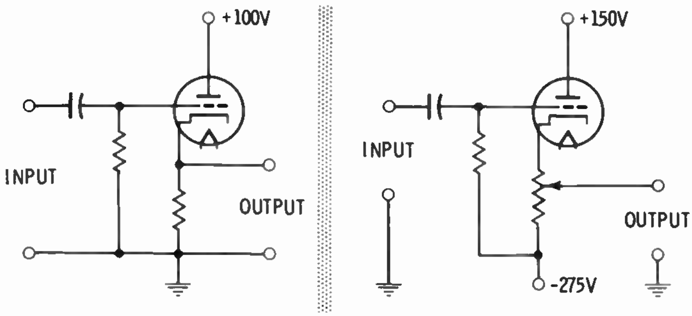
Visual, touch, and substitution tests are useful methods of identifying defective tubes. However, a test instrument could make these checks more rapidly. Such an instrument is called a **tube tester** or **tube checker.**

What Will a Tube Tester Check?

A tube tester can check almost all characteristics of a tube that you may desire to know. Expensive laboratory models are designed to duplicate the operating conditions of the circuit in which the tube is to be used. In other words, the tube tester is capable of imitating the circuitry so closely that it is, in effect, a controlled substitution check.

Although expensive, this type of tube tester gives the kind of positive check that only actual circuit conditions make possible. A single tube type can be used in many different kinds of circuits. Within each of these circuit types there are many variations in circuitry and applied voltages. An example of this is shown below.

CATHODE-FOLLOWER CIRCUITS



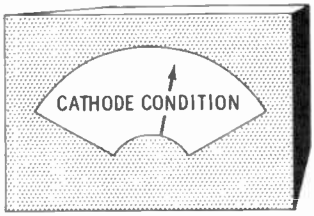
The only true way to determine whether the same triode will operate in either one of these cathode-follower circuits is actual trial in the circuit and observation of its performance. Laboratory models of tube testers approach this capability, but the simpler types do not.

Practical Tube Testers

There are two varieties of practical tube testers—**emission** testers and **mutual-conductance** testers.

Emission Tester—As its name implies, the emission tester measures the ability of the cathode to emit electrons. Although a defect in cathode emission is one of the more frequent causes of tube failure, it does not tell the full story about a tube. In the first place, the tester can only give a fair approximation of the life left in the cathode. Secondly, an emission test will not reveal the ability of single and multigrid tubes to amplify.

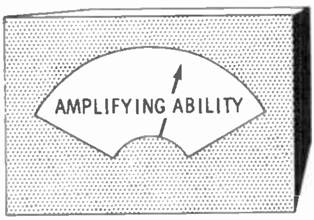
PURPOSE OF AN EMISSION TESTER



Mutual-Conductance Tester—The terms mutual conductance and transconductance both have the same meaning. The term mutual conductance is usually used when discussing tube testers.

The mutual-conductance tester measures the amplifying ability of a tube having grids. Mutual conductance is an electron-tube rating equal to the change in plate current divided by the change in grid voltage that causes the plate current change (if the amounts of change are small and the plate voltage is constant).

PURPOSE OF A MUTUAL-CONDUCTANCE TESTER



Q6. What is the only positive test for a vacuum tube?

Q7. Will an emission tester give a fair test of a diode?

Your Answers Should Be:

A6. The only positive check for a vacuum tube is to determine whether or not it will operate properly **in its designated circuit.**

A7. Yes. Since a diode does not amplify (has no grid elements), an emission test provides a fair indication of its operating quality.

Measuring Mutual Conductance

The mutual-conductance tube tester measures the amplification factor of a tube by solving the formula for mutual conductance, g_m.

$$g_m = \frac{\Delta I_p}{\Delta E_g} \text{ (with } E_p \text{ constant)}$$

where,

ΔI_p is a small change in plate current,
ΔE_g is the change in grid voltage that causes I_p,
E_p is the plate voltage.

Mutual conductance is the ratio of a small change in plate current to the small change in grid voltage that produced it. In effect, a mutual-conductance tester holds the plate voltage constant while changing the grid voltage. It then measures the change in plate current that takes place. The resulting measured value in **micromhos** can be compared against the average value for the tube type.

There are two types of mutual-conductance testers. One is called the **absolute**, or **direct-reading**, type. Its circuitry is designed to measure changes in plate current so closely that it can give a direct reading on a meter calibrated in micromhos. The other type, called a **relative**, or **dynamic**, tester, approximates the change taking place and provides a reading on a scale containing words or symbols.

The tube tester most frequently used by technicians is the dynamic mutual-conductance type. It is not as expensive as the direct-reading model, but it is many times more useful than the emission tester.

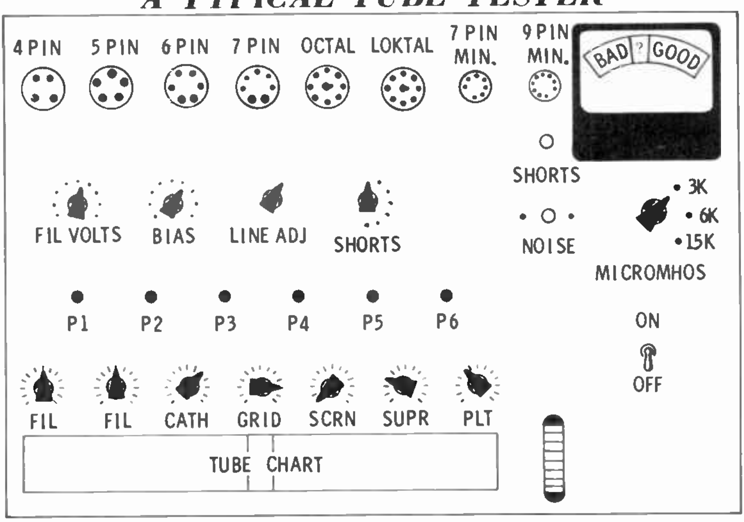
Either type of g_m tester also tests for shorts, noise, and gas. The better emission testers also make these tests.

Essential Parts

Whether it is an emission or mutual-conductance type, a tube tester consists of a minimum of four main areas. These four areas are tube sockets, switches, test directions, and a meter. More complicated testers may contain additional functions.

Tube Sockets—Tube sockets are required to hold the tube in the tester. Since there are a variety of different tube bases, there should be one socket for each of the popular types. A mutual-conductance tester might have as few as eight or as many as fourteen sockets, depending on how many different tube bases it is designed to accept. An emission tester repeats the same tube sockets a number of times to decrease the number of required switches.

A TYPICAL TUBE TESTER



Q8. Will a dynamic tube tester test for emission?

Q9. What are the four basic areas in a tube tester?

Your Answers Should Be:

A8. **Yes.** Since it measures the transconductance of a tube, the dynamic tube tester also indicates cathode emission capability.

A9. **Tube sockets, switches, test directions,** and a **meter** are the four basic areas.

Switches—An emission tester can have as few as one or two switches. This tester is limited to making plate-current readings and possibly checking for shorts or gas. A mutual-conductance tester has several switches. Rotary wafer switches can be used to connect standard voltages to the appropriate terminals of the socket, depending on the pin-number arrangement (filament, grid, plate, etc.) of the tube being tested. Other switches include filament volts, bias, line adjust (to zero meter), shorts (checking each pin with respect to the others), micromhos (select proper range for meter reading), and several push buttons (to select the desired test).

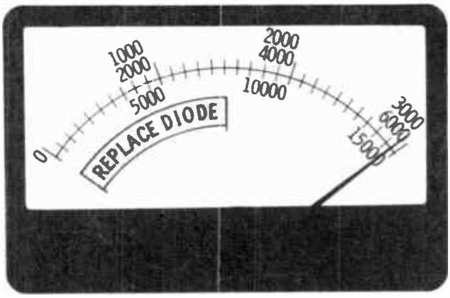
Test Directions—Directions for setting the switches are included in a manual that accompanies the tester or on a paper roll built into the tester, as shown in the figure on the preceding page. A section of a typical chart is shown below.

TUBE CHART

TUBE TYPE	FIL VOLTS	SELECTOR SWITCHES FIL	FIL	CAT	GRD	SCN	SUP	PLT	BIAS	SCALE	PRESS	MUT COND	NOTES
12A4	12.6	5	6	2	9	1	2	1	25	6K	P2	4900	
12A5	12.6	8	7	4	2	3	5	1	50	3K	P2	1130	

Meter—All tube testers have a meter. Some have a scale that is divided into three areas marked, GOOD—WEAK—REPLACE, or similar words. Such a scale can be found on either an emission or mutual-conductance tester. Another meter may have its scale calibrated in micromhos to measure transconductance directly. This type of meter would be found only on a mutual-conductance tester. Some mutual-conductance testers have both micromho and word scales.

TEST METER

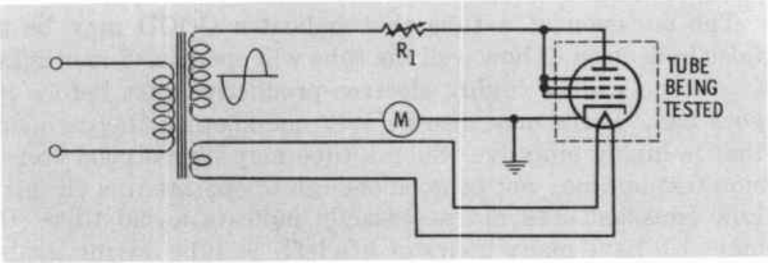


HOW TUBE TESTERS OPERATE

The amount of plate current that flows in a tube can be used as an indication of the emitting capability of the cathode. The circuit below provides this type of measurement.

Emission Test

In an emission test of grid-type tubes, the grid(s) and plate are connected together by switching or prewired tube sockets. The tube will then operate as a diode. R_1 is set at the proper value for each tube so that the meter will read



GOOD, WEAK, or BAD. Since plate current will be pulsating DC, the meter will read its average value.

Q10. For a 12A4 tube, which switch would you set to 6K? Refer to the opposite page.

Q11. What test would be made when P2 is pressed?

Q12. What is the purpose of the Mut Cond column on the chart?

Q13. What would the meter read if the cathode were open?

Q14. What would it read if the grid and cathode were shorted?

Your Answers Should Be:

A10. "6K" refers to a setting for the **MICROMHO** switch.

A11. Pressing P2 would connect the meter to read the **mutual conductance** of the tube.

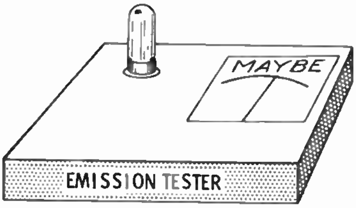
A12. Each number under the **Mut Cond** column identifies the **minimum value in micromhos that a tube of a given type should indicate.** If the reading is below this number, the tube should be rejected.

A13. **BAD.** If the cathode were open, no current would flow.

A14. **Too GOOD.** Unless the meter or transformer were properly fused, the meter would be damaged by the excessive current flow. For this reason, a **tube should always be checked for shorts before being tested for emission or mutual conductance.**

Limitations of an Emission Test

The emission of a tube that indicates GOOD may be a false indication of how well the tube will operate. Sometimes a cathode will be highly electron-productive just before it goes bad. There may also be only one spot on the cathode that is highly emissive. Such a tube may give a good emission test but may not be good enough to operate in a circuit. Low emission does not necessarily indicate a bad tube. It may still have many hours of life left. A tube having grids may show good emission and yet not operate in a circuit.



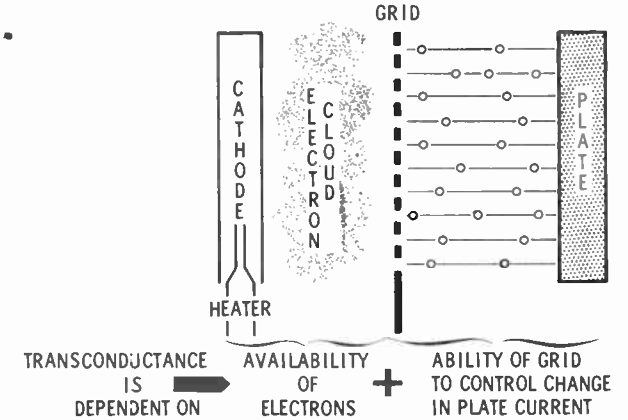
EMISSION TEST HAS LIMITATIONS

Testing for Transconductance

As stated previously, mutual conductance, has the same meaning as transconductance. It is a figure of merit designed into a tube. Transconductance indicates the ability of a tube to amplify by specifying the change in plate current for a given change in grid voltage. A value of transconductance, expressed in micromhos, is assigned to each tube type in accordance with its design.

Transconductance will decrease in a tube as it is being used. Reduction of transconductance will result from continued weakening of cathode emission and/or distortion of grid structure through periodic heating and cooling. A minimum value of transconductance can be assigned to each tube type. Any tube measuring below this value can then be considered to have fallen below the desired amplifying capability and should be discarded.

FACTORS AFFECTING TRANSCONDUCTANCE



Q15. What is transconductance?

Q16. Transconductance is expressed in terms of what units?

Q17. What factors reduce the transconductance of a tube?

Q18. Transconductance of a tube will ________ as the tube is used.

Q19. Does a low emission reading always indicate a bad tube?

Your Answers Should Be:

A15. Transconductance is the **ratio of plate-current change to grid-voltage change.**

A16. Transconductance is expressed in terms of **micro-mhos.**

A17. The transconductance of a tube is reduced by **weakening of the cathode emission** and **distortion of the grid structure.**

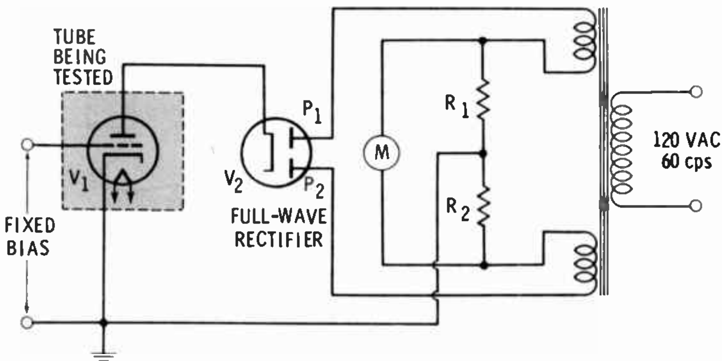
A18. Transconductance of a tube will **decrease** as the tube is used.

A19. No.

Circuit Used To Measure Transconductance

V_1 is the tube being tested. V_2 is a full-wave rectifier in the tube tester. Its plates are each connected to equal secondary windings of a transformer. R_1 and R_2 are equal re-

TRANSCONDUCTANCE TESTER



sistances shunted across the meter in the tester. When a fixed bias is placed on the grid of V_1, it will conduct through the rectifier. When voltage on the secondary is such that P_1 of the rectifier is positive and P_2 is negative, current will flow through R_1 from top to bottom. The pointer in the meter will tend to swing in one direction. During the next half cycle, P_2 will conduct. Current will flow through R_2 from the bottom to the top. The meter will tend to swing in the other direction. At 60 cps the net movement of the meter is zero.

An AC voltage can be applied to the grid of V_1 from a separate secondary winding. Suppose that this voltage makes the grid of V_1 less negative when P_1 is positive. During this half cycle, plate current will increase in V_1. A larger amount of current will flow through P_1 and R_1, tending to swing the meter pointer a greater distance across the scale than before. During the other half cycle, plate current decreases in V_1. Less current flows through P_2 and R_2 than before, causing the pointer to tend to swing a smaller distance. Since the meter is passing more current in one direction than the other, the pointer will have a net deflection in one direction. The meter scale can then be calibrated in terms of the change of plate current that takes place with respect to a change in grid voltage.

Limitations of a Mutual-Conductance Tester

There are some limitations in the mutual-conductance tester. Manufacturers usually design their testers to show a tube defective when its transconductance has decreased to 70% of rated value. This figure is an average value. It is not valid under all conditions. Voltages applied to tube elements by the tester are only approximations of actual voltages applied in a circuit. Therefore, this is not a positive indication of how well the tube will operate in its designated circuit.

Testing for Gas

As was mentioned before, a small amount of gas is sometimes present inside the tube envelope. When electrons from the cathode strike the gas atoms, electrons from these atoms are separated from their nuclei. The atoms become positive ions. They are attracted to the negative grid and draw electrons from the grid circuit. Tube conditions are now no longer normal.

Q20. Can a transconductance test be made on a diode?

Q21. A tube is defective when its transconductance has decreased to approximately ___ of its rated value.

Q22. What must a tube tester be able to measure to determine the transconductance of a tube?

Your Answers Should Be:

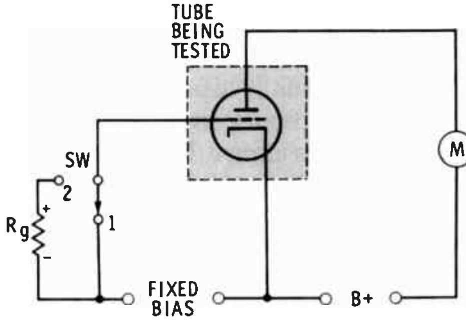
A20. No. A diode has no control grid; therefore, the meter would read zero.

A21. A tube is defective when its transconductance has decreased to approximately 70% of its rated value.

A22. It must measure a **change in plate current** when a change in grid voltage is applied.

A Circuit To Indicate the Presence of Gas

The circuit below, which is found in most tube testers, will determine the presence of gas. With the switch in position 1, the meter will indicate a value of plate current. When the switch is changed to position 2, there will be no change in



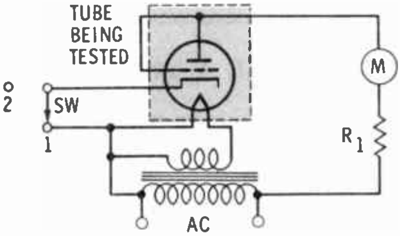
the meter reading if very little or no gas is present. However, if positive gas ions are present, current will flow through R_g and develop a positive polarity from the grid to cathode. Bias will be reduced, plate current will increase, and an increased reading of the meter will be noted.

Testing for Noise

Noise is caused by loose electrodes, nonuniform electron emission, and heater-cathode current leakage.

Nonuniform emission may or may not be detected by an emission or transconductance check. Tube substitution may be the only reliable check. If the equipment has an audible or visual output, tapping the suspected tube may verify the suspicion of loose electrodes. Some tube testers provide a pair of earphone jacks to make such an audible check.

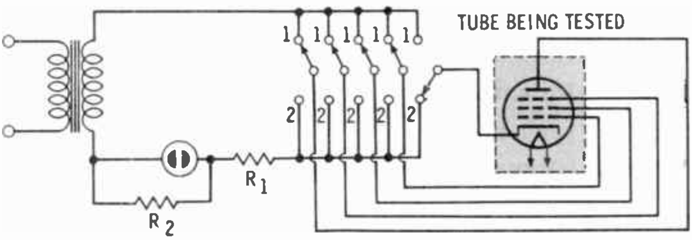
The tube below is connected (switch position 1) as a diode, with the plate and cathode across the primary of the tester transformer. Plate current flows through the meter and a current-limiting resistance R_1. In position 2 the cathode is "floating." If there is no current leakage between cathode



and heater, the meter pointer will drop to zero. If there is leakage, the meter pointer will drop, but not to zero.

Testing for Shorts

When the cathode switch is in position 2, the cathode is connected to one side of the secondary through a neon bulb. All other switches are in position 1, connecting the tube elements to the other side of the secondary. Current will



flow only if the cathode is shorted to any of the other elements. If current does flow, both halves of the neon bulb will light. If the cathode is not shorted, only half of the bulb will light during the half cycle when the cathode is negative with respect to the other elements. All elements can be checked one at a time in this manner. R_1 is a current-limiting resistance to protect the lamp. R_2 bypasses any small, stray, alternating currents around the lamp to prevent it from fully lighting when there are no shorted elements. Since tube elements may be loose, the tube should be tapped sharply while making the check.

Q23. What factors cause a tube to produce noise?

Your Answer Should Be:

A23. The factors that cause a tube to produce noise are: **loose electrodes, nonuniform emission,** and **current leakage between cathode and heater.**

HOW TO USE A TUBE TESTER

A tube tester is not difficult to use. Follow the instructions contained in its manual, and apply them with common sense and a knowledge of how the instrument operates. Carefully follow instructions that apply to setting up the tester. In addition to the serious error of a false reading, improper settings could damage a tube.

After proper settings have been made, insert the tube in the proper socket, turn the power on, and move the meter pointer to the setting prescribed with the **LINE ADJUSTMENT** control. Tubes should be allowed to warm up for at least one minute before making a test. Just before testing, make sure that the pointer is at its designated mark.

Make tests in this order:

1. Test for shorts.
2. Test for cathode-to-heater leakage.
3. Test for noise.
4. Test for mutual conductance or emission.

WHAT YOU HAVE LEARNED ABOUT TUBE TESTERS

1. There are two general types of tube testers. An emission tester checks the capability of a cathode to produce electrons for plate current. A mutual-conductance tester approximates the g_m (transconductance) of a tube.
2. A GOOD reading on an emission tester can be invalid, since a cathode is capable of emitting large quantities of electrons just before it fails. A BAD reading can be false, since a cathode may emit electrons at a decreased but steady rate for a long period of time. Although an emission test may be suitable for diodes, it does not measure the true quality of grid-type tubes.

3. In a mutual-conductance tester, tubes are checked under voltage and circuit conditions that approximate but do not duplicate the exact operating conditions of the circuit in which the tube will be used.
4. A tube tester is made up of sockets (to test a variety of tubes), switches (to establish appropriate testing conditions for a particular tube), a meter (to provide a measurement of tube condition), and a chart or table (to provide switch-setting and testing instructions).
5. Meter scales on tube testers are of two general varieties. The better mutual-conductance tester has a scale calibrated in micromhos. Other mutual-conductance and most emission testers have scales containing words similar to GOOD—WEAK—BAD.
6. Most good tube testers also check for noise, gas, and shorts.
7. The only positive check of the quality of a tube is whether or not it will work properly in a specific circuit. This test is called a tube substitution check and can be made without a tube tester. Other checks that do not require a tube tester include visual and touch tests.

Q24. Name three types of tests that can be made without a tube tester.

Q25. Why is the mutual-conductance test a better indication of the condition of a triode than the emission test?

Q26. How could you determine, without using a tube tester, whether the heaters of a metal tube were working?

Q27. What tube test should you make first?

Q28. What does the mutual-conductance tester check?

Q29. What does the emission tester check?

Q30. A 12AU7 twin triode is connected in the amplifier circuit of a radio. The plate voltage (300V) is kept constant. The transconductance of the tube is equal to 3,100 μmhos. What is the change in plate current when the voltage applied to the grid changes from 0V to —8.5V? (Hint: $g_m = \Delta I_p / \Delta E_g$ when E_p is kept constant.)

Your Answers Should Be:

A24. The tests include visual (by eye), **touch** (by finger), and **substitution** (with a known good tube).

A25. Since mutual conductance is a measure of the change in plate current that will occur as the result of a change in grid voltage, **this test comes fairly close to measuring a tube under normal operating conditions.** An emission test will only measure the ability of the tube to pass plate current.

A26. **Metal tubes would feel warm,** sometimes very hot, if the heaters were working and the equipment were operating. Another check might be the use of an ohmmeter to measure for an open across the heater pins (with the tube not in the socket).

A27. Test for **shorts** first.

A28. A mutual-conductance tester measures a **change in plate current when a change in grid voltage is applied.**

A29. An emission tester measures the **ability of the cathode to emit electrons.**

A30. $g_m = \frac{\Delta I_p}{\Delta E_g}$

$\Delta I_p = g_m \times \Delta E_g = 3{,}100\ \mu\text{mhos} \times 8.5\text{V} = $ **26.4 ma**

SEMICONDUCTOR TESTING

Semiconductors are relatively reliable devices. Some transistors, for example, are capable of operating for more than 30,000 hours.

One example of this reliability is a digital computer that was recently tested during its development. The computer contained over 100,000 crystal diodes and transistors. The test was run for two years, averaging 20 hours of operation per day. Within that period there were only three semiconductor failures.

While vacuum tubes are the source of most troubles in equipment in which they are used, semiconductors, particularly transistors, are relatively troublefree. However, a technician still must determine when a semiconductor device is operating properly.

Locating a Faulty Semiconductor

The approach to finding a bad semiconductor is the same as that for locating any other defective component. You do not test a component unless you have a good reason to suspect that it is defective.

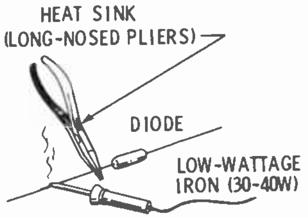
Since most semiconductors are soldered into position, the advice above becomes even more meaningful. Soldering and unsoldering a number of transistors to find a suspected bad one can be a tedious, time-consuming chore. Excessive heating can ruin a semiconductor. Therefore, be sure there is a good reason for removing a transistor before doing so.

Substitution Test—When you are reasonably sure you have found the circuit containing the trouble and that the trouble is, in fact, a semiconductor, you can verify and correct the trouble by a substitution test. As with vacuum tubes, this is probably the simplest and most reliable of all tests. When substitution of a good diode or transistor has restored the circuit to proper operation, the semiconductor that it replaced was the cause of the trouble.

Be very careful when removing and replacing semiconductors. Although strongly constructed, semiconductors are sensitive to excessive voltage, current, and heat.

When soldering or unsoldering a semiconductor, use the minimum heat required. Keep the semiconductor away from the chassis. Use a low-voltage soldering iron (30 to 40 watts) and a heat sink, as shown in the illustration below. A heat sink is a device for dissipating heat.

PLIERS USED AS HEAT SINK

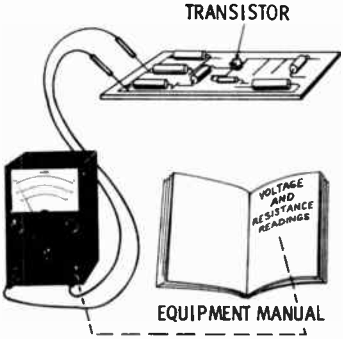


HEAT-SINK BETWEEN DIODE AND IRON TO DISSIPATE HEAT

Q31. What factors can ruin a semiconductor?

> **Your Answer Should Be:**
> **A31.** Excessive **current, voltage,** or **heat** can ruin a semiconductor.

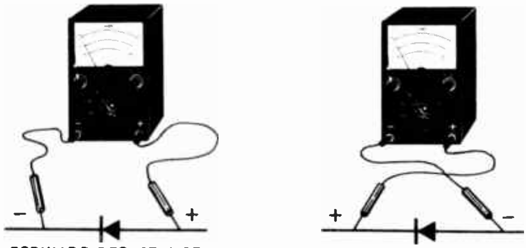
When a semiconductor is known to be defective, check the circuit for defects that may have caused the damage. If the defects are not eliminated, they will also damage the substituted unit. These checks can be made with a voltmeter and ohmmeter. Compare readings with those in the equipment manual.



Crystal-Diode Tests

A crystal diode is a semiconductor. Among the crystal-diode family are general-purpose germanium and silicon rectifiers (diodes) and silicon diodes constructed for high-power or very high-frequency purposes. Although these diodes may be effectively tested only under circuit operating conditions, other tests can be made.

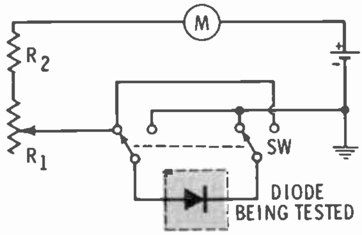
Resistance Measurement—A good diode will have a high resistance to current in one direction and a low resistance in the other. The ratio should be at least 10 to 1 for the diode to function as a rectifier. This is called a **reverse-to-forward** (sometimes **back-to-front**) resistance ratio, with the greater value being in the reverse direction.



DIODE RESISTANCE MEASUREMENT

Diode Test Set—Test sets are available to check the rectifying qualities of a diode. Some of them provide a combination resistance and current test. When the set is used as an ohmmeter, it will measure forward and reverse resistance. When it is used as a milliammeter, it will measure forward and reverse current. Others use one or the other to obtain the forward-to-reverse ratio. Most sets are constructed as shown in the following diagram.

DIODE TESTER

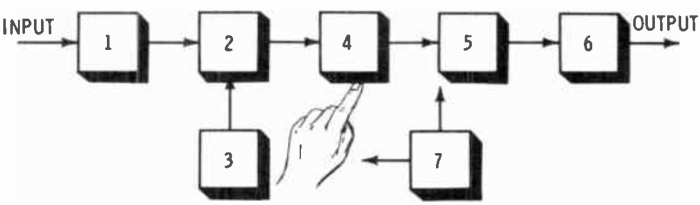


The diode is inserted in the device, and R_1 is used to adjust the meter reading so that the pointer will remain on scale when the switch is thrown. The switch reverses the current direction through the diode. R_2 limits the current to a safe value.

Transistor Testing

There are laboratory instruments that measure transistor characteristics in out-of-circuit and in-operating-circuit conditions. Test sets of lesser capabilities are available for use by technicians concerned with repair, rather than design, of transistor equipment. However, many worthwhile checks can be made without the use of a transistor tester.

When trouble occurs in transistor equipment, isolate the source of the trouble to a specific circuit before touching a single transistor.



Q32. The reverse-to-forward resistance ratio of a diode should be at least _ to _.

> **Your Answer Should Be:**
>
> A32. The reverse-to-forward resistance ratio of a diode should be at least **10 to 1.**

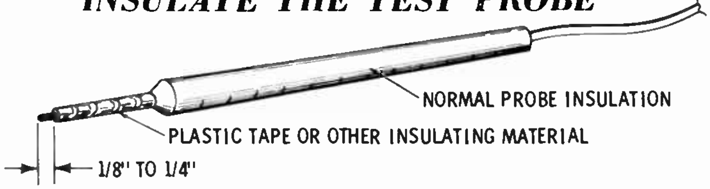
Transistor Testing Precautions

If the equipment manual contains waveforms at test points on a schematic or block diagram, an oscilloscope should be used to locate the circuit that is causing the trouble. If there are no waveforms available, voltage and resistance readings can be used to achieve the same results. As mentioned before, put off actual testing of a transistor until you are sure that it needs testing. When the faulty stage is isolated, use a multimeter to test the other parts of the circuit to determine whether abnormal conditions exist.

The multimeter used should have a high impedance to prevent loading the circuit. Low impedance across a circuit will change resistance and current values and provide a false voltage reading. The battery voltage of the ohmmeter used should not be in excess of 3 volts. Larger voltages may send an excessive amount of current through the transistor.

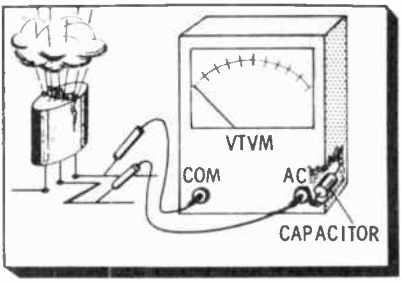
Parts and connecting leads are usually mounted very close together in the construction of transistor circuits. The metal tips of test probes are long enough to short-circuit leads when taking measurements. If this happens, excessive circuit voltage or current could be shunted to another part. To prevent this, insulate the metal portion of the probes so that only a short portion of the tip is exposed.

INSULATE THE TEST PROBE



When using a test instrument such as an AC voltmeter that could have a capacitor in series with the test lead, ground the probe to make sure the capacitor is discharged. If the capacitor were to discharge through a transistor, the transistor would likely be damaged.

DISCHARGE CAPACITORS IN TEST EQUIPMENT BEFORE USING

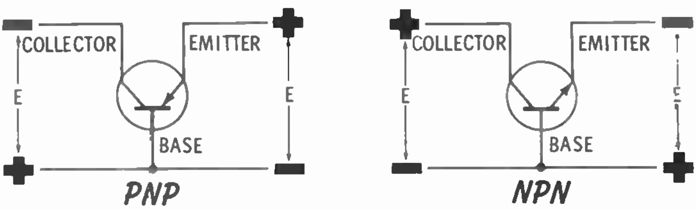


During the circuit-checking tests it is best to remove the transistor if it is the plug-in type. Removal is not absolutely necessary if you exercise necessary care.

The technical manual for the equipment should supply sufficient information to make circuit checks that include the transistor. These tests involve the amount of bias or voltage applied to and the current through the elements of a transistor. With the exception of some circuits (pulse and power-amplifier stages, for example), transistors are usually biased so that ½ to 3 milliamperes flow through the emitter, and voltage from collector to base is usually 3 to 15 volts.

Polarity, as well as the value of voltages, is particularly important to the safe operation of transistors. Check the amount of voltage first to be sure that it is not too high. Then determine if the polarity is in the correct direction. Voltage on PNP transistors must be negative on the collector and positive on the emitter with respect to the base. Polarities in NPN transistors are the reverse of those in PNP types.

TRANSISTOR VOLTAGE POLARITIES



Q33. If the trouble in a piece of equipment is isolated to one circuit, why should tests be made on other circuit components before testing the transistor?

Your Answer Should Be:

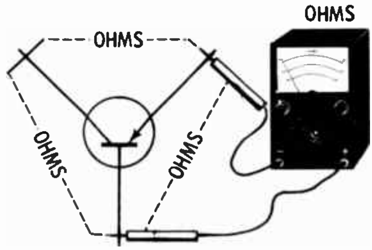
A33. Detection and elimination of any abnormal circuit conditions will **protect the new transistor.** The transistor should not be unsoldered until you have determined the transistor may be defective.

Transistor Tests

If all checks indicate that the transistor may be defective and the transistor must be removed for further testing or replacement, turn off the power to the equipment. Removing or inserting a transistor in an operating unit causes the current in the circuit to surge (rise) for instant. The surge may be enough to damage the transistor.

Ohmmeter Test—Forward- and reverse-resistance checks of the transistor elements provide an indication of its condition.

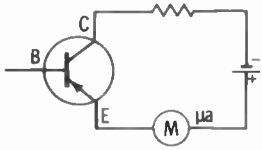
RESISTANCE TEST



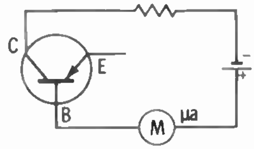
To make the test, ohmmeter readings should be taken in both directions (reverse the test leads) from emitter to base, collector to base, and collector to emitter. The purpose of the test is to determine whether shorts or decreased resistances between elements have occurred. The large-to-small ratios for emitter to base and collector to base should be 500 to 1 or more. Direction of the ratio depends on whether the transistor is an NPN or PNP type. The resistance from collector to emitter should be nearly the same when measured in either direction.

Most of the commercial testers are simple in design. Of the several tests that can be made in the laboratory, only a few are found in test sets normally used by technicians. The two most common tests are for leakage and gain.

Leakage Test—To determine leakage between elements, most testers place the transistor in series with a meter, battery, and current-limiting resistance. A good tester has a



MEASURING LEAKAGE BETWEEN COLLECTOR AND EMITTER



MEASURING LEAKAGE BETWEEN COLLECTOR AND BASE

microammeter. If current readings exceed those stated for the transistor, it should be discarded.

Gain Test—If transistor leakage current is within suitable limits, gain can be tested. Gain is a measurement of the change that occurs in collector current as a result of a small change in base current. The reason for this test is that the current gain capability of a transistor can decrease with age.

A variety of circuits are used to measure gain. All result in a ratio of I_c/I_b (collector current to base current). This ratio is matched against the minimum standard for the particular transistor. If the measured gain is too low, the resistor should be discarded. This test is often referred to as **direct-current gain,** since changes in DC current are involved.

Other Tests—More expensive sets measure the **punch-through** (or break-through) voltage level between collector and emitter to base. If current passes at a prescribed rise in voltage between the elements, the transistor would be considered defective.

An **AC-gain** test on a transistor is quite similar to a transconductance test for vacuum tubes. This test measures the ratio of collector-current change to emitter-current change as an **alpha amplification factor.** The ratio of collector-current change to base-current change is a **beta amplification factor.** Both ratios are measured with AC applied to the transistor and are then compared with desired values in a chart.

Q34. What does a leakage test indicate?

Q35. What does a gain test indicate?

Your Answers Should Be:

A34. A leakage test reveals an **excessive flow of current between the elements** in a transistor.

A35. A gain test determines the **ratio of the change** in collector current to a corresponding change in base current.

WHAT YOU HAVE LEARNED ABOUT SEMICONDUCTOR TESTERS

1. Semiconductors, particularly transistors, are reliable and have a long life expectancy.
2. A crystal diode is a semiconductor that allows current to pass more readily in one direction than the other.
3. Transistors are sensitive to excessive heat, voltage, and current.
4. When testing transistor circuits, observe these rules:
   (a) An ohmmeter that applies a voltage in excess of 3 volts should not be used on a transistor.
   (b) Test-probe tips should be insulated to prevent application of undesired voltages to transistors.
   (c) Capacitors in test leads or instruments should not be allowed to discharge through the transistor.
   (d) Make voltage and resistance readings in the circuit to locate any abnormal situation.
   (e) Do not remove or install a transistor when equipment is energized.
   (f) To prevent loading, use a high-impedance voltmeter when taking voltage readings.
5. Bias voltages and collector current can be measured in a transistor while it is still in a circuit. Measurement of reverse and forward resistances between the separate elements will indicate a defective transistor.
6. A diode tester is designed to accurately determine reverse-to-forward resistance ratios.
7. Transistor testers include circuits to measure collector leakage, DC gain, AC gain, and punch-through voltage.

5

Bridge Instruments

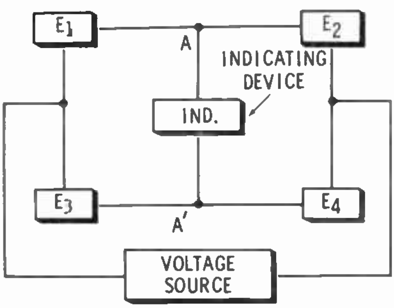
What You Will Learn

When you have completed this chapter, you will be able to explain the fundamental principles on which a bridge circuit is based. You will be able to determine how values of resistance, capacitance, and inductance can be accurately measured by a bridge instrument. On completion of this chapter, you will be able to use a bridge instrument after only a brief period of study of the individual bridge device you intend to use.

WHAT IS A BRIDGE?

A bridge is a simple parallel circuit designed with a means of determining a potential difference between two parallel legs, as shown in the illustration below.

BASIC BRIDGE CIRCUIT



If voltage were applied across the bridge (parallel) circuit, current through the indicating device would be zero only when the voltages appearing at points A and A′ were equal.

Another fundamental principle is that the voltage across a parallel network is the same for either leg. In other words (disregarding voltage dropped in the conductors),

$$E_1 + E_2 = E_3 + E_4 = \text{Source voltage}$$

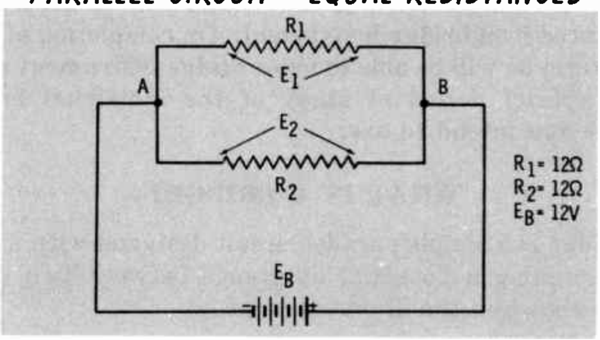
This means that a balance could be achieved between the two legs (no current flowing between A and A′) if the ratio of voltages on either side of A were equal to the ratio of the voltages on the respective sides of A′, or

$$\frac{E_1}{E_2} = \frac{E_3}{E_4}$$

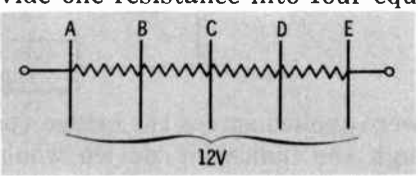
HOW DOES A BRIDGE CIRCUIT WORK?

A brief review of circuit fundamentals may clarify this balance, or equality, between voltage ratios. In the parallel circuit shown below, $R_1 = R_2$.

PARALLEL CIRCUIT—EQUAL RESISTANCES

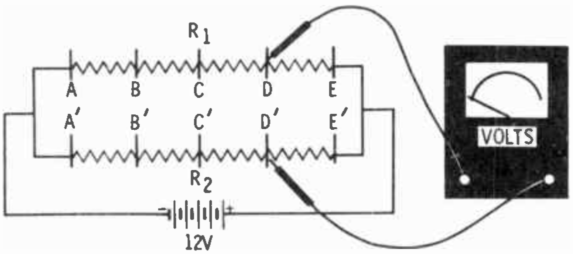


Disregarding the voltage drop in the conductors, the voltage difference between points A and B (above) will be that of the source (12V). The current through R_1 and R_2 will be 1 amp each, or a total circuit current of 2 amps. Since the resistances and currents in both legs are equal, E_1 is equal to E_2. Now divide one resistance into four equal parts.



If the resistance, which shows a voltage difference of 12V from one end to the other, were divided into equal quarters, each quarter would represent 3V. Now divide both resistances of the parallel circuit into equal quarters.

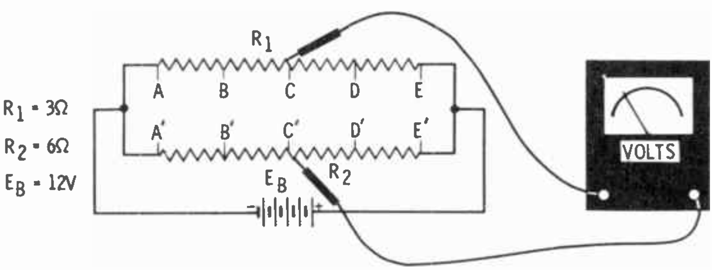
EQUAL VOLTAGE POINTS



How much voltage would you measure between points D and D′? The answer is zero volts. The potential difference between A and D is 9V; this is equal to the difference between A′ and D′. Therefore, no potential difference exists.

To show that the measurement works equally well from either end reference point, start from the other end of the network. The voltage at B with respect to E is —9V; the voltage at D′ with respect to E′ is —3V. Therefore the difference, 6 volts. will be measured from B to D′.

Parallel Circuit—Unequal Resistances



Suppose that a parallel circuit had unequal resistances, as shown above. The voltage across R_1 or R_2 would be identical, that is, 12V. Again assume quarter-section divisions.

Q1. What is the current through R_1? Through R_2?

Q2. What is the value of resistance in each quarter section of R_1? Of R_2?

Q3. What is the voltage difference between A and B (R_1)? Between A′ and B′ (R_2)?

Your Answers Should Be:

A1. The current through R_1 is 4 **amps**; through R_2, **2 amps.**

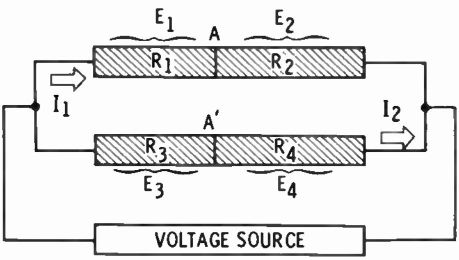
A2. The value of resistance in each quarter section of R_1 is **0.75Ω**; of R_2, **1.5Ω.**

A3. The voltage difference between A and B (R_1) is **3V**; between A′ and B′ (R_2), **3V.**

$$I_1 \times R_1 = 4 \text{ amps} \times 0.75\Omega = \mathbf{3V}$$
$$I_2 \times R_2 = 2 \text{ amps} \times 1.5\Omega = \mathbf{3V}$$

Voltage Relationships in Parallel Circuits

For every point on one parallel resistance leg, there is a point on the other leg that is at the same potential. This is true whether or not the total leg resistances are equal.



The voltage across a parallel network is the same for either leg. You can state that $E_1 = E_3$ and $E_2 = E_4$ in the figure above if A and A′ are at the same potential. These voltage relationships can be stated in terms of equal ratios:

$$\frac{E_1}{E_2} = \frac{E_3}{E_4}$$

Since E is equal to IR, the above ratios can be stated in another manner:

$$E_1 = I_1 \times R_1 \qquad E_3 = I_2 \times R_3$$
$$E_2 = I_1 \times R_2 \qquad E_4 = I_2 \times R_4$$

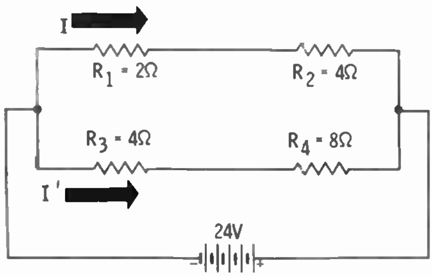
therefore,

$$\frac{I_1R_1}{I_1R_2} = \frac{I_2R_3}{I_2R_4}$$

How could the IR equation be restated in terms of resistance only? I in each ratio is the same, and it can be cancelled. Therefore:

$$\frac{R_1}{R_2} = \frac{R_3}{R_4}$$

Since the voltage drop across each resistor equals the leg current times the resistance, the resistances must have the same ratio as the voltages. The ratio can also be reasoned from the example below:



Both resistance ratios are equal to ½:

$$\frac{2}{4} = \frac{4}{8} = \frac{1}{2}$$

The current in each leg is:

$$I = \frac{24V}{R_1 + R_2} = \frac{24V}{6\Omega} = 4 \text{ amps}$$

$$I' = \frac{24V}{R_3 + R_4} = \frac{24V}{12\Omega} = 2 \text{ amps}$$

Both voltage ratios are ½ also.

$$\frac{IR_1}{IR_2} = \frac{I'R_3}{I'R_4}$$

$$\frac{4 \times 2}{4 \times 4} = \frac{2 \times 4}{2 \times 8} = \frac{1}{2}$$

Q4. Resistances in two parallel legs of a circuit will have a ____ potential difference between two proportional points on either resistance.

Q5. The voltage ratios in each leg of a parallel circuit must be equal to what?

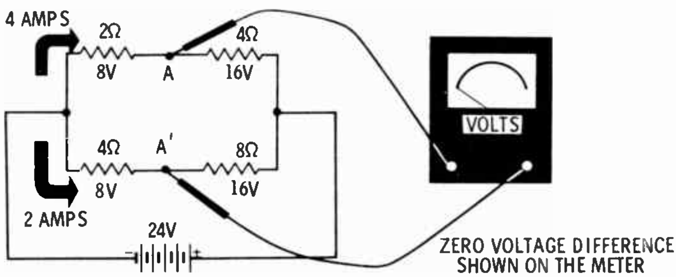
Your Answers Should Be:

A4. Resistances in two parallel legs of a circuit will have a **zero** potential difference between two proportional points on either resistance.

A5. The voltage ratios in each leg of a parallel circuit must be equal to **the resistance ratios of the respective legs.**

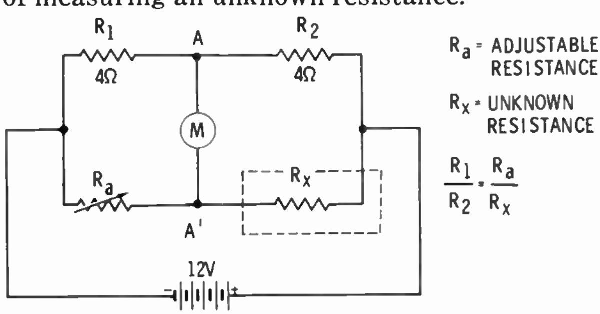
RESISTANCE BRIDGES

If the ratios of two resistors in each leg of a parallel network are the same, the voltages at each of the corresponding junction points between resistance pairs are the same.



Suppose the 8-ohm resistor in the illustration above is changed to 4 ohms. The resistance ratios are no longer equal. The current in the lower leg is now 3 amps, and the voltage at A′ becomes 12V compared to 16V at A. The meter now reads 4V.

If you change this circuit to that shown below, you have a means of measuring an unknown resistance.



When the resistance ratios in the legs are not equal, there will be a voltage difference between A and A′. Current will flow through the meter. When R_a is adjusted to register zero current, $R_1/R_2 = R_a/R_x$. If there were a means provided to show the value of R_a at this setting, how could you determine the value of R_x?

Assume R_a is equal to 13 ohms:

$$(1)\quad \frac{R_1}{R_2} = \frac{R_a}{R_x}$$

$$\frac{4}{4} = \frac{1}{1} = \frac{13}{R_x};\ R_x = 13\Omega$$

If R_1 is 4Ω, R_2 is 3Ω, and R_a is 8Ω, what is the value of R_x?

$$\frac{R_1}{R_2} = \frac{R_a}{R_x}$$

$$\frac{4}{3} = \frac{8}{R_x};\ R_x = 6\Omega$$

Both problems were solved by selecting a value for R_x that would make the right-hand ratio proportional to the left. Since R_a was twice R_1, R_2 was multiplied by 2 to get R_x. solution becomes more difficult.

Multiply both sides of equation (1) by both denominators: When ratios do not result in these convenient multiples, the

$$\frac{R_2}{1} \times \frac{R_x}{1} \times \frac{R_1}{R_2} = \frac{R_a}{R_x} \times \frac{R_2}{1} \times \frac{R_x}{1}$$

Cancel like terms in numerators and denominators on either side of the equality sign. This results in:

$$R_x \times R_1 = R_a \times R_2$$

Divide both sides by R_1 to obtain

$$(2)\quad R_x = \frac{R_a \times R_2}{R_1}$$

Find R_x when:

Q6. **R_1 is 200, R_2 is 400, R_a is 80.**

Q7. **R_1 is 80. R_2 is 20, R_a is 42.**

Q8. **R_1 is 30. R_2 is 70, R_a is 9.**

Q9. **R_1 is 40, R_2 is 56, R_a is 10.**

Your Answers Should Be:

A6. 160 ohms. $R_x = \frac{80 \times 400}{200}$

A7. 10.5 ohms. $R_x = \frac{42 \times 20}{80}$

A8. 21 ohms. $R_x = \frac{9 \times 70}{30}$

A9. 14 ohms. $R_x = \frac{10 \times 56}{40}$

THE WHEATSTONE BRIDGE

You have, in effect, constructed a bridge for measuring an unknown resistance that is quite similar to an actual bridge. You have performed the mathematics required to find the value of the unknown resistance in the same manner as if you were actually using a bridge.

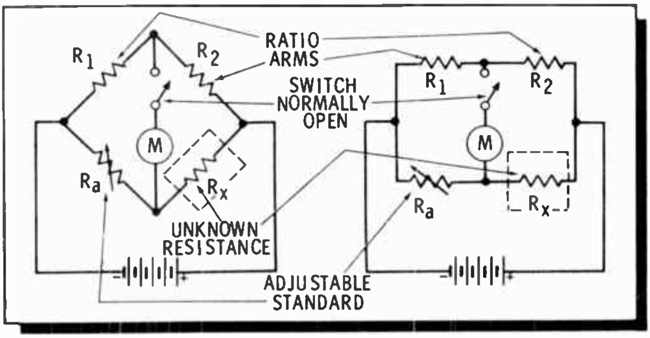
The most common type of bridge used for measurement is the Wheatstone bridge. Commercial models of this type of bridge can measure values of resistance from 1 ohm to 1 megohm with an accuracy of $\pm 1\%$. More expensive models can accurately measure resistances between 0.1 ohm and approximately 12 megohms.

Necessary components include a voltage source (usually a battery for resistance measurements), an indicating device (usually a sensitive galvanometer similar to those used in multimeters), accurate standard resistances that establish the ratio for measuring purposes (R_1 and R_2), a variable resistance for achieving a voltage balance between the two parallel legs (usually an accurate potentiometer with a scale on the front panel), and a means of connecting an unknown resistance into the bridge. All parts are designed for precise values to insure the highest degree of accuracy. The meter is usually shielded to prevent stray fields from adding error or fluctuation to the reading.

Schematic Representation

In nearly all cases, the commercial bridge is shown schematically in diamond shape. Both diamond and rectangular shapes are shown on the opposite page.

WHEATSTONE BRIDGE

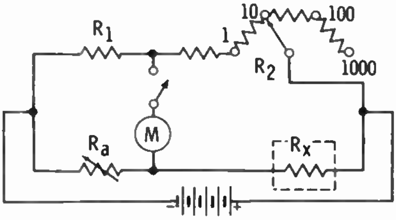


The meter is usually the type that has a center-scale zero. This permits the meter to record current going in either direction between the two parallel legs. A momentary-contact switch in series with the meter is normally open to keep the meter out of the circuit during the setting-up process. The switch is closed momentarily to observe meter deflection. The amount of deflection and its direction provide an estimate of how much R_a should be changed. Adjusting R_a for a zero reading is often called adjusting for a **null**.

Bridge Operation

In the typical circuit below, R_2 can be set at one of four positions to establish the R_1/R_2 ratio. In position 1 the ratio is **1**/**1**; in position 10 it is **1**/10, etc.

RESISTANCE BRIDGE



R_a may be a single wirewound potentiometer with values calibrated on a front-panel scale, or it may be several **decade (10-position) switches** in series. One switch adds resistances in multiples of one, a second in multiples of 10, etc.

Q10. How accurate is a good Wheatstone bridge?

Q11. What is a decade switch?

Your Answers Should Be:

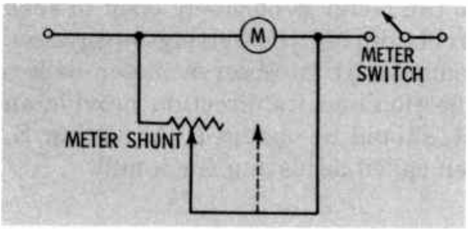
A10. A good Wheatstone bridge has an accuracy of **about 1%.**

A11. A decade switch has **ten calibrated contact positions.**

Operating the Wheatstone Bridge

In some bridges the power supplies are variable types to provide low current for low resistances and high current for high resistances. In many models the desired current is obtained by means of a current-limiting resistance.

Since the meter could be damaged if there were a large potential difference between the two legs, the shunt resistance connected to the meter is often made variable.

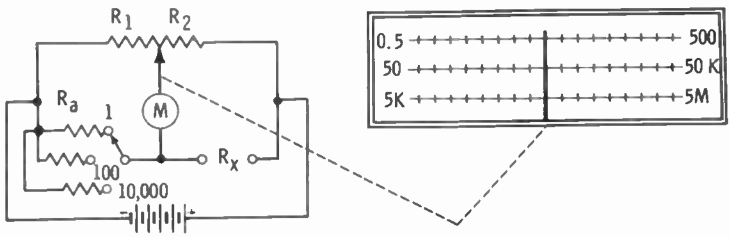


METER PROTECTION

It is not often possible to make a reasonable guess as to the value of the unknown resistance. In such a case, the bridge ratio and R_a cannot be set at values that are close to the unknown, thereby keeping the potential difference across the meter to a minimum. When securing R_x to the measuring posts, the meter shunt should be moved to its lowest resistance. The meter switch is depressed, and meter deflection is noted. As R_a and the bridge ratio are adjusted closer to the value of R_x (less difference of potential), the meter shunt is increased in resistance to permit greater sensitivity of measurement. During the final adjustment for a meter null (zero), the shunt arm is no longer contacting resistance, and all available current is flowing through the meter.

Another Resistance Bridge

There are variations of the basic Wheatstone bridge, such as the one shown at the top of the next page.



In this bridge the R_1/R_2 ratio is established by a potentiometer. The movable contact of the potentiometer is connected to a pointer on a direct-reading scale. The potentiometer is adjusted for a null reading on the meter, and the value of R_x is read directly from the scale in the range that depends on the setting of R_a. The three resistances of R_a increase in multiples to make it possible for a single pointer to serve all three scales. If R_a were 15 ohms in position 1 and 1,500 ohms in position 2, it would be 150,000 ohms in position 3. Other multiples could be used, as well as a different number of resistances. The sample shows a bridge capacity from 0.5 ohm to 5 megohms in three ranges.

Q12. Why is the power supply of a resistance bridge made variable?

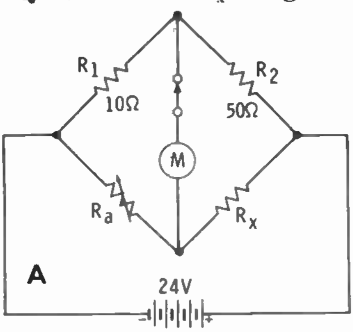
Q13. How is this done?

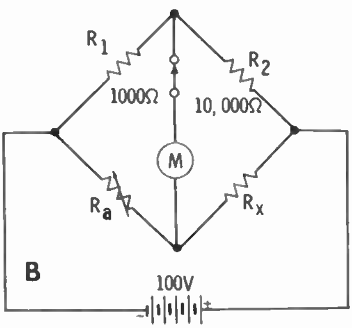
Q14. What is meant by a meter null?

Q15. What method is normally employed to protect the meter from large voltages?

Q16. What is the value of R_x in figure A below when R_a is set at 5 ohms?

Q17. What is R_x in figure B when R_a is 500 ohms?





Your Answers Should Be:

A12. The power supply is made variable **to provide the correct amount of current** for the various values of resistances.

A13. This is done by means of a **current-limiting resistance.**

A14. A meter null is that reading when the **pointer indicates zero.**

A15. The **shunt resistance** connected to the meter is varied with respect to the amount of voltage applied.

A16. R_x equals **25 ohms.**

$$R_x = \frac{R_2 \times R_a}{R_1}$$

$$R_x = \frac{50 \times 5}{10}$$

$$R_x = 25 \text{ ohms}$$

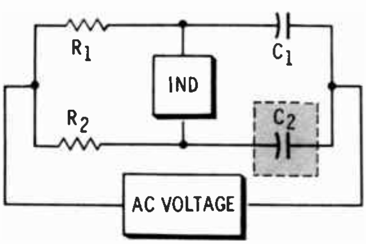
A17. R_x equals **5,000 ohms.**

$$R_x = \frac{10{,}000 \times 500}{1{,}000}$$

$$R_x = 5{,}000 \text{ ohms}$$

MEASURING CAPACITANCE WITH A BRIDGE

Using the same ratio principles, a bridge can also be made to measure the value of an unknown capacitance. The basic circuit is shown below.



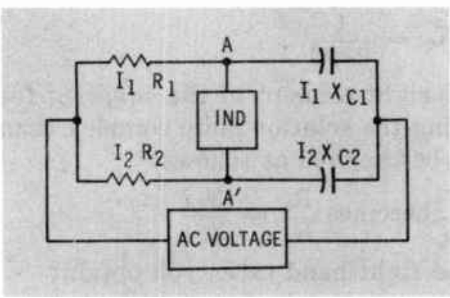
CAPACITANCE BRIDGE

A DC voltage source cannot be used because of the capacitors. As shown, the source must be AC. Most commercial models employ a frequency of either 60 or 1,000 cps. If the instrument is designed for a 60-cycle source, voltage may be taken directly from the power line. For 1,000 cycles, some models may have an oscillator built into the bridge, and others may have provisions for connection to an external oscillator.

The indicator may be a built-in AC meter that allows current to pass through it in one direction only. Some units have jacks into which earphones can be plugged to listen for the null. Greater accuracy can be achieved by using a VTVM. This is because the VTVM can give a relatively large meter deflection even though the voltage difference between the legs of the bridge is small.

The principle of voltage ratios that you learned about a resistance bridge applies to the capacitance bridge as well. To obtain a null reading on the indicator, the voltage ratios in each leg of the parallel network must be proportional.

BRIDGE RATIOS



FOR NULL INDICATION, VOLTAGES AT A AND A′ MUST BE EQUAL. THEREFORE:

$$\frac{I_1 R_1}{I_1 X_{C1}} = \frac{I_2 R_2}{I_2 X_{C2}}$$

Q18. What type of voltage source must be used in the capacitance-bridge circuit?

Q19. What type of indicator offers the greatest accuracy in a capacitance bridge?

Q20. To obtain a null reading on the indicator, the voltage ratios in each leg of the bridge must be ____________ to each other.

Q21. If the voltage drop across one of the resistors is expressed as IR, how would you indicate the voltage across one of the capacitors?

Your Answers Should Be:

A18. An **AC voltage source** must be used in a capacitance bridge.

A19. A **VTVM** is the most accurate indicator for a capacitance bridge.

A20. To obtain a null reading on the indicator, the voltage ratios in each leg of the bridge must be **proportional** to each other.

A21. **IX_C.** As you recall, voltage across a capacitor depends on its reactance, X_C.

Determining Capacitance-Bridge Ratios

As before, the current symbols cancel out, leaving ratios expressed in terms of resistance and reactance. If you wish to use the bridge for its intended purpose, reactance must be converted into capacitance. Capacitive reactance is:

$$X_C = \frac{1}{2\pi fC}$$

Before substituting the right element of the equation for X_C in the ratios and making the solution more complex than necessary, the ratios can be changed as follows:

$$\frac{R_1}{X_{C1}} = \frac{R_2}{X_{C2}} \text{ becomes } \frac{R_1}{R_2} = \frac{X_{C1}}{X_{C2}}$$

Substituting for X_C in the right-hand ratio, you obtain:

$$\frac{1}{2\pi fC_1} \div \frac{1}{2\pi fC_2}$$

Inverting and multiplying:

$$\frac{1}{2\pi fC_1} \times \frac{2\pi fC_2}{1} = \frac{C_2}{C_1}$$

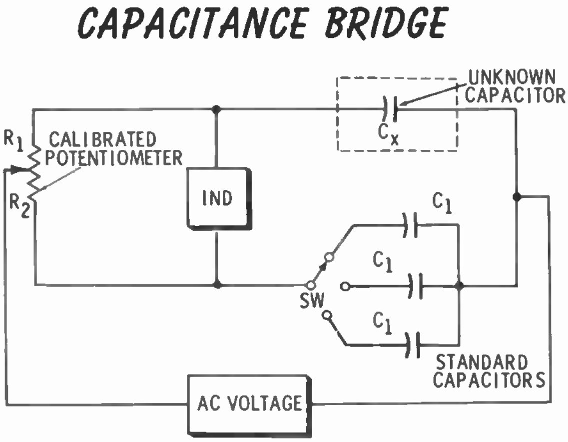
The $2\pi f$'s cancel out. The expression in terms of C is now:

$$\frac{R_1}{R_2} = \frac{C_2}{C_1}$$

The values of C are inversely proportional to the values of R in their legs of the circuit. This makes sense because a large capacitance has a small reactance.

Practical Capacitance Bridge

The schematic for a typical capacitance bridge is shown below. A close study of this illustration will reveal that it is essentially the same type of parallel circuit as those on the preceding pages.



By manipulating a switch, one of several capacitors can be selected as a standard, depending on the size of unknown C_x. A calibrated potentiometer adjusts the bridge ratio (R_1/R_2) for a null reading on the indicator. With this arrangement the arm of the potentiometer can be connected to a pointer that moves on a scale calibrated in capacitance values. This will be true only if all of the standard capacitors increase in value by the same multiple.

The above bridge is suitable for measuring capacitors with little or no series resistance and no leakage between the plates. Significant values of either series or parallel resistance (leakage) will prevent balancing the bridge. This bridge can check most paper, ceramic, and mica capacitors.

Q22. What must the relationship of the standard capacitors be to permit adjustment of the potentiometer to proportional bridge ratios?

Q23. If R_1/R_2 is 1/10 and C_1 is 1,200 $\mu\mu$f, what is the value of C_2? (Refer to the circuit on page 174.)

Q24. If R_1/R_2 is 1/100 and C_2 is 12 μf, what is the value of C_1?

Your Answers Should Be:

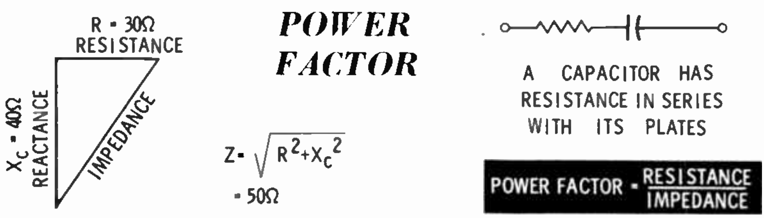
A22. The capacitors must increase in value **by the same multiple.**

A23. $C_2 = 120\ \mu\mu f.\ \frac{R_1}{R_2} = \frac{C_2}{C_1}$

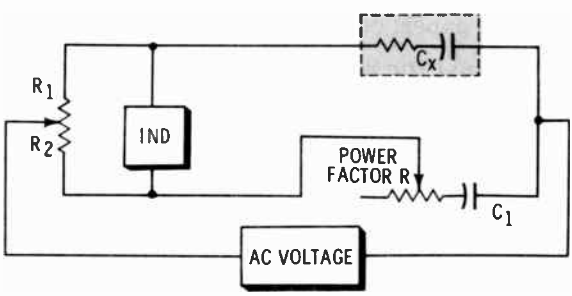
A24. $C_1 = 1{,}200\ \mu f$

Measuring Power Factor

Large capacitors have an internal resistance. This resistance must not only be compensated for in the bridge to obtain a null reading, but it also must be measured to determine the power factor of the capacitor.



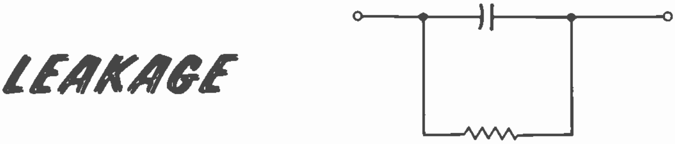
As shown above, the power factor of a capacitor varies in accordance with the size of its internal resistance. The diagram on the left shows the relationship between the resistance and impedance elements of a capacitor; it also shows how impedance can be determined for the power-factor formula. If the internal resistance is zero, the power factor is zero. If the power factor is large (stated in percentage), it may seriously affect the operation of the circuit or device. Many bridges contain provisions for measuring power factor. One method is shown below.



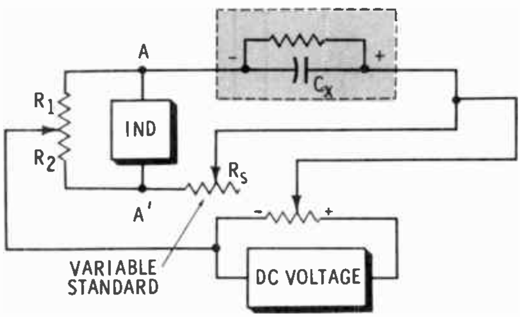
The R_1/R_2 potentiometer is adjusted for a null indication as was done before, or as close as the resistance of C_x will permit. The variable resistance in series with C_1 is then adjusted for the final null reading. A front-panel extension of the variable resistance, probably labeled **POWER FACTOR,** will give the precentage of power factor.

Measuring for Capacitor Leakage

A leaky capacitor is one in which the dielectric, having lost some of its insulating quality, permits electrons to travel



from one plate to the other. Leakage is considered to be a resistance in parallel with the capacitor.



Essentially this is the same basic circuit as before. A switch on the front panel connects a variable resistance in place of C_1 and changes the voltage source to a variable DC. Voltage is set at the rated working voltage of the capacitor. An electrolytic capacitor will be damaged if polarities are not observed when connecting it to the measuring posts. R_s is adjusted to balance the bridge and obtain a null reading. If the measured resistance is low, leakage is high.

Q25. In the illustration above, the voltage at A should be (greater than, the same as, less than) the voltage at A′ to get a null reading on the indicator.

Q26. Why is a DC voltage used to measure capacitor leakage in the above circuit?

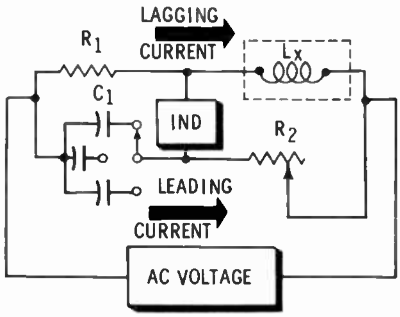
Your Answers Should Be:

A25. The voltage at A should be **the same** as the voltage at A′.

A26. If AC were used, reactance would be added to the upper leg of the circuit. The **bridge could not be balanced using R_s.**

MEASURING INDUCTANCE WITH A BRIDGE

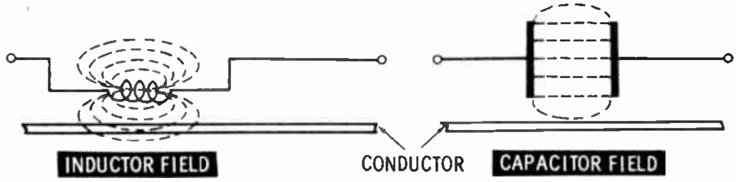
Inductance can be measured with the bridge shown here. In previous bridges, a resistor was used for balancing a resistor, and a capacitor was used for balancing a capacitor.



INDUCTANCE BRIDGE

In this circuit, however, a capacitor is used to balance the inductance of a coil. A standard inductance could be used in place of the capacitance, but this would result in a few undesirable conditions.

The illustration below shows how the electromagnetic field around a coil can cut through a conductor and induce error-producing currents. The capacitor electrostatic field,



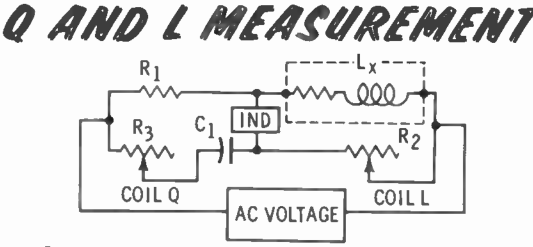
however, is mostly contained within the capacitor. An additional advantage of the capacitor is that it does not pick up stray fields as a coil does.

If inductors were used to balance the bridge, they would be larger and more expensive than equivalent capacitors. Size and cost of the instrument would be greater. Finally, the same capacitors can be used for measuring both inductance and capacitance in the same bridge.

Using a capacitor opposite an inductor in a bridge, however, has one disadvantage. The current through the coil branch lags the current through the capacitor branch. The phase difference makes it impossible to balance the bridge. This condition can be compensated for by placing the unknown coil and the standard capacitor in opposite legs of the bridge across the indicator, as shown in the illustration on the opposite page.

Typical Inductance Bridge

In the inductance bridge below and the one just discussed, a null condition is established by the values of C_1 and R_2. With a proper value of C_1, R_2 (a variable resistance) is adjusted for a zero reading. The position on a front-panel scale of a pointer linked to R_2 indicates the value of L_x.



Measuring the Q of an Inductor

An inductor has a Q level, or figure of merit, that is its reactance-to-resistance ratio ($2\pi fL/R$). Resistance is that of the wire used in the coil and is considered to be in series with its reactance. Heavy wire and a small number of turns produce a high Q; a smaller wire and more turns produce a lower Q. Since Q, a measure of quality, is a factor used to determine the sharpness of resonance of a circuit employing both L and C, it is desirable that the Q of the coil be measured. R_3 in the circuit above is used for this purpose. Its scale can be calibrated in Q.

Q27. What is used to balance the coil inductance in an inductance bridge?

Your Answer Should Be:

A27. A **capacitor** is used to balance the inductance of the coil in an inductance bridge.

WHAT YOU HAVE LEARNED

1. A bridge is a test instrument capable of accurately measuring resistance, capacitance, inductance, and reactance. Although a bridge may not have a scale calibrated in reactance, you can determine reactance if you know C or L and the frequency.
2. The Wheatstone bridge utilizes the basic principle on which all bridge circuits are built. The arrangement of the bridge elements is such that the voltage ratios between the elements in the parallel legs can be adjusted to achieve a null (zero current) in an indicator placed between the parallel legs.
3. Each bridge requires a source of voltage, a parallel network containing sufficient variable elements to balance the bridge, an indicator to determine when the bridge is balanced (null indication), a scale to determine the ratio of the elements involved or a direct readout of the unknown value, and operating controls and jacks.
4. A resistance bridge contains a DC voltage source, a sensitive DC meter, and a parallel network of resistances. When a condition of balance exists, the unknown resistance can be determined by a direct reading from a calibrated scale or by calculation.
5. A capacitance bridge contains an AC voltage source, a sensitive AC meter (or headphones), and a parallel network of resistance and capacitance.
6. With appropriate modifications, a capacitance bridge can measure the power factor and leakage of a capacitor.
7. An inductance bridge contains the same voltage source and indicating devices as the capacitance bridge, but its parallel network is normally made up of resistance, capacitance, and the unknown inductance.

6

The Signal Generator

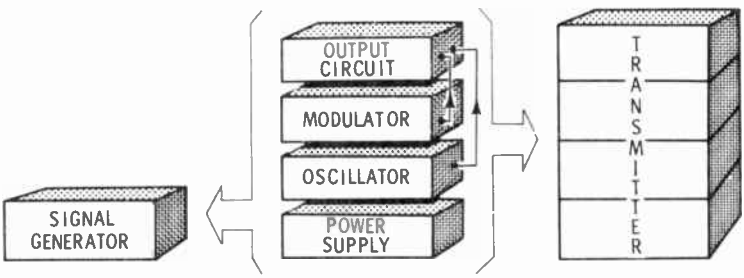
What You Will Learn

There are occasions when a technician finds it necessary to apply a standard signal to an electronic circuit or device for testing or troubleshooting purposes. A signal generator is an instrument that serves as a source for such a signal. Within its designed range, it provides a signal having controllable frequency, amplitude, and modulation characteristics for testing or troubleshooting.

On completion of this chapter you will be able to apply an understanding of basic electronic principles to the operation of a signal generator. You will learn how to effectively operate a signal generator after a brief study of its operating manual. You will also be able to use a signal generator in making troubleshooting checks.

WHAT IS A SIGNAL GENERATOR?

A signal generator is basically a transmitter. Although a



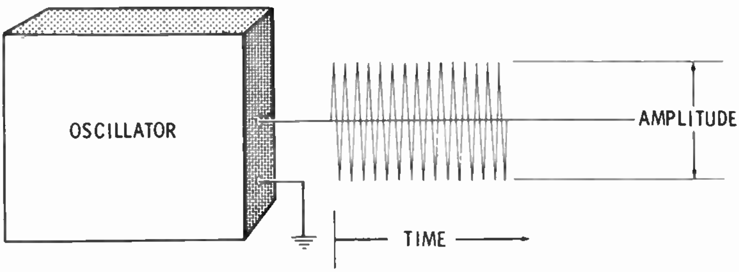
transmitter may emit signals at a higher power and include more circuitry than a signal generator, the basic functions of the two are identical. As shown, the basic functions include a power supply, an oscillator, a modulator, and an output circuit. Each function may require a group of many circuits in a transmitter; in a signal generator, however, each can be accomplished by only one or two circuits.

FUNCTIONAL UNITS IN A SIGNAL GENERATOR

Since the power supply of a signal generator is fairly standard, it will not be described. However, an understanding of how the other circuits work will be very helpful when using a signal generator.

Generator Oscillator

An oscillator is a circuit capable of generating a series of identical waveforms at some desired frequency (number of oscillations per second).



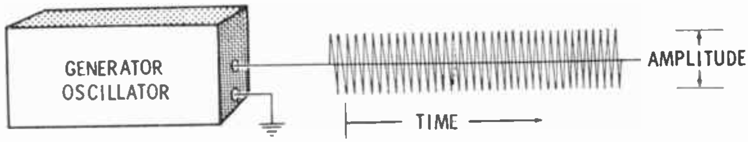
Signal generators are classified in accordance with the frequency range of their oscillators. Audio-frequency (AF) generators usually cover a range from about 20 to 20,000 cps. Radio frequency (RF) generators begin at 20,000 cps and end at several thousand megacycles.

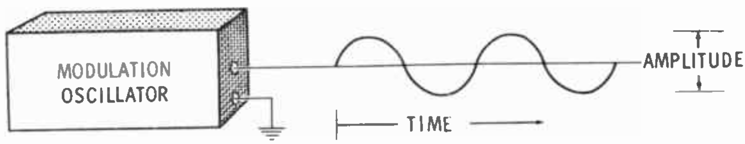
Modulation Oscillator

In a transmitter, the frequency generated by the oscillator is called a **carrier frequency.** Waves produced by a current of this frequency are capable of traveling many miles. The carrier wave has a constant frequency and amplitude; its purpose is to carry information, or intelligence, from a transmitter to a receiver. The carrier is altered by having another frequency, representing the intelligence, superimposed on it.

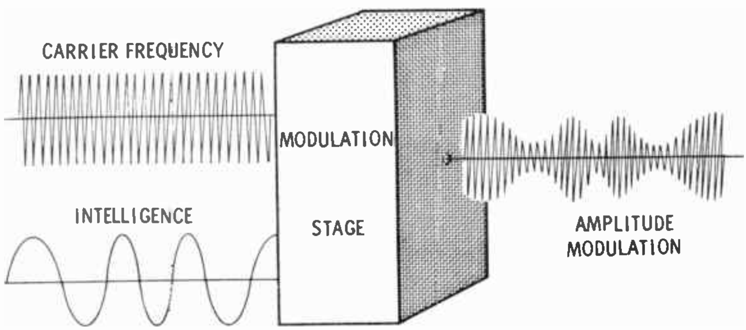
For example, the standard broadcast band has carrier frequencies between 535 and 1,605 kilocycles. Intelligence, in the form of sound (voice, music, etc.), is superimposed on the carrier and later taken from it in the receiving set.

The process of superimposing intelligence frequencies on a carrier frequency is called **modulation.** To be useful, an RF signal generator must be capable of modulating its carrier. It does so with an audio-frequency signal developed by a **modulation oscillator.**





Amplitude Modulation—There are several types of modulation. **Amplitude modulation** is the form used in standard broadcast transmissions (535 to 1,605 kc) and is defined as the process by which the carrier is varied in amplitude to resemble the amplitude and frequency of the intelligence.



Q1. What is the name given to the transmitted frequency that the generator oscillator duplicates?

Q2. Why is amplitude modulation the name given to the type of waveform shown in the above illustration?

Your Answers Should Be:

A1. Carrier frequency. It carries the frequency of the intelligence superimposed on it.

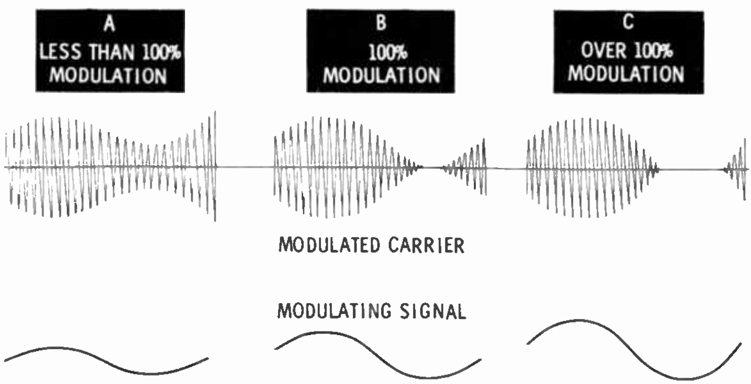
A2. The **amplitude** of the constant carrier frequency is **modulated** (varied) to conform with the frequency and amplitude of the intelligence signal.

Modulation Requirements

Although the generator oscillator must be capable of reproducing the frequency of the carrier, the modulation oscillator need not cover the entire audio range. In some signal generators, only a single modulation frequency is developed. Other signal generators may have two or three modulation frequencies or a variable modulation frequency.

Per Cent of Modulation—The amount that the carrier amplitude is varied is called **per cent of modulation.** It is controlled by the amplitude of the modulating signal.

MODULATION PERCENTAGE

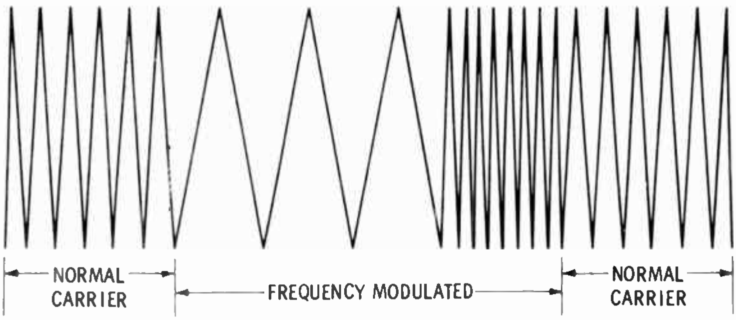


The amplitude of the modulating signal in part B above is such that the **envelope** (outline of modulation on the carrier) is caused to become zero for an instant before rising again. This is 100% modulation. Modulation is less than 100% in part A. The exact percentage is determined by the relationship between the amplitudes of the carrier and modulating waves. Part C shows modulation greater than 100%. This causes distortion in reception.

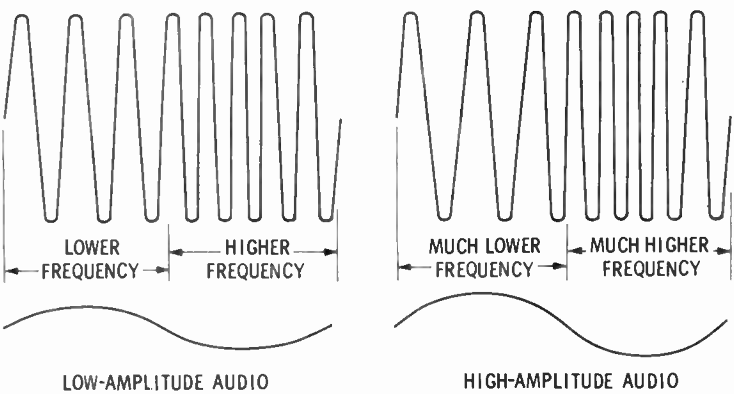
Since there is little need for modulating an audio frequency, this feature is seldom found in AF signal generators. Better models of RF generators always incorporate some form of modulating capability. In some RF generators the amplitude of the modulation-oscillator signal can be varied; in others it cannot. Some models permit an external audio oscillator to be used for modulation.

Frequency Modulation—Another method of superimposing an intelligence signal on the carrier is called **frequency modulation (FM).** In frequency modulation, the **frequency of the carrier is varied in accordance with the frequency and amplitude of the modulating signal.**

FREQUENCY MODULATION



Notice in the diagram above that the frequency of the FM carrier varies, but its amplitude remains the same. Study the following diagrams.



Q3. What is the difference between AM and FM?

Your Answer Should Be:

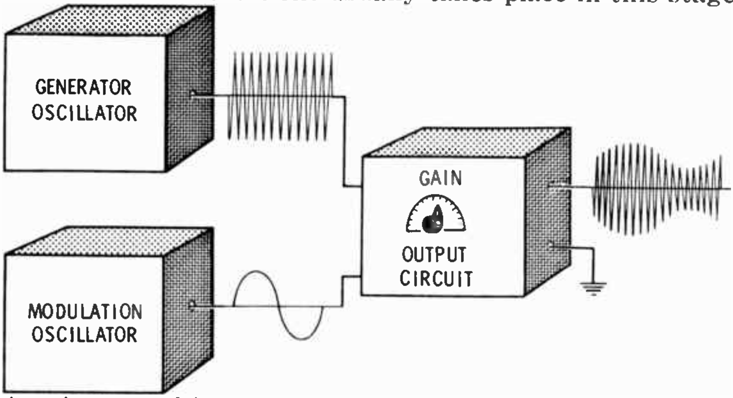
A3. In AM (amplitude modulation) the **amplitude** of the carrier is varied in accordance with the amplitude of the modulating signal. In FM (frequency modulation) the **frequency** of the carrier is varied in accordance with the frequency and amplitude of the modulating signal.

In the examples illustrated by the two diagrams at the bottom of the preceding page, the frequency of the carrier is decreased by the positive portion of the audio signal and increased by the negative portion. The higher the amplitude of the modulating signal, the greater the shift in carrier frequency will be. However, the **average** carrier frequency during a complete cycle of modulation is equal to the normal frequency of the carrier because the shifts of carrier frequency balance each other.

Some RF signal generators generate a frequency-modulated signal. Other generators are designed with provisions for both amplitude and frequency modulation.

Output Circuit

Since the amplitude of the signal developed by most oscillators is relatively low, many signal generators include at least one stage of amplification. The mixing of generator and modulation oscillations usually takes place in this stage.



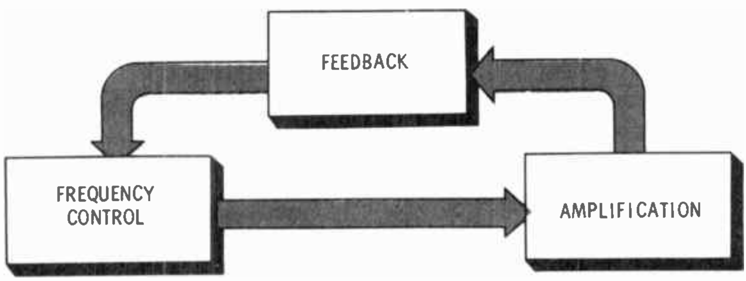
A gain control is normally provided to vary the amplitude of the output signal. To permit impedance matching of the signal generator with the circuit to which the test signal is fed, a cathode follower or similar impedance-matching stage is often employed. An attenuating network may be included to provide signals at a precise level of amplitude.

AUDIO-FREQUENCY SIGNAL GENERATOR

As previously indicated, an AF signal generator covers the audible frequency range. Most AF generators include a generator oscillator and an amplifier stage.

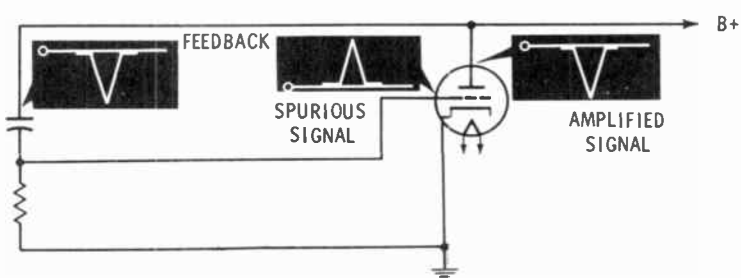
Requirements for Oscillation

A circuit must fulfill three requirements before it will oscillate. It must have a means of **amplification**, a method of **feedback**, and some manner of **frequency control.**



Amplification—An amplifier with plate current flowing will normally amplify any spurious signals appearing at the grid. A spurious signal is any unwanted signal generated either in the equipment itself or externally.

AMPLIFICATION AND NEGATIVE FEEDBACK



Q4. What is the purpose of a gain control?

Q5. What are the circuit requirements for oscillation?

Your Answers Should Be:

A4. The gain control varies **the amplitude of the output signal.**

A5. An oscillating circuit must possess means of **amplification, feedback,** and **frequency control.**

The signal appearing at the plate will be of the same shape as the grid signal, but it will be larger in amplitude and reversed in phase by 180°. If a negative-going signal from the plate were fed back to the grid in addition to a positive-going input signal, the two signals would cancel. This process is called **negative feedback.** The signal returned from the

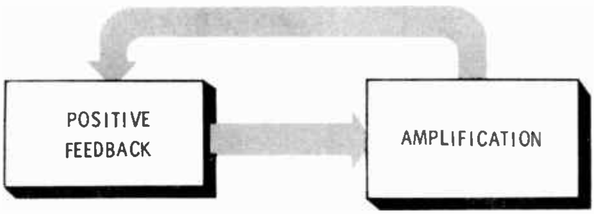
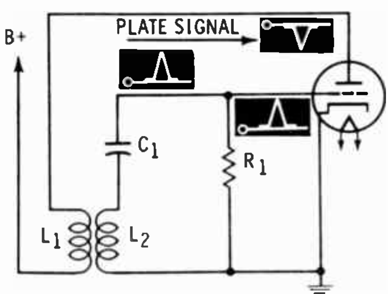


plate must go through another 180° of phase reversal before it will be in phase with the grid signal and in a position to aid amplification. This aiding feedback is called **positive feedback.**

Positive Feedback—Although there are several ways of accomplishing a second phase reversal of 180°, the basic principle is shown below.



AMPLIFICATION AND POSITIVE FEEDBACK

If the coils of the transformer between the plate and the grid are wound so that they cause a 180° phase inversion between primary and secondary, the resultant signal will be in phase with the signal on the grid. The amplitude of the signal will depend on the amount of voltage across L_1 and the resistive losses in the circuit. R_1 and C_1 produce the grid-leak bias for the tube.

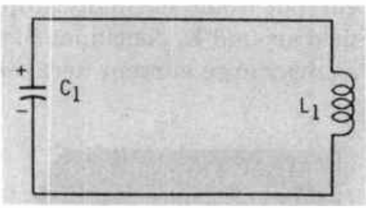
The remaining voltage is added to the grid-to-cathode positive potential, causing an increase in plate current. The signal returning to the grid on the next cycle will be increased proportionately. Waveforms in each succeeding cycle will be increased in amplitude in a similar manner. The signal amplitude will increase to a level established by the saturation point of the tube.

You have seen how positive feedback aids in the build-up of a signal. However, something more must be added to the circuit before it will generate a steady signal of known frequency.

Frequency Control—Positive feedback will provide for a steady state of amplification and produce a constant-amplitude signal at the plate, but it cannot achieve a constant frequency. The circuit shown on the opposite page will amplify any spurious signal that appears at the grid. The frequency of oscillation will be random. The third requirement of an oscillator, frequency control, now becomes apparent.

First, how can frequency be regulated? How can one frequency of a group be selected for amplification in preference to the rest? The answer is the resonant circuit.

RESONANT CIRCUIT



Q6. If a charge were placed on C_1 (shown in the above figure), in which direction would the capacitor discharge through the circuit, clockwise or counterclockwise?

Q7. Would current flow be maximum or minimum at the instant discharge begins?

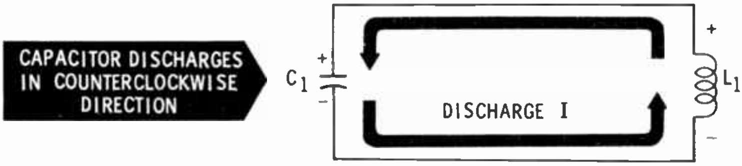
Q8. What effect would L_1 have on the discharge current?

Your Answers Should Be:

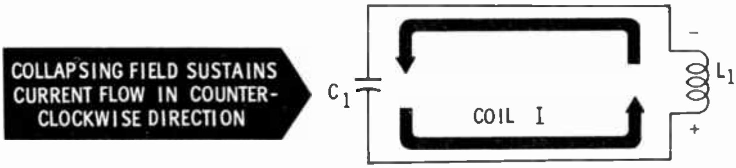
A6. Discharge current would flow **counterclockwise** through the circuit, from the negative plate, through the coil, and back to the positive plate.

A7. At the instant discharge begins, current flow would be **maximum.**

A8. As the initial current surge flowed through L_1, it would produce an expanding magnetic field that would cause current in opposition to the surge. As the discharge current decayed, the field would collapse and cause a current in opposition to the decay of current. In effect, L_1 becomes a current generator to the degree that it **sustains the flow of current in one direction.**

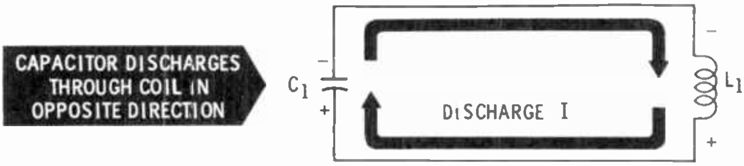


When the source is removed from C_1, the capacitor will begin to discharge. Current will flow through L_1 in the direction indicated and develop a magnetic field around the turns of L_1. When the charges on the plates of C_1 have equalized, current would normally stop flowing. However, the magnetic field around L_1 continues to collapse (initial collapse occurred as discharge current decayed), sustaining the current flow.



L_1 now becomes a voltage source, taking on the polarity shown in the figure above. Collapsing magnetic lines cut the coil turns, producing a current that builds an excess of electrons on the upper plate of C_1. C_1 is now charged in the opposite direction.

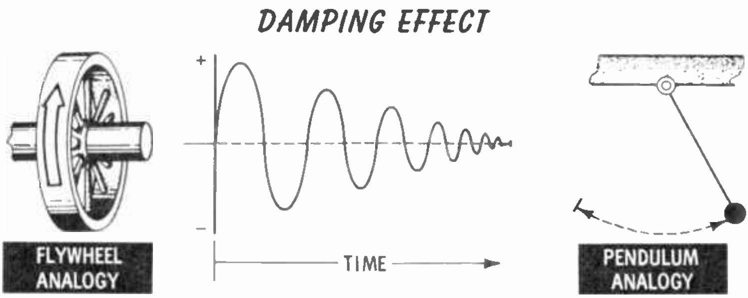
After the initial surge of current as C_1 discharges in the opposite direction, a magnetic field is developed to its maxi-



mum level across L_1. As discharge current begins to decrease, the field starts to collapse, developing a coil current in the same direction as the capacitor current.

When the capacitor has discharged, continuing collapse of the magnetic field will maintain current flow and charge the opposite plate of the capacitor. Charge and discharge of C_1 will continue for several cycles.

The decreasing amplitude of current is often compared to two mechanical analogies. If you plotted the voltage across the capacitor in the previous example, you would obtain a graph resembling the one below.



The LC circuit, the flywheel, and the pendulum have one quality in common—**damping effect.** Damping is the reduction of energy in a mechanical or electrical system as a result, in these cases, of absorption. The flywheel and the pendulum lose energy through absorption which is caused by the friction of the bearings and the surrounding air. The LC circuit (containing an unseen R) gives up part of its energy in the form of heat as the current passes through the resistive parts of the circuit.

Q9. What characteristic of the circuit prevents the cycling of current from continuing forever?

Your Answer Should Be:

A9. The **resistance** of the coil wire and circuit conductors dissipates some of the energy in the form of heat each time current cycles through the circuit. Because of these losses, current flow will eventually decrease to zero. If there were no resistance in the circuit, the cycling would continue forever.

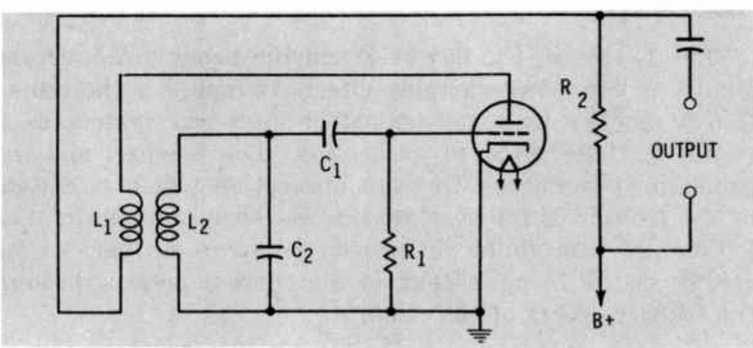
There is another analogy that explains the cycling action of the LC circuit. The momentum of the flywheel causes it to coast through several cycles of revolution. The momentum or potential energy built up by the pendulum as it completes each alternation of swing enables it to return through the next alternation to the other end of its swing. The corresponding effect in the LC circuit, of course, is the potential energy of the magnetic field developed by capacitor discharge current in passing through the coil. The collapsing field causes current flow to build up a charge on the capacitor in the opposite direction.

Self-Excited Oscillator

If an LC circuit were added as a frequency-control device to the other requirements of oscillation (feedback and amplification), the circuit should oscillate.

By adding a capacitor (C_2) across L_2, an oscillating circuit is developed that will be resonant at some specific frequency.

SELF-EXCITED OSCILLATOR



L_2 and C_2 form the resonant circuit. A signal in the plate circuit will be induced by L_1, called a **tickler coil,** into L_2. The voltage across L_2 will be in phase with the signal already on the grid. The grid voltage will be increased when it coincides with the instant of maximum voltage, plus-to-minus, top-to-bottom, across the resonant circuit. This will occur at a regular frequency determined by the values of L_2 and C_2; their size determines the charge and discharge time of the capacitor. As you recall, the resonant frequency of an LC circuit can be computed by:

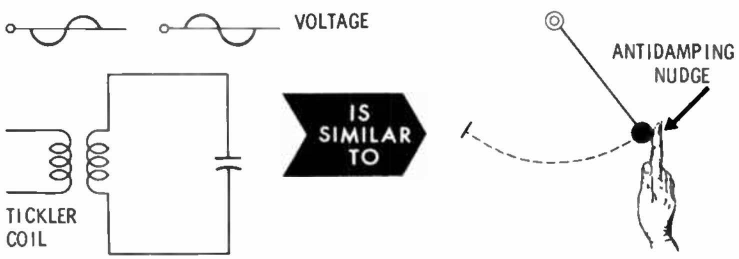
$$\text{resonant frequency} = \frac{1}{2\pi\sqrt{LC}}$$

If L_2 were 1 mh and C_1 were 10 microfarads (both fairly large components), the resonant frequency of LC would be 1,592 cycles per second.

An LC circuit is often referred to as a **tank circuit.** The complete circuit, because of its tickler-coil feature, is called a **self-excited oscillator.**

The damping effect of the tank circuit is overcome by the induced voltage applied by the tickler coil in phase with the signal on the grid. The principle is much the same as applying a nudge to a pendulum sufficient to cause it to swing through the same distance of arc in each oscillation.

PREVENTION OF SIGNAL DAMPING



Q10. If either L and C, or both, are increased in value, what happens to the resonant frequency?

Q11. What is the resonant frequency of a tank circuit that has a capacitance of 25 micromicrofarads and an inductance of 9 mh?

Your Answers Should Be:

A10. If L or C or both are increased in value, the resonant frequency of the oscillator will be **decreased.**

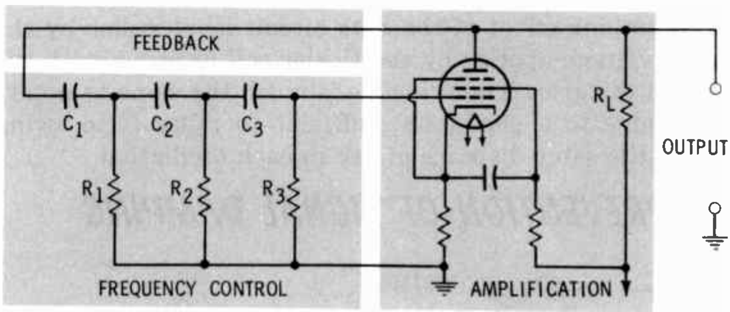
A11. The resonant frequency is **335 kc.**

A constant frequency of tank-circuit oscillation is practical for only a few purposes. It can be used, for example, as a code practice oscillator for learning International Morse code or for testing circuits where a single frequency is adequate. To make the self-excited oscillator more versatile, either L or C must be capable of being changed. In most applications, C is a variable capacitor.

Phase-Shift Oscillator

Another circuit that is often used as an oscillating stage in an AF signal generator is a **phase-shift oscillator.**

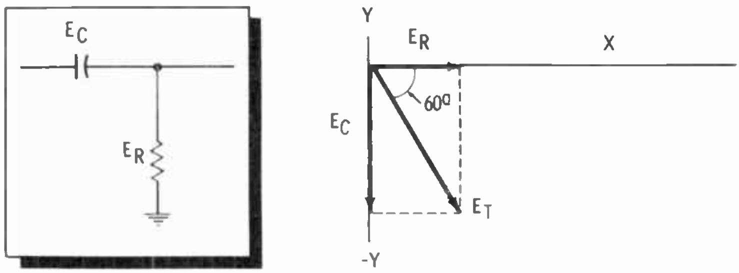
PHASE-SHIFT OSCILLATOR



Notice that the frequency-control portion of the circuit does not contain a tank circuit. Instead, the frequency control uses three capacitors and three resistors. The RC combinations will not oscillate. They will, however, shift the phase of the feed-back signal an amount dependent on the ratio of R to C. If the values of each RC combination are selected to shift the signal 60°, the total shift of the returned signal at the grid will be 180°. This meets the basic requirement of frequency control, returning the signal in phase with the grid signal. The signal on the plate has already been shifted 180°.

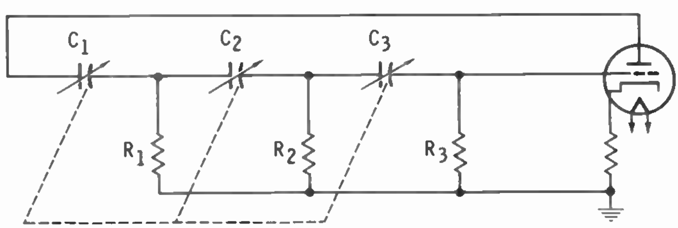
Current through a capacitor will lead an AC voltage applied across the capacitor. If it is a pure capacitance with no resistance involved, the angle of lead will be 90°. Obviously, two capacitors (with no resistance) in series with the grid circuit behave as one capacitor and will not achieve the required 180° phase shift. Resistance is required to develop the desired voltage between the grid and cathode.

Although any number of RC combinations can be selected to accomplish the desired phase shift, a set of three is the best compromise. A 60° phase shift in one set can be explained by the following diagram.



The values of C and R are selected so that the current in the circuit leads the applied voltage (E_T) by an angle of 60°. The voltage (E_R) across the resistor also leads the applied voltage by 60°; E_R is the output voltage of the RC combination. Three RC combinations produce a phase shift of 180°.

For a given value of C, there is only one frequency at which the phase shift of the RC combination is exactly 60°. The three capacitors in a typical phase-shift oscillator, as shown below, can be simultaneously varied to achieve a wide range of audio frequencies.



Q12. What characteristics of R and C, as shown in the above schematic, establish the value of frequency?

Your Answer Should Be:

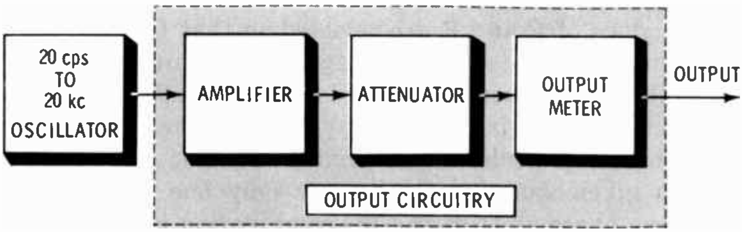
A12. The **size of R or C** determines the frequency as well as the amount of time required for the capacitor to charge or discharge through the resistance. The longer the charge time, the lower the frequency will be.

Other Types of Oscillators

There are other types of oscillators used in an AF frequency generator. Another popular type, operating on principles similar to the RC applications in the phase-shift oscillator, is the **Wien-bridge oscillator.** A few signal generators, requiring only a single frequency output, use the accurate oscillating frequency of a **tuning fork.**

Typical AF Signal Generator

The block diagram below represents a typical AF signal generator. There are many other variations.

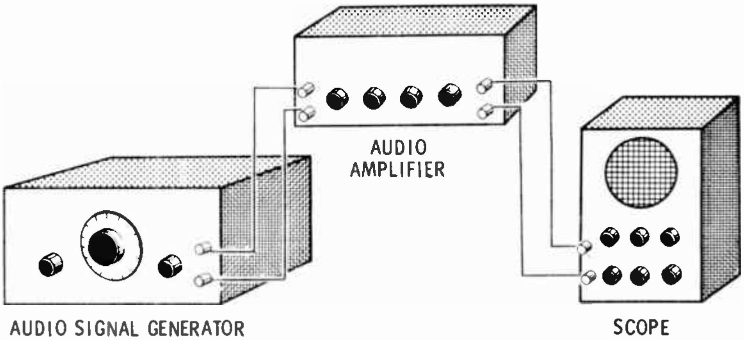


Usually the output circuitry contains an amplifier with a network or attachment that permits matching the impedance of the external circuit to that of the generator. If the impedance mismatch is severe, the generator may be loaded down enough to change the oscillator frequency.

Some AF signal generators have an output meter to indicate the amplitude of the generated signal. This feature is necessary when a signal of a specified amplitude is required for testing purposes—measuring the gain of a stage, for example. Attenuating networks composed of series and parallel resistances are used to supply signals at specified amplitudes. Some generators incorporate the features of both an output meter and attenuating networks.

USING AN AF SIGNAL GENERATOR

An audio-frequency signal generator (sometimes called an audio oscillator) has several useful test purposes. Within the range of its frequency coverage (generally 20 cps to 20 kc) it can be used as a signal source to check equipment or circuits designed to pass an audio signal.



Frequency Response and Fidelity

An audio amplifier used with a record player, hi-fi system, or stereo system must have a good **frequency response** through the audible frequency range. Most people have an audible range between 15 and 15,000 cycles per second. Audio equipment with a flat frequency response between these limits is considered to be a faithful reproducer of sound. The word **fidelity** is often used with reference to sound equipment. Good fidelity and flat frequency response both refer to the accuracy with which an input signal is reproduced at the output of a circuit or piece of equipment.

Q13. What are the main circuits in an audio-frequency signal generator?

Q14. Why must you be careful when matching the output impedance of a signal generator with that of the circuit being tested?

Q15. Why would an output meter be required in an AF signal generator?

Q16. What is the normal frequency range of an AF signal generator?

Q17. What is meant by fidelity and flat frequency response?

Your Answers Should Be:

A13. Oscillator, amplifier, attenuator, and **output meter.**

A14. If they were badly mismatched in impedance, the signal generator would load down and could cause the oscillator to **change frequency.**

A15. The output meter is required to determine when a signal is of the **required amplitude** for a specific purpose.

A16. 20 to 20,000 cps.

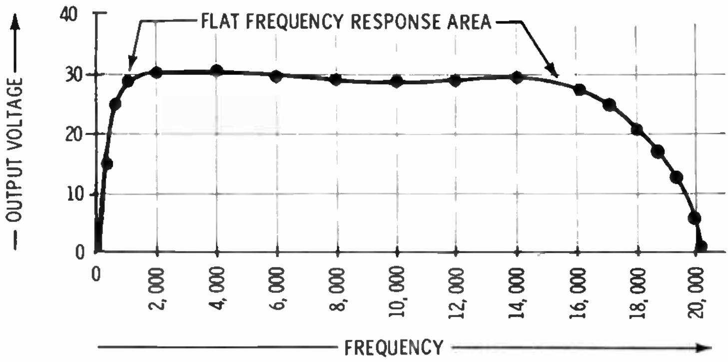
A17. They are both a **measure of the accuracy** with which the input characteristics of a signal are reproduced at the output of a circuit.

Plotting Frequency Response in the Audio Range

Evaluation of fidelity or plotting a frequency-response curve is accomplished by the equipment setup shown on the preceding page. If an oscilloscope is being used as the output indicator, it should have a graticule and be calibrated to measure AC voltage accurately.

Allow 15 minutes for the signal generator and amplifier to warm up. After each new frequency setting, plot the voltage reading on a graph as shown below. Generator set-

PLOTTING FREQUENCY RESPONSE



tings for readings in the rising and falling portions of the curve should be made in multiples of 500 cps. Intervals of 2,000 cps are satisfactory along the top part of the curve.

A frequency response curve is a line drawn through the dots plotted on the graph. It will reveal the fidelity of the amplifier for which it has been made. Do not adjust the gain of any equipment (generator, amplifier, or scope) during the test. If you do, output readings will be in error.

Determining Response at High Frequencies

A square wave has numerous odd harmonics. Depending on the steepness of the slope and flatness of the peak, the square wave can contain harmonics with frequencies 10 to 100 times the frequency of the fundamental sine wave. Because of this quality, the square wave can be used to reveal frequency response when it is applied to the input of a circuit and its output is observed on a scope. Typical response indications are shown below.

NO DISTORTION

LOSS OF LOW-FREQUENCY RESPONSE

VERY POOR LOW-FREQUENCY RESPONSE

LOSS OF HIGH-FREQUENCY RESPONSE

VERY POOR HIGH-FREQUENCY RESPONSE

DISTORTION—CIRCUIT TRYING TO OSCILLATE

Although commercial square-wave generators are available, there is a more economical way to develop a square wave for testing purposes. The sine wave from an AF signal generator is fed into an amplifier operated in the class-A portion of the characteristic curve. Amplifier gain is increased until the tube is driven into saturation on the positive cycles and cut-off on the negative. In effect, this operation flattens out the positive and negative peaks of the sine wave. The output is a reasonable and suitable copy of a square wave.

Q18. Why should you not adjust the settings (other than frequency) of equipment during a frequency-response check?

Your Answer Should Be:

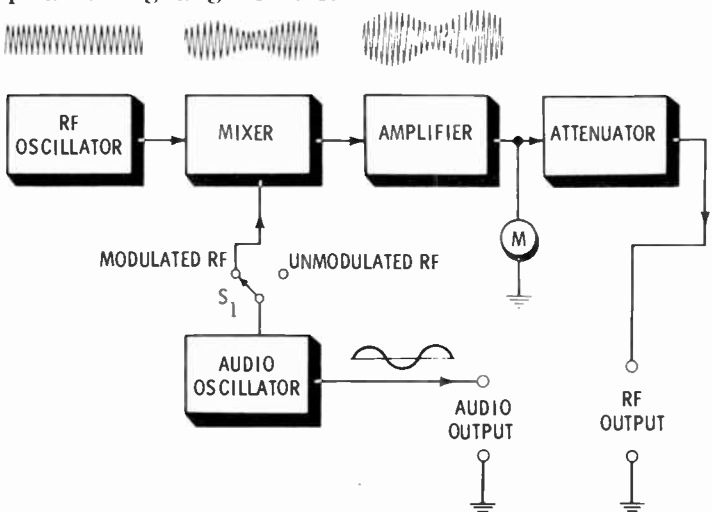
A18. If gain or similar adjustments are made to equipment during a frequency-response check, **false amplitude** readings will be obtained.

RADIO-FREQUENCY SIGNAL GENERATOR

The RF signal generator is identical in principle to the AF generator except that the RF signal generator can develop frequencies up to several hundred megacycles.

Typical RF Signal Generator

The diagram below shows a simplified block diagram of a typical RF signal generator.

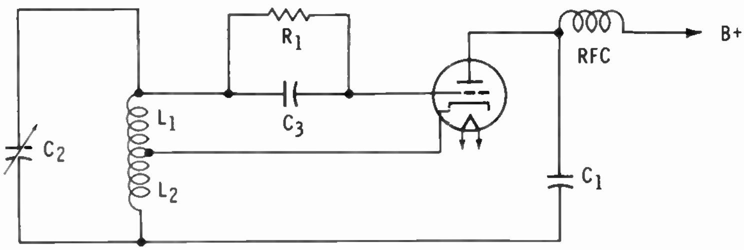


Notice that the RF and audio oscillators are connected to a mixer stage when S_1 is in the MODULATED RF position. The mixer circuit superimposes the audio on the RF carrier and feeds the modulated wave to the output through the amplifier, attenuator, and meter. When S_1 is in the UNMODULATED RF position, a pure carrier frequency appears at the RF OUTPUT and an audio signal is fed to the AUDIO.

RF Oscillator—There are several types of oscillator circircuits that can be used as RF generators. A widely used circuit for this purpose is the **Hartley oscillator.**

L_1, L_2, and C_2 form the tank circuit. The plate signal is fed through the DC blocking capacitor (C_1) to the bottom of L_2. L_2 induces a voltage in L_1 that is 180° out of phase with the plate signal (in phase with the grid signal). The

HARTLEY OSCILLATOR

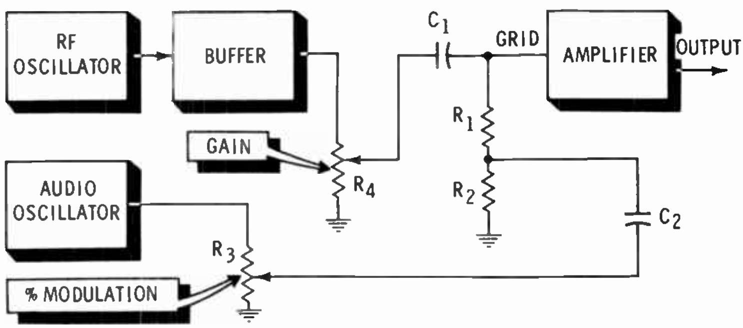


frequency of the tank is adjusted by C_2. The RFC (radio-frequency choke) in the B+ line prevents AC on the plate from entering the B+ source. R_1 and C_3 establish grid bias.

Audio Oscillator—The major purpose of the audio oscillator is to modulate the carrier at an audible rate.

Buffer and Mixing Stage—In the circuit shown below, the two signals are applied across a resistance network which feeds the resultant voltage to the grid of the next stage.

A METHOD OF MIXING SIGNALS



Q19. What is the major difference between an AF and an RF signal generator?

Q20. What are the main circuits in the RF signal generator?

Q21. What is the purpose of the mixing stage?

Your Answers Should Be:

A19. An AF signal generator can usually produce frequencies up to **20,000 cps,** while some RF signal generators can develop frequencies up to **several hundred megacycles.**

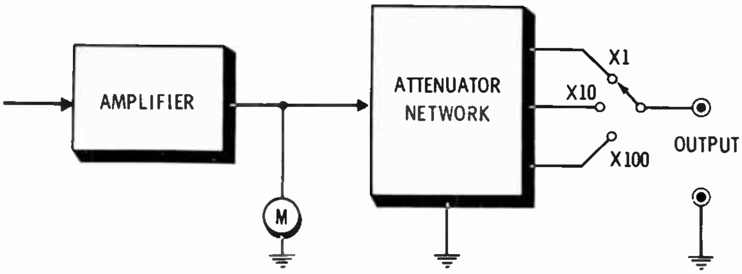
A20. The **RF oscillator, mixer, AF oscillator, amplifier,** and **attenuator.** An output meter is often included, but it is not a necessity.

A21. The mixer stage joins the carrier and audio frequencies **to produce a modulated carrier.**

The buffer places a stage of amplification between the RF oscillator and the output, thereby isolating the oscillator from the loading effects of an external circuit. The buffer also separates the RF oscillator from the modulating voltages of the audio oscillator. The carrier output from the buffer is across R_4 (marked GAIN on the front panel), a variable resistance. The control may have other names, but its purpose is to regulate the amplitude of the carrier. Voltage is taken off R_4 and distributed across R_1 and R_2 and fed to the grid of the amplifier.

The output of the audio oscillator appears across R_3, which is adjusted to select the desired percentage of modulation. This voltage is applied to the junction of R_1 and R_2. Voltage, changing at an audio rate across R_2, is subtracted from or added to the carrier amplitude at the grid of the amplifier.

Attenuator—Attenuators are resistive networks that permit selection of resonably precise voltages as outputs. The meter reading is usually multiplied by the indicated number to obtain the output amplitude of the waveform.

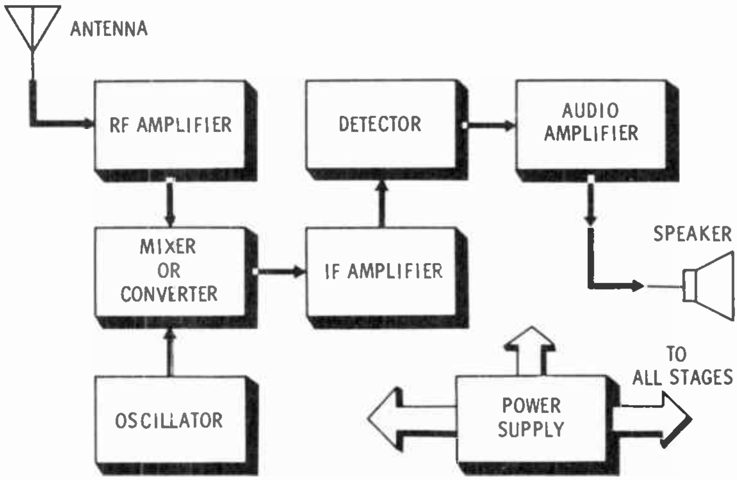


USING AN RF SIGNAL GENERATOR

The most significant application of an RF signal generator is its use in tuning, aligning, and troubleshooting radio receivers and other equipment.

Superheterodyne Receiver

A **superhet** (common name for superheterodyne) receiver is manufactured in two general varieties. One has a transformer power supply and the other does not. The latter is often referred to as an AC-DC set. A block diagram for a typical superhet is shown below.



The purpose of the radio receiver is to amplify the weak signal of a selected RF carrier and its audio modulation, remove the audio component from the carrier, and then amplify the audio so that it can be heard clearly on a speaker.

Antenna—The antenna is usually a loop or flat coil of wire attached to the back of the cabinet; it can be several turns of wire wrapped around an insulated rod. The antenna picks up carrier signals from transmitters within range of the receiver and feeds a selected signal to the first stage.

Q22. What is the purpose of the gain control on the RF signal generator?

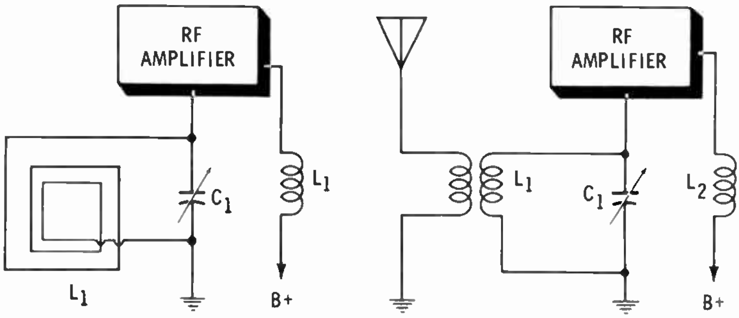
Q23. What is the RF signal generator used most frequently for?

Your Answers Should Be:

A22. The gain control regulates the **amplitude** of the carrier signal.

A23. **Tuning, aligning,** and **troubleshooting** equipment are the main uses for the RF signal generator.

RF Amplifier—In some sets, the antenna, in addition to picking up the signal, serves as a coil to form a resonant circuit with a capacitor. In other sets, a separate coil is used

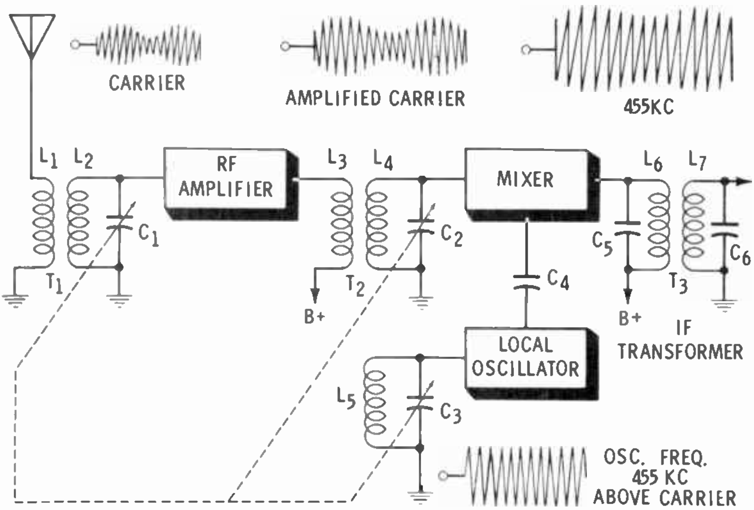


for this purpose. By varying the capacitor, L_1 and C_1 can be made resonant to a specific carrier frequency among the many appearing at the antenna. The selected frequency develops its voltage across the tank. The voltage is fed to the grid of the RF amplifier. The amplified signal (carrier plus audio modulation) is applied across L_2, the primary of a transformer connecting the amplifier to the next stage. In some receivers that do not have an RF amplifier, the antenna coil is fed to the mixer stage.

Oscillator—This stage is designed in accordance with the basic principles of any oscillator—a stage of amplification, a means of signal feedback, and a method of frequency control. In this case, frequency is controlled by a tuned resonant circuit similar to the type used in the RF amplifier.

Mixer—Carrier and local-oscillator frequencies are heterodyned together in the mixer. **Heterodyning** is the mixing together of two signals to produce two additional frequencies which are the sum and difference of the originals. The purpose is to develop an **intermediate frequency**—the difference between the RF-carrier and the local-oscillator frequencies. If the intermediate frequency (IF) is the same for all broadcast frequencies, the IF amplifier and its frequency-selecting networks need only be capable of passing and amplifying one frequency.

This is the task accomplished by the mixer. It beats (another word for heterodyning) the oscillator and RF frequencies together and passes a total of four frequencies to the plate—carrier frequency, local-oscillator frequency, a sum frequency (carrier plus oscillator), and a difference frequency (oscillator minus carrier). In most sets, the value of the difference frequency is 455 or 456 kc. It is obtained by tuning the oscillator tank circuit to a value always 455 or 456 kc above any setting of the carrier-selecting circuits.



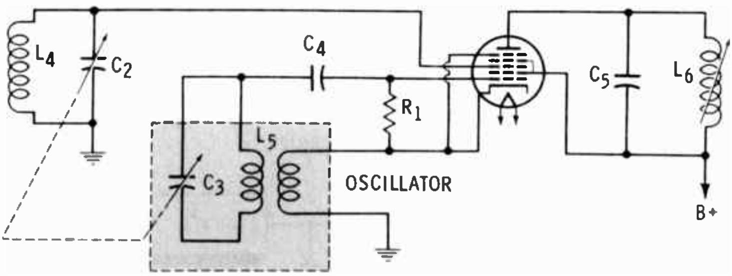
As can be seen from the diagram above, C_1, C_2, and C_3 are ganged together to a single tuning control. C_1 (RF amplifier) and C_2 (mixer) are tuned to the desired carrier frequency, rejecting all other carriers. C_3 (local oscillator) is tuned to exactly 455 kc (the IF that will be used in the rest of this chapter) above the carrier; this is true no matter which station is selected. Of the four frequencies that appear at the plate of the mixer, only the difference frequency (455 kc) will be selected by the IF transformer.

Q24. What is heterodyning?

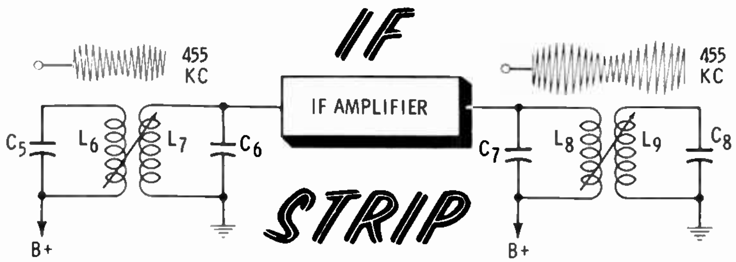
Your Answer Should Be:

A24. Heterodyning is the process of **mixing** two frequencies together to produce two other frequencies equal to the sum and difference of the first two frequencies.

Converter—The distinction between a mixer and a converter depends on whether or not the local oscillator employs a separate tube. If it does not, as is the case in most AC-DC superhets, the mixing tube acts both as a mixer for the radio and as a means of amplification for the oscillator tank circuit.



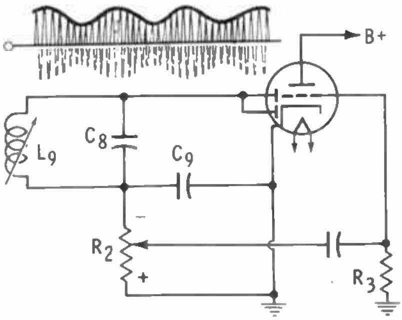
IF Amplifier—The IF stage consists of two tunable transformers separated by an amplifier. More sensitive receivers may have two amplifiers and three transformers. Each of the coils in the transformers has a metallic core that can be adjusted to give the value of inductance necessary to make the respective tank circuits resonant at 455 kc. By this method, only the difference frequency from the mixer or



converter will be allowed to enter the IF strip. **IF strip** is a common term that includes the IF-amplifier tubes and transformers.

Detector—The two small plates and the cathode of the tube act as a diode that passes only the positive parts of the IF signal. The time constant of R_2 and C_9 is long enough that the voltage across R_2 follows the envelope of the carrier rather than the individual half cycles. Thus the audio signal is removed from the IF carrier.

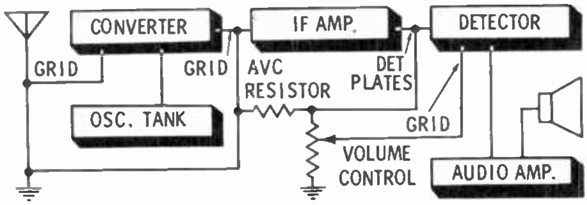
DETECTOR



Audio Amplifier—This stage further amplifies the audio signal and feeds it to the primary of the speaker transformer. The speaker is energized, and the audio originating at the broadcast studio is reproduced.

Automatic Volume Control (AVC)—AVC is a feedback circuit that takes the average value of the rectified voltage (audio component) from the detector and feeds this average voltage back to the grids of the preceding tubes. This feedback voltage tends to change the bias on the tubes. The gain is therefore changed to compensate for changes in received signal voltage.

AC-DC SUPERHET



Q25. Among the many carrier frequencies that appear on the antenna, how does a superhet select a single frequency?

Q26. What is the difference between a mixer and a converter stage in a superhet receiver?

Your Answers Should Be:

A25. C_1 and L_2 of the RF transformer (T_1) and C_2 and L_4 of the mixer transformer (T_2) are **resonant circuits** that can be tuned to a specific frequency, selecting the one desired carrier.

A26. A mixer **heterodynes,** or beats, the carrier and local-oscillator frequencies together to obtain two other frequencies, called sum-and-difference frequencies. The converter stage performs the functions of the **mixer and oscillator** in one tube stage.

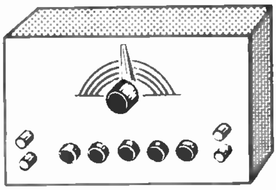
Superhet Alignment

Although you may have enough background knowledge to undertake the task of receiver alignment, a word of caution is necessary. Make certain that you understand how your signal generator operates and how it is to be adjusted for use. Also, be sure you know how the receiver you are going to align works.

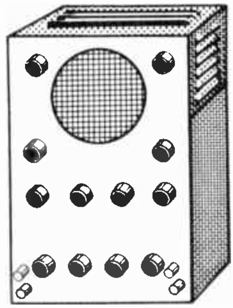
Why Should a Receiver Be Aligned?—The operating characteristics of tubes and other parts change with age. Periodic heating and cooling of parts is largely responsible for these changes. The change may not be great enough to make the set fail to operate, but it may be enough to throw the set out of alignment. In fact, most home receivers require at least a slight realignment. Improper alignment results in a lower receiver output, poor separation of stations, and a decrease in tone quality.

You should work from the schematic diagram of a receiver to obtain the information needed for alignment. Unfortunately, these diagrams are not always provided with commercial equipment. However, printed service information is available at most local electronic parts supply houses. The service data usually contains a clearly drawn schematic for the equipment specified, showing the values of all parts and the voltages that should be read at significant test points. A parts list, the location of alignment test points, and photographs showing the location of all parts are usually included.

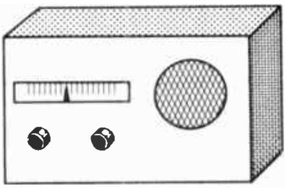
Items Required for Realignment—The bare minimum of tools is shown in the illustration below.



SOURCE OF SIGNAL
(RF SIGNAL GENERATOR)

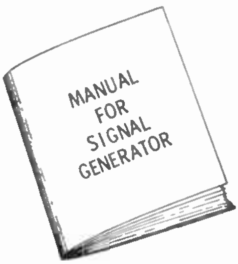


OUTPUT INDICATOR
(SCOPE)



SET TO BE ALIGNED

INSULATED ALIGNMENT
SCREWDRIVER



There are six items shown above, and each is important. A few other common hand tools are also needed to remove the receiver from the cabinet. An insulated screwdriver is used to prevent shorting or detuning of circuits while they are being adjusted.

Q26. What is the value of the following tools when re-aligning a receiver?

(a) RF signal generator.

(b) Output indicator.

(c) Operating manual for your signal generator.

(d) Service folder for the receiver.

(e) Common-sense application of technical knowledge.

Your Answers Should Be:

A27. (a) **Provides a carrier frequency** under controlled conditions.

(b) Permits **observation of the results of adjustments** made to produce best performance.

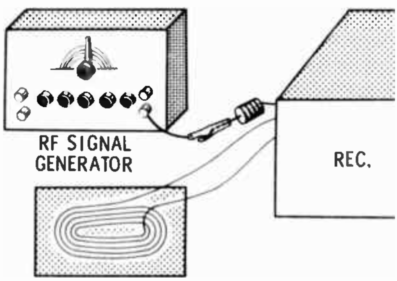
(c) Provides **the proper operating procedures.**

(d) Provides a schematic diagram and other **information necessary for alignment.**

(e) **Without** a common-sense application of your technical knowledge, many **unnecessary mistakes will be made.**

Calibrating the Generator

Although most generators are designed to give good accuracy, it is always best to calibrate the output of the generator with a broadcast station. After the signal generator



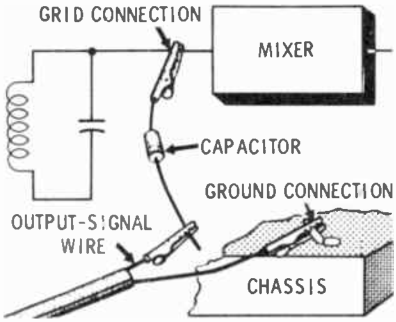
CALIBRATING THE SIGNAL GENERATOR

has been on for about 15 minutes and the receiver has been tuned to a strong local station, hold the signal generator test clip or probe near the antenna terminal of the receiver. Adjust the signal generator dial approximately to the station frequency. If a tone or a squeal cannot be heard, connect the probe to the antenna terminal through a small-value capacitor. A noise should be heard on either side of **zero beat** (a point of silence). When the generator dial is at zero beat, the generator frequency is the same as the station frequency. Without retuning the generator, adjust the generator dial to read this frequency. (Consult the generator instruction manual.)

Alignment Steps

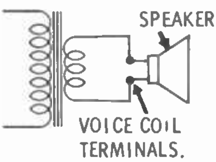
Receiver alignment consists of two steps. The IF circuits are first tuned to 455 kc, or whatever IF the manufacturer specifies. Then the RF, mixer, and oscillator circuits are tuned, in that order, for maximum signal. Connect the generator as shown below.

CONNECTIONS FOR TUNING IF STRIP



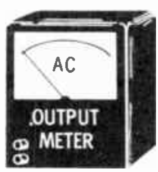
There is a choice of output indicators available. Whichever you choose, adjustments are made for maximum output indication and not for a precise numerical reading.

OUTPUT INDICATORS



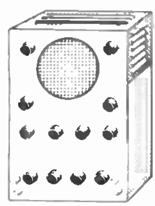
LEVEL OF SOUND OUTPUT IS MEASURING VEHICLE. NOT AS SENSITIVE AS OTHERS.

FAIR



VTVM OR OTHER AC MEASURING INSTRUMENT. ATTACH PROBES TO SPEAKER VOICE-COIL TERMINALS.

BETTER



ATTACH LEAD TO SPEAKER VOICE-COIL TERMINALS.

BEST

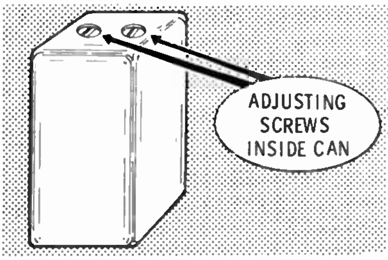
Set the signal generator frequency to the IF of the receiver, and modulate the carrier with an audio signal. Set the receiver volume control to maximum gain. Ground the AVC to the chassis for best output performance. Ground the grid of the local-oscillator tube, if the set has one, to prevent undesired signals from entering the IF strip.

Q28. What steps are required to align a receiver?

Your Answer Should Be:

A28. First, the **IF circuits must be tuned to the specified IF** (normally, 455 kc). Then, the **RF, mixer**, and **oscillator circuits are tuned for maximum signal.**

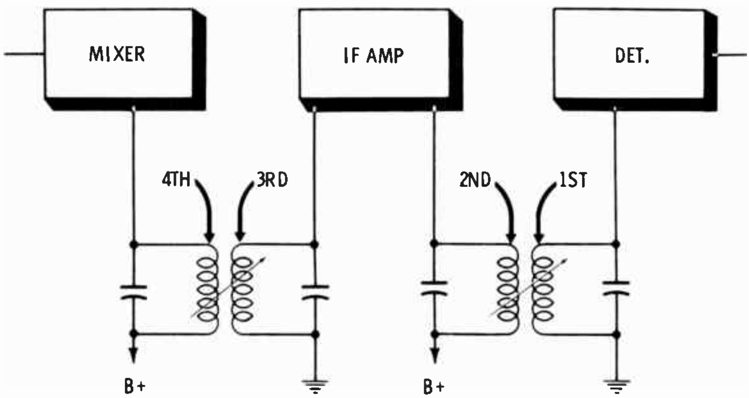
Tuning is accomplished by adjusting each of the two screws inside the top of the IF can. Be sure to use an insulated screwdriver for this operation.



IF CAN (TRANSFORMER)

Carefully adjust the screws for maximum reading on the output indicator. Start with the coil nearest the detector and adjust each, in turn, working toward the mixer.

IF TUNING SEQUENCE

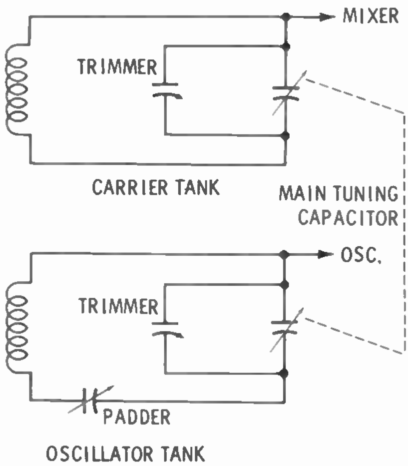


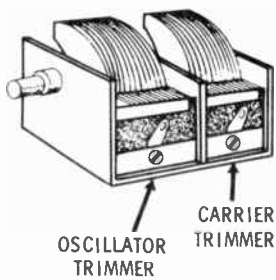
During this and all following alignment steps, keep the gain of the signal generator no higher than necessary to give an indication on the output indicator used. If the gain is too high, receiver stages will overload or saturate, and output readings will be invalid. Readjust all coils until you are sure they have been peaked to maximum.

After the IF coils have been peaked for a maximum output indication, the mixer and oscillator tuning circuits also must be adjusted to give a maximum-signal indication. **Front end** is a term applied to these tuning stages. There are some sets that have an RF amplifier; the tuning circuit of the RF amplifier must be adjusted in a similar manner.

To tune the front end, attach the generator high lead with its capacitor to the antenna terminal. Unground the oscillator grid if it was grounded. Tuning procedures involve adjusting the small **trimmer** capacitors attached to the main tuning capacitor and a **padder** capacitor in the oscillator tank circuit.

TUNING CAPACITOR





To arrive at the best tuning, the trimmers and padder are adjusted for a maximum reading on the output indicator. As shown in the diagram above, the trimmers are in parallel across the respective sections of the main tuning capacitor. The padder is in series with the coil and main capacitor section of the oscillator tank.

Q29. At what end of the receiver should the first IF adjustment be made?

Q30. During the tuning of IF coils, at what frequency and amplitude should the signal generator be set?

Q31. At what point in the receiver should the generator leads be connected while adjusting the IF coils?

Your Answers Should Be:

A29. The IF coil to be adjusted first is the one **nearest the detector stage.**

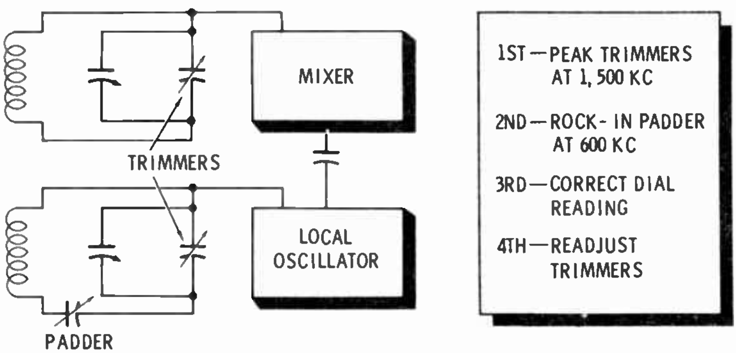
A30. The signal generator should be set at **the IF of the receiver,** modulated with an audio tone, and set at the **lowest amplitude that gives an output-indicator reading.**

A31. The high-side generator lead should be connected to the **mixer grid** and the other lead should be connected to the chassis of the receiver.

Not only must the carrier and oscillator tank circuits be tuned for maximum performance, but their resonant frequencies must differ by 455 kc.

First, set the signal generator to 1,500 kc, leaving the audio modulation on. Rotate the main tuning capacitor of the receiver to the position of maximum output at the high end of the dial. Adjust both trimmers for highest output.

FRONT-END TUNING



Now, set the generator and receiver dials to 600 kc. **Rock-in** the padder tuning by making the same adjustment at several settings on either side of the 600-kc dial reading. The setting at which the highest output reading is noted is the true 600-kc position. Adjust the receiver dial pointer to indicate 600 kc. Recheck the trimmers for maximum output again, first at 1,500 kc and then at 600 kc. If no change is evident, tuning is completed.

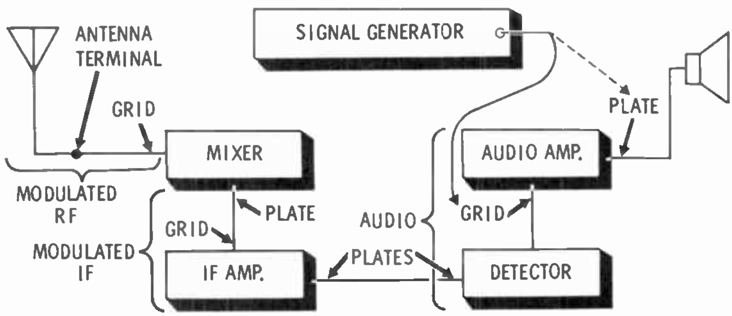
TROUBLESHOOTING A RADIO RECEIVER

A signal generator is frequently used for troubleshooting a receiver. The signal generator can supply the proper signal through all of the stages except two, the power supply and local oscillator. The local oscillator generates its own frequency, and little test value is gained by passing another signal through it.

Two different methods are used to isolate the trouble in a receiver by means of a signal generator. One is called **signal substitution**, and the other **signal tracing.**

Signal Substitution

In signal substitution, the output of an RF signal generator is applied to each stage in sequence. The faulty stage lies between the points at which the generator did and then did not pass a signal through the receiver.



The principle of signal substitution is simply to start at the output end of the receiver and work toward the front end, applying the appropriate signal at each stage. Use a capacitor in series with the test lead to keep DC out of the generator. The first check is made at the plate of the audio amplifier with an audio signal (only) from the generator. If a sound is heard in the speaker, the speaker and the circuitry between the speaker and audio amplifier plate are not the cause of the trouble. If there is no output from the speaker, the trouble is in this area. The trouble could be in the speaker, the output transformer, or in the several connections between the speaker and amplifier.

Q32. What two signal-generator methods are used to isolate trouble in a radio-receiver circuit?

Your Answer Should Be:

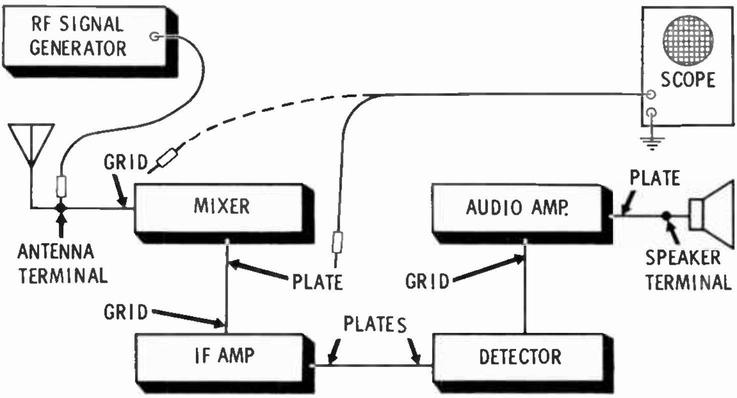
A32. The two methods used to isolate a bad circuit are **signal substitution** and **signal tracing.**

If the first check is good, apply the audio signal to the control grid of each audio stage. Audio from the speaker indicates that these stages are probably good.

Set the generator for a modulated IF, and connect its output to the plates of the detector, the plate and grid of the IF amplifiers, and the plate of the mixer. Apply modulated RF to the grid of the mixer and the antenna terminal. Somewhere in the sequence, no signal will reach the speaker. The trouble is between that point and the last good check point.

Signal Tracing

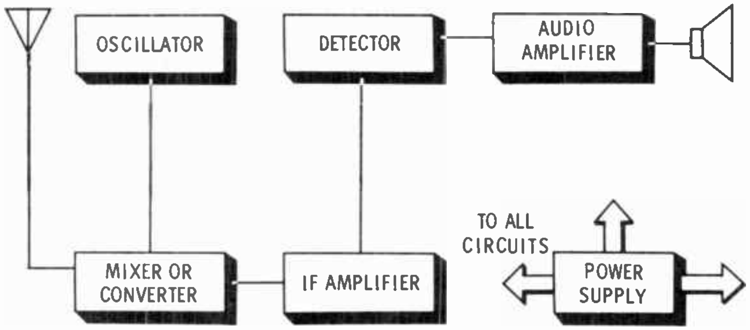
Signal tracing is almost the inverse of signal substitution. The signal generator is set up to provide a modulated RF signal within the range of the receiver; the test lead is connected to the antenna terminals. An indicating device—oscilloscope or VTVM, for example—is used to trace the signal from the front end to the output end of the receiver, making checks at the input and output of each stage.



An oscilloscope is best for signal tracing. You can use a VTVM, however, to check for the presence of a signal. You must use an RF probe with the meter when testing at points where either RF or IF signals are present.

The checks are made first at the grid of the mixer, then at its plate, and so on down the line from grid to plate to grid until no output appears at a check point. The trouble is located between this point and the previous point where an output was indicated. Use a VTVM or a multimeter in that area to find the faulty part.

The signal-tracing method can also be used for keeping a record of receiver sensitivity. At a time when the receiver is known to be in a satisfactory condition, connect the generator to the set, as indicated for signal tracing. Set the generator and receiver gain to the minimum level that will cause a readable signal to pass through the set. Record the amplitude of the signal at each check point, using a VTVM or oscilloscope. Also record the setting of the gain control and attenuator on the generator. If you wish, you can divide the output reading of each stage by its input reading to determine gain, the factor for sensitivity. These readings can be used at a later date for comparison purposes when a decrease in sensitivity is suspected. A loss of gain in a stage will indicate actual or impending trouble.



Q33. Which method of receiver troubleshooting using a signal generator is better, signal substitution or tracing?

Q34. If you were using a VTVM as the indicating device in signal tracing, at what check point in the receiver diagramed above would you change from an RF probe to the normal AC probe?

Your Answers Should Be:

A33. **Both methods are equally good.** The choice is merely a matter of personal preference.

A34. In the front-to-back signal-tracing method, the RF probe should be used last **at the plates of the detector.**

WHAT YOU HAVE LEARNED

1. An RF signal generator has much in common with a radio transmitter. They both have a means of generating a frequency, modulating it, and applying the output signal to a load. For this reason, a signal generator can take the place of a transmitter when you are checking the performance of a receiver.
2. Signal generators can be classified in terms of the frequencies generated by their main oscillators. An AF (audio frequency) generator can develop a signal within the 20- to 20,000-cps range. An RF (radio frequency) generator can have a range starting at about 20 kc and reaching as high as several thousand megacycles. No single generator, however, can cover the entire range. Most RF generators have a means of modulating their carrier frequency.
3. There are several types of modulation. The two most used are amplitude modulation (AM) and frequency modulation (FM).
4. There are many types of oscillators. Each type requires a means of amplification, a method of feedback, and some manner of frequency control.
5. The frequency at which an oscillator operates is controlled by the inductance and capacitance in the tank circuit. If either L or C is increased, the resonant frequency will decrease. Decrease either L or C, and the frequency will increase.
6. Oscillators in a resonant tank are damped (die out) because of the resistance (coil and conductors) in the circuit. Feedback from the amplifier plate, if properly

applied, provides the periodic surge required to keep the oscillations going.

7. An AF signal generator can be used with an oscilloscope to plot the frequency-response curve of an amplifier.
8. When the output of an AF signal generator is fed into an overdriven amplifier, the output will be a fairly good square wave. Since a square wave is rich in harmonics (multiples of the fundamental frequency), the frequency response of an amplifier can be studied by observing the type of distortion produced in the square wave as it passes through the circuit.
9. A typical RF generator contains an RF oscillator, an audio oscillator, a stage for mixing the two, an amplifier, a means of controlled attenuation, and an output meter. Such a generator provides a pure RF signal, an audio signal, or a modulated signal.
10. In a superhet receiver, modulated RF and the oscillator frequency are applied to the mixer stage. They are heterodyned to produce a sum and a difference frequency. The difference frequency, still containing the modulation envelope, is referred to as the IF and is amplified in the next stage. The detector extracts the audio signal from the IF carrier and feeds it to the audio amplifier and then to the speaker. Some superhets have an additional stage, called an RF amplifier, ahead of the mixer. A converter combines the output from the mixer and oscillator stages.
11. Alignment of a superhet receiver is a relatively simple task if the technician understands how his signal generator and receiver operate. Specific information for the generator is contained in the operating manual, and for the receiver, in a service folder.
12. The steps for receiver alignment are:
    (a) Tune the IF transformers.
    (b) Tune the front end.
13. An RF signal generator can also be used for isolating trouble in a receiver to one of its stages. There are two methods, signal substitution and signal tracing.

7

Troubleshooting Electronic Equipment

What You Will Learn

The primary task of any electronic technician is to troubleshoot equipment. Since most technicians have difficulty in acquiring a reliable method, this chapter will explain one that is used by most good technicians. Some technicians call it systematic troubleshooting; others call it common-sense troubleshooting. The title that seems to embody both names, and the one that will be used in this chapter, is logical troubleshooting. There are many methods other than the one that will be described; however, by comparison these methods have been found to be ineffective and time consuming.

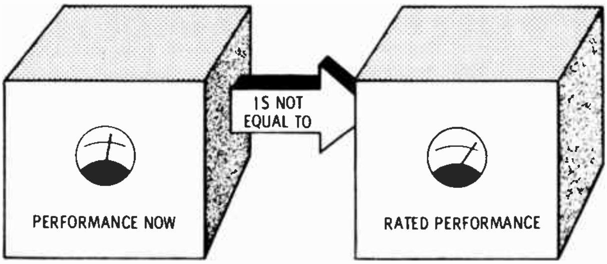
THE NEED FOR TROUBLESHOOTING

As you have already determined, troubleshooting is the process of locating the fault that causes a piece of equipment to operate at less than desired or designed performance.

Any equipment operating at less than the best performance requires the services of a troubleshooter. A hi-fi set that is garbling its highs or lows, even though it has good rated frequency response, has an electronic fault that needs repair. A home radio that begins to pick up two stations at once contains a defect. A TV set that has poor contrast between blacks and whites also needs repair.

The remedy may be no more than the proper adjustment of one or two controls, but the trouble will remain until the appropriate adjustment is located and made.

The need for troubleshooting (locating the cause of faulty performance) exists whenever the equipment fails to meet the rated performance as set forth by the manufacturer.



TROUBLESHOOTING PREREQUISITES

Good troubleshooting is not a talent with which a person is born. It is a skill that can be acquired by anyone with a suitable electronics background. You can become a good troubleshooter if you have:

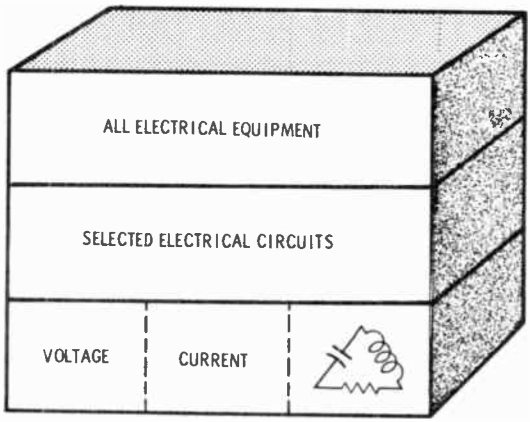
1. Sufficient electronic knowledge to learn how a piece of equipment works.
2. Suitable skill in reading and interpreting data contained in the technical manual or service folder.
3. Suitable skill in operating test equipment and interpreting test readings.
4. The ability to troubleshoot in a logical manner.

Electronic Knowledge

If you have carefully studied the preceding volumes in this series (or have an equivalent knowledge) and have been able to apply these electronic principles, you can learn how electronic equipment works. You will encounter many circuits and pieces of equipment that are not familiar as you gain experience, but gaining an understanding of how they work is merely a process of applying what you have already learned.

What is this foundation that can be applied to all electronic devices? The answer is the set of principles you learned about DC and AC electricity and have been applying in this volume.

The illustration shows that **all electronic equipment** is made up of or based on **selected electronic circuits** which, in turn, operate in accordance with the fundamental principles of voltage and current and the characteristics of inductance,



capacitance, and resistance. If you reduce any electronic equipment to the bare essentials, you will find that the equipment operates the way it does because of the circuit arrangement of L, C, and R and their effect on current and voltage.

If you have the foundation for understanding how electronic equipment operates, you need only experience and more study if you wish to become skilled.

Reading and Interpreting Electronic Data

Most electronic devices have operating or servicing manuals, often called technical manuals or instruction books. They contain text, diagrams, and other data required for troubleshooting. Equipment used in the home, such as radios, television receivers, and audio equipment, usually has service folders that contain similar information. These service folders can usually be procured from any local electronic parts supply house.

Q1. What is troubleshooting?

Q2. What are the requirements for a good electronics troubleshooter?

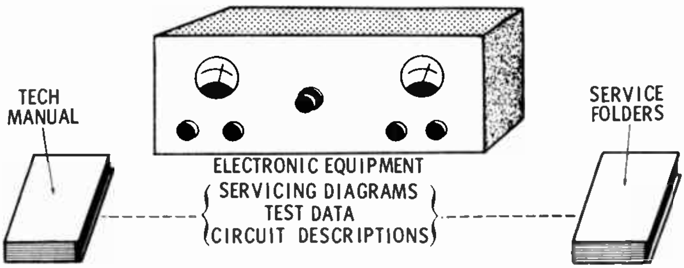
Your Answers Should Be:

A1. Troubleshooting is the process of **locating** the causes of malfunctions in an electronic circuit.

A2. The basic requirements for a good troubleshooter are a basic **knowledge of electronics**, an **ability to read and interpret data**, the ability **to operate** various **test equipment**, and a **logical testing method.**

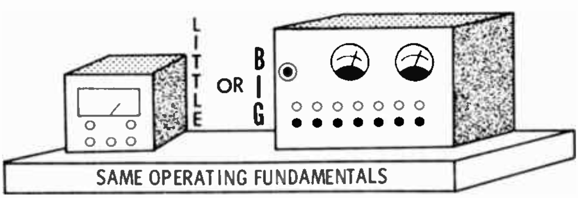
Reading Technical Data

Will you be able to read these manuals and folders? Yes, if you were able to understand the information presented thus far in this volume. The portions of schematic and block diagrams, the type of circuit descriptions, and the kind of test data that you have encountered are all representative of the information you will find in the manuals and folders.



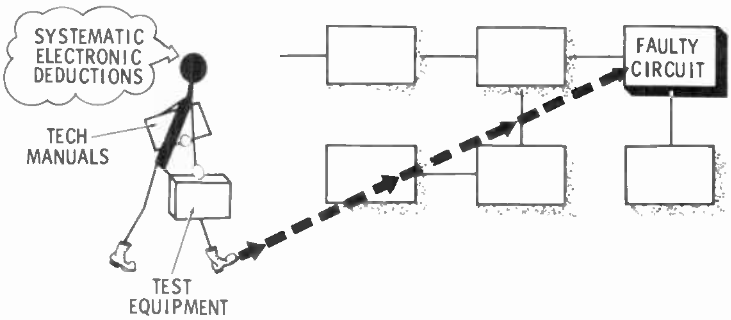
Test Equipment

You have studied the basic types of test equipment. All other types of test equipment are more or less complex adaptations of those included in this volume. Like any electronic equipment, their operation is founded on a basic set of principles. Therefore, you have the capability of learning how to operate and use them. Again, experience is the instruction needed to gain greater skill.



LOGICAL TROUBLESHOOTING

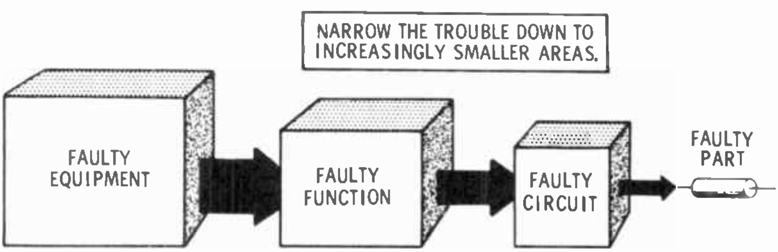
Logical troubleshooting is a systematic, common-sense method of isolating the fault in a malfunctioning piece of equipment. It does not employ the time-wasting or ineffective procedures of trial-and-error methods. The logical troubleshooter uses his knowledge of electronic principles,



his ability to extract data from a technical publication, and his skill in using test equipment.

Logical troubleshooting is a time-proven procedure used by all experienced technicians. Most of them have applied the procedure so often that they no longer pay attention to its fine points. Through habit and years of experience, they may have forgotten the specific details.

Probably no two technicians would explain the procedure alike. However, all would agree that logical troubleshooting consists of a series of sequential steps. Each step is based on valid electronic deductions that systematically narrow down the trouble to increasingly smaller areas in the equipment and finally to the faulty part, wire, or connection. Some technicians might list the procedure in two or three steps; others would count a dozen or more. Regardless of the number, the principle is the same.



Five steps are listed below as the most reliable method of learning and applying this procedure. They can be applied to any equipment, regardless of size. The steps in the proper order are:

STEP 1. Search for all trouble symptoms.

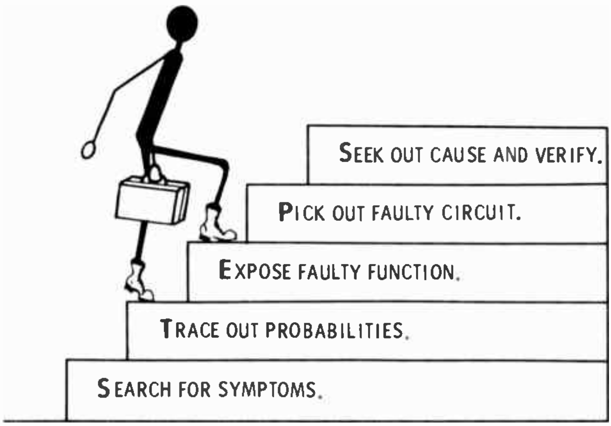
STEP 2. Trace out all probable faulty functions.

STEP 3. Expose the single faulty function.

STEP 4. Pick out the faulty circuit.

STEP 5. Seek out and verify the cause of the trouble.

Note that the first letter in each step, read from top to bottom, spells STEPS. This fact will help you to remember logical troubleshooting.

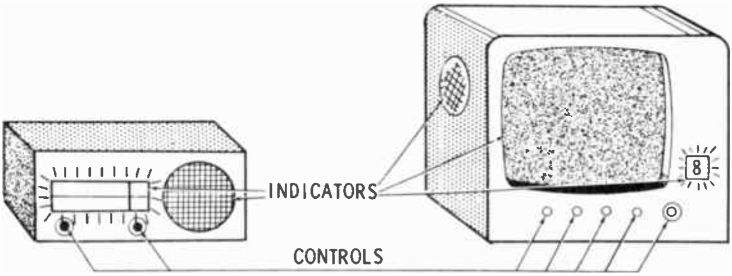


STEP 1. SEARCH FOR ALL TROUBLE SYMPTOMS

A trouble symptom is an outward indication that a piece of equipment is not working properly. In dead equipment the indication is fairly obvious. A hum in a radio receiver, a distorted picture on a TV set, or harsh, flat notes from a hi-fi set are also obvious and make further use of the equipment undesirable. Then there are the less obvious indications as the performance of the equipment slowly worsens over a period of time. These are tolerated until the output becomes obviously distorted or blanked out.

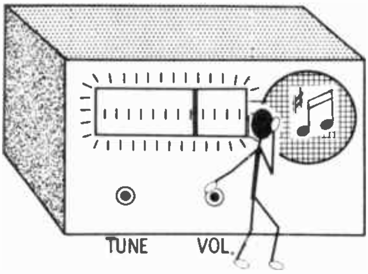
Symptom Indicators

Audible and/or visual outputs of an item of equipment are symptom indicators which, by the use of the front-panel controls, can help you to pinpoint the source of trouble.



Many radio receivers have two output indicators, a speaker and a light (usually illuminating the dial); the receiver also has at least two controls. The change from desired performance can be registered in many ways—hums, squeals, squawks, low volume, two stations instead of one, or no sound at all. The light is either on or off.

The controls can be used to obtain more information about the symptom. How does the audio change, if at all, when the volume control is rotated from one extreme to the other? Does the hum or other noise become louder, or does it remain the same? If there is no undesirable noise, will the control smoothly increase the volume of the station program?



Q3. If the dial light is out, what are the possible causes of the trouble symptom?

Q4. If you have determined that a radio is receiving only two stations instead of many, would this fact be a useful trouble symptom?

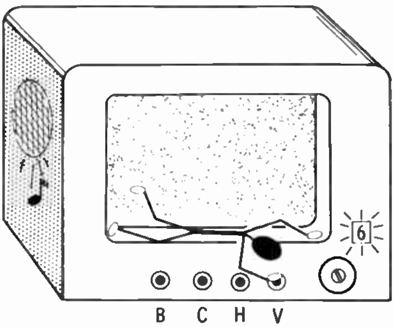
Your Answers Should Be:

A3. If the dial light is out, the trouble could be **no power to the radio; a burned-out lamp; a faulty switch;** or **faulty conductors, connections, or parts** within the set.

A4. **Yes.** If this information is not determined before proceeding further into the troubleshooting procedure, much time could be spent in checking unnecessary areas of the radio.

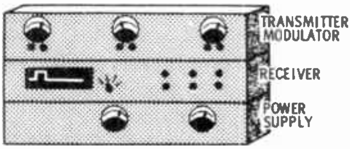
Obtain as much symptom information as you can during Step 1. Learning as much as you can about the trouble symptoms is the only effective way to begin a search for the cause and its source.

A television receiver has an additional output and a greater number of front-panel controls that can be used in searching for trouble symptoms. It has a speaker, a dial



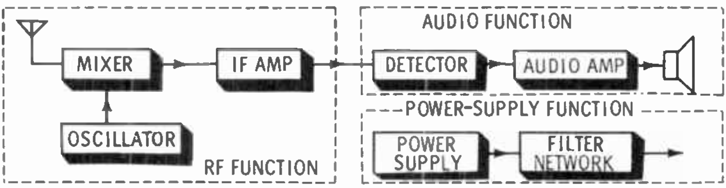
light, and a visual output indicator to detect trouble symptoms, and several controls that can be adjusted to observe additional symptoms or changes in output. Another advantage in first looking for all symptoms is that proper adjustment of a control will quite frequently eliminate the trouble. Ragged, slanted lines on the TV screen might be corrected by adjustment of the horizontal control. Distortion in height of the picture (large heads and short legs, for example) might be corrected by adjustment of the vertical-linearity control. If these adjustments correct the fault and there are no other symptoms, the troubleshooting job is completed.

The more complex equipment used in commercial, industrial, and service installations provides additional means for tuning and setting-up operations.



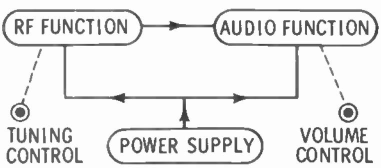
STEP 2. TRACE OUT ALL PROBABLE FAULTY FUNCTIONS

As applied to electronic equipment, a **function** is the purpose of the equipment, group of circuits, or circuit. In the narrowing-down feature of logical troubleshooting, the idea is to pick out a few of the several functional circuit groups in which the trouble most probably lies. When this is accomplished, the search is narrowed down to a smaller area.



In smaller equipment such as the radio receiver illustrated above, the number of circuit-group functions may be limited. Further limitations are imposed by the receiver, which has only two controls—tuning and volume. However, the antenna, mixer, oscillator, and IF amplifiers of the set shown can be grouped within a radio-frequency function. The combination of detector, audio amplifier, and speaker is desig-

FUNCTIONAL CIRCUIT GROUP

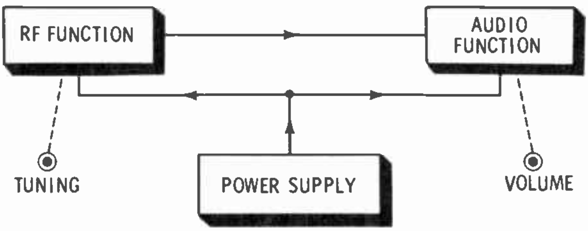


nated as an audio function; the power supply, its filter network, and power cord become the power-supply function.

Isolating Faulty Radio Functions

The tuning control of the receiver is connected to the inputs of the mixer and oscillator, and the volume control is connected in the input circuit of the first audio amplifier stage. Information obtained from adjustment of these controls can therefore be associated with the respective functional groups. The purpose of the second step is to trace out and identify the functions whose symptoms indicate a malfunction.

The following is an example of the second step. The original symptom in the radio receiver is weak output. Adjusting the volume control makes little or no difference. The tuning control shows a small but significant difference between loud and weak stations. The dial lamp is on. In which function(s) is the probable location of the trouble? The most probable location is the audio function. The power-supply function is a possibility, but the RF function can almost be eliminated. If you were to list all three functions as probables, based on your technical knowledge of how the receiver works, your answer could be just as correct as the one given. As stated in the title for Step 2, trace out all the probable faulty functions. Place them in the most logical order.



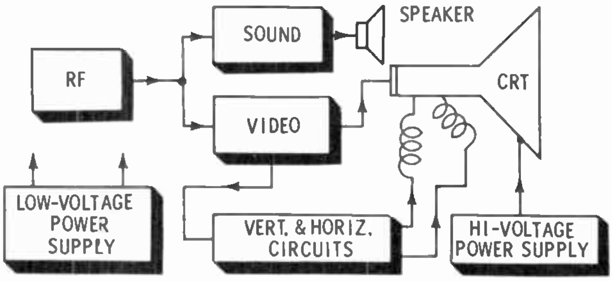
Try another problem. During Step 1, no stations are heard, regardless of where the tuning control is set. The dial lamp is on. Rotation of the volume control causes an increased crackling, rushing noise in the speaker. In which function(s) would you expect to find the trouble?

The most probable location of the trouble in this case is the RF function. The noise heard in the speaker is the normal noise generated by the vacuum tubes in the radio. This noise indicates that the tubes are getting voltage from the power supply and that the audio stages are performing their amplifying function.

Television Functions

A television receiver can be broken down into a large number of sharply defined circuit-group functions. The thirty or forty circuits in one type of television receiver can be visualized in functional circuit groups as shown below.

FUNCTIONAL GROUPS IN A TV RECEIVER



Suppose that during Step 1 you learned the following symptoms. Audio appears to be good, but the picture covers only half of the screen vertically. Width appears to be proper. Adjustment of the vertical control makes no apparent change in height, but does cause the picture to roll.

Since audio (sound) and image (picture) appear to be good, the sound and video functions are eliminated. If these are working properly, the RF function must be operating properly. If the high voltage were low or absent there would be no picture on the screen. The low voltage must be good since the picture, its width, and the sound are good. Logical reasoning indicates that the trouble must be in the vertical and horizontal circuits.

As a result of reaching only the second step in logical troubleshooting, you have limited the trouble to a half-dozen circuits out of a possible thirty or forty. This is much better than checking them all. In addition, the logical deductions you have made have given you a good idea as to the type of trouble you are looking for. Evidently the output voltage of the vertical deflection signal is not large enough to swing the electron beam over the full height of the screen.

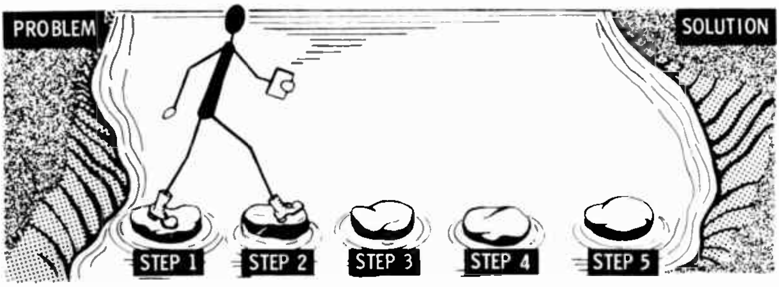
Q5. Which function in the diagram above is the most probable location of trouble if the picture is good but there is no audio output?

Your Answer Should Be:

A5. **Sound** (including the speaker) is the only probable malfunction. A good picture indicates that the other functions must be working properly. The RF and low-voltage power-supply functions feed both the sound and picture sections; since the picture is proper, both of these functions must be working.

Review of Steps 1 and 2

During the first two steps of the logical troubleshooting procedure, analysis is confined to information obtained from outside the equipment.



After obtaining all the information you can about the original trouble symptom(s) by manipulation of front-panel controls and observation of output indicators during Step 1, you proceed to the second step and trace out all probable faulty functions. In Step 2 you use the symptom information to make logical technical deductions and identify the functional areas of the equipment that may contain the trouble. Up to this point you have neither entered the equipment nor used any external testing devices.

While making technical deductions during Step 2, you may find it desirable to obtain additional symptom information. Returning to the procedures of Step 1 will not violate any rules. You may often find it necessary to return to a previous step or steps for re-evaluation purposes.

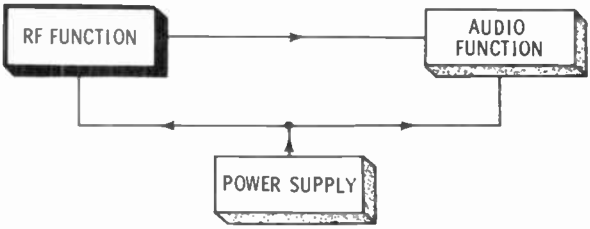
Until you become experienced in troubleshooting, write out the data obtained or conclusions reached during each step. You will find that this procedure reduces the necessity of returning to a previous step for verification.

STEP 3. EXPOSE THE SINGLE FAULTY FUNCTION

In Step 3 you can use test equipment to determine which one of the probable faulty functions contains the trouble.

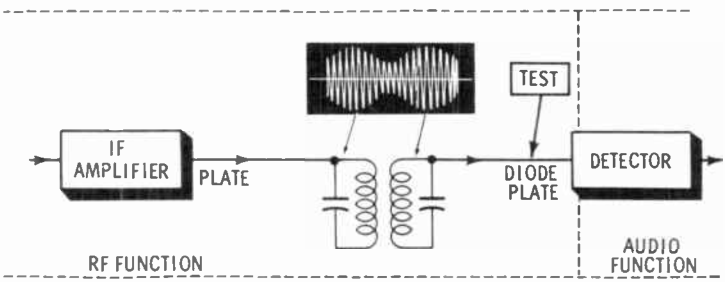
Radio Application

Refer to one of the radio receiver examples used in the preceding step as the first example. No stations were heard at any frequency. The lighted dial lamp indicated that power was applied. An increase in receiver background noise as the volume control was adjusted indicated that the audio function was good. It was decided that the radio-frequency function was suspected to be defective.



The only purpose of Step 3 is to locate the single function that is causing the equipment to operate improperly. In the example above, either a scope or a VTVM can be used.

TESTING FOR PRESENCE OF A SIGNAL



From the schematic diagram of the receiver, locate the pin number of the upper diode plate of the detector. Connect the oscilloscope to the proper socket terminal and rotate the tuning control. If no audio-modulated signal is noted at several station settings, the RF function is not operating properly.

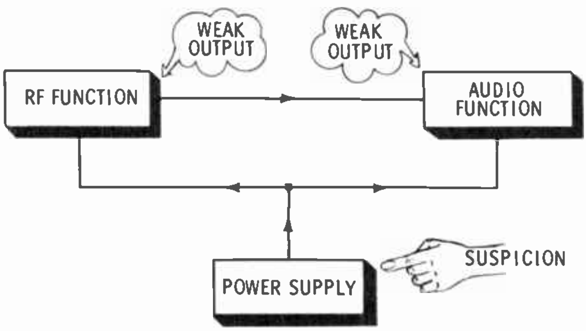
Q6. What would you look for with a VTVM?

Your Answer Should Be:

A6. You would look for an **AC signal.** If this signal is present, the voltage would not be very large and the meter reading would show a steady average of the changing amplitude. For this reason, an oscilloscope would give better confirmation of a signal if one were present.

If a good, but weaker-than-normal, signal is obtained, deductions made during Step 2 are erroneous. However, the effort made thus far in Step 3 is not wasted. You have added more data to your store of symptom information. You can now go back to Step-2 procedures and the functional block diagram better equipped to select the probable faulty function(s).

Having recorded a weak output for the RF function, you also conclude that the weak signal should have been passed through the audio function if it were good. When a recheck is made of speaker output with the volume control at maximum, background noise this time seems weak. Since both functions are weak, you suspect the power supply of faulty performance.



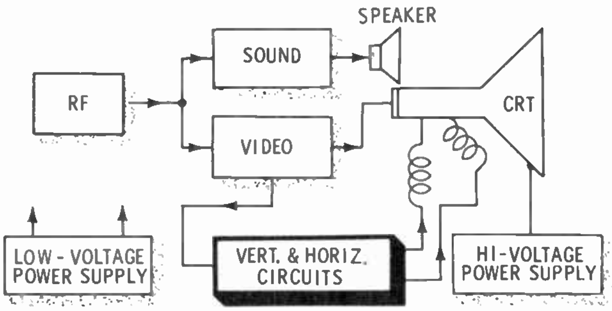
The new Step-2 conclusion places the probable location of the trouble in the power-supply function. A Step-3 check of the schematic for the receiver indicates that there should be a pulsating DC output of 90V. With a VTVM or multimeter, the DC reading shows less than half this value. The faulty function has been confirmed.

TV Receiver Application

The results of the first and second steps for a TV receiver could be the following:

STEP 1. **Symptoms**—Good audio; good picture image but it covers only half the height of the screen; there is no change noted while adjusting the vertical control.

STEP 2. **Deductions**—The trouble is probably in the vertical and horizontal functions.



The schematic diagram included in the technical manual or servicing folder for the receiver should be used in locating the output test point of the probable faulty function. You will find that a schematic diagram will be your most valuable single item for troubleshooting.

The oscilloscope is the best piece of equipment to use for obtaining readings at a suspected trouble point, since you can observe the shape of a waveform as well as measure the amplitude (voltage, in this case). To measure voltage, the oscilloscope screen with its graticule must first be calibrated from a known voltage source. Multimeter or VTVM AC voltage readings are difficult to use for confirming whether the output is good or bad. TV receiver schematics usually show waveform outputs with peak-to-peak (p-p) voltage values. These are difficult to convert to meter readings.

Q7. How would you locate the correct test point to verify that the trouble is in a certain function?

Q8. What test equipment would you use to check the waveform at the test point?

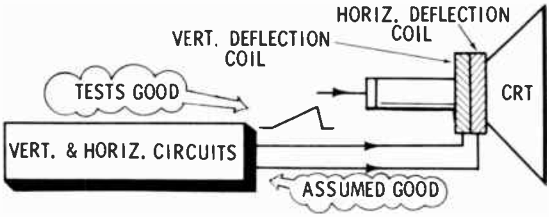
Your Answers Should Be:

A7. Use the **schematic or block diagram** that comes with the equipment to locate individual test points.

A8. The **oscilloscope** is the best piece of equipment to use when checking waveforms.

A low reading would substantiate the Step-2 deduction that vertical and horizontal circuits probably contained the fault. However, care should be taken in making this decision. The reading should be substantially lower than that shown in the service data—about half as much in this case. Since there is a variation in part values among pieces of equipment, test values on a diagram are representative only of those found in most equipment of the same model. However, the equipment readings should be within a few per cent of those specified. If the output of the vertical section reads low in this example, Step 3 would be successfully concluded.

If the reading is very close to normal, your conclusion must be that the vertical and horizontal functions are probably not at fault. If the oscilloscope test produced these results, what should you do next? Revert to Step-2 procedures; trace out all probable faulty functions, and then apply the new information you have learned.



In re-evaluating your symptom information on the Step-2 level, you find:

1. Good sound and picture image, therefore power-supply voltages must be correct.
2. Horizontal width of the picture on the screen seems proper, so that portion of the circuit can be assumed to be good.

3. The verifying test showed that the vertical output was operating as it should. Frequency, shape, and amplitude of the sawtooth output appeared good.

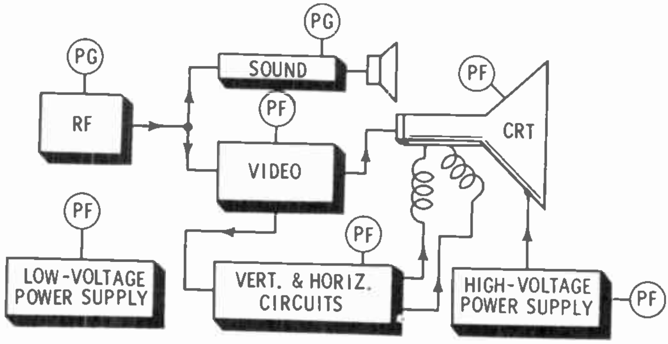
Since deductions and tests show that all other functions are good, the possibility is very strong that the fault is in the vertical-deflection coil, since this is the only remaining part that has any control over the height of the picture.

Now apply Step 3 to a more difficult TV malfunction. This is what you might write down for the first two steps:

STEP 1. **Symptoms**—Sound is good, but weaker than normal. The screen is blank; there is no picture or raster (horizontal lines on the screen when station is not on the air). The adjustment of contrast, brightness, vertical, horizontal, and fine-tuning controls makes no change. Moving the channel-selector switch to other stations has the same results.

STEP 2. **Deductions**—Sound and RF functions are probably good. The low-voltage power supply might be good, since the sound circuits are operating. However, the power supply might be providing just enough voltage for sound and RF, but the output is too low for one or more of the other functions. All the other functions—video, CRT, high-voltage power supply, and horizontal and vertical circuits—are probable causes of trouble.

In the functional block diagram of the TV receiver shown below, the suspected functions are marked with PF (probably faulty), and the unsuspected, with PG (probably good).



Five functions are suspected as being probably faulty. In which order should they be tested to arrive at a Step-3 conclusion (exposure of the single faulty function)?

Three rules should be applied in answering this question. **First,** make only those tests that are safe to make. **Second,** make the tests in the order of least difficulty. One that requires dismantling a section of the equipment is an example of a difficult test. **Third,** test those functions first that will eliminate one or more of the other functions considered probably faulty. Those that are equal in terms of these rules become a matter of personal choice in the testing sequence. A good sequence of function tests is the following:

1. Vertical and horizontal circuit function—This is selected first because if it were operating properly a raster would be present on the screen, whether the video function is sending sync signals to it or not. Under the conditions of a completely blank screen, there is neither a vertical nor a horizontal output, if this is the faulty function. If the function checks to be good with an oscilloscope test of the two outputs, the low-voltage supply is considered good. Sufficient voltage is being applied to operate the sync function.

2. Video function—Although the output of the video function could not be responsible for the missing raster, the function is worth testing. Video output to the CRT is checked for proper values of image and blanking pulse, and the output of the sync function is measured for sync pulses.

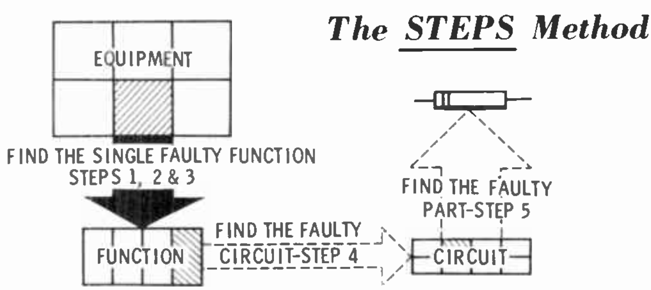
3. Cathode-ray tube—The CRT should be checked before the high-voltage power supply. By looking down into the base of the tube you can determine whether the heater is working. If it is, there will be a bright glow. Also check for gas. This is determined by a bluish glow within the neck of the CRT. A small blue cloud near the base, although not desirable, will have little effect on the beam and does not explain a blank screen.

4. High-voltage power supply—If all the preceding functions have been tested and rated as probably good, the high-voltage power supply could be exposed as the single

faulty function by default. A review of the symptoms and test results makes this a logical deduction. If high voltage is missing from the CRT, the electron beam will not reach the screen. As a result, neither a raster nor a picture will appear.

Review of Steps 1, 2, and 3

The STEPS procedure has been three-fifths completed. The approach has quickly narrowed the trouble to a single function among several by making logical technical deductions on the basis of accumulated data.



STEP 4. PICK OUT THE FAULTY CIRCUIT

The narrowing-down process continues in the fourth step by working toward the faulty circuit within a functional group. The procedure is carried out by making technical deductions from accumulated symptom and test data. These deductions result from studying the servicing block diagram and then closing in on the malfunctioning circuit.

The Servicing Block Diagram

This is a diagram that you have used many times in this volume. It consists of individual blocks representing each circuit within the functional group. The blocks are interconnected to show the direction of signal flow, and input and output test points are indicated. Some servicing block diagrams include waveform data at significant points within the diagram.

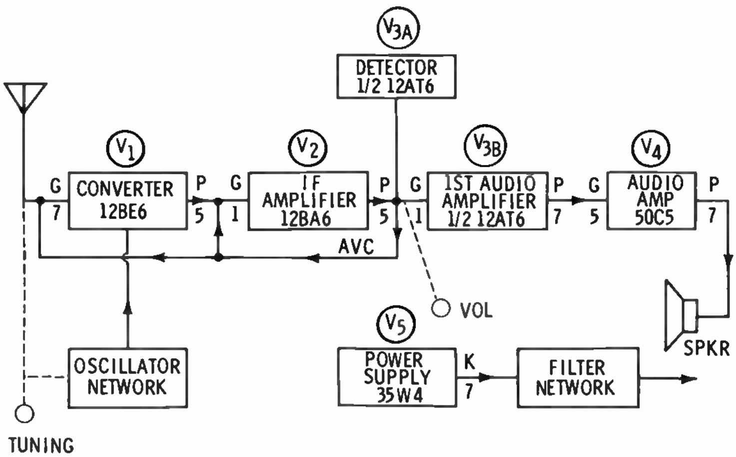
Q9. Testing which TV receiver function would violate the rule: "make only those tests that are safe"?

Your Answer Should Be:

A9. The **high-voltage power supply** would be unsafe to test. The output could be as high as 30,000V.

Quite often, the equipment you will be troubleshooting may not have a servicing block diagram. The schematic diagram can be used instead. However, until you become accustomed to visualizing the schematic of individual circuits as a simple functional block without the distracting influence of its parts, you should draw your own block diagram.

A complete servicing block diagram for a radio receiver is shown below.



With waveforms shown between stages and input and output tests points identified, a servicing block diagram can be used for isolating a faulty circuit. In the above diagram, V_1, V_2 and V_{3A} are included in the RF function, and V_{3B} and V_4 in the audio function. V_5 is the power-supply tube.

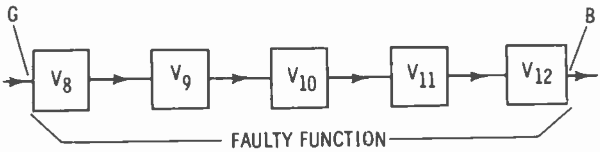
Closing-in Procedure

When picking out the faulty circuit in Step 4, it is neither desirable nor necessary to check the inputs and outputs of each circuit contained in the faulty function. Some functions may have two or three, and others a dozen or more, stages. Finding the faulty circuit with a minimum number of tests is accomplished by using a **closing-in,** or **bracketing,** process.

When working from a servicing block diagram that contains the faulty function identified in Step 3, enclosing indicators are placed at the inputs and outputs of the functional group. These can be pencil marks as shown below, or they can be small weights to eliminate damage from repeated erasures. You can even depend on your memory for locating and recalling the enclosing marks. A G (good) mark at the input(s) indicates that this point has been tested and found to be satisfactory. A B (bad) mark at the output(s) indicates a test has revealed the output waveform is improper or nonexistent.

Linear Circuits

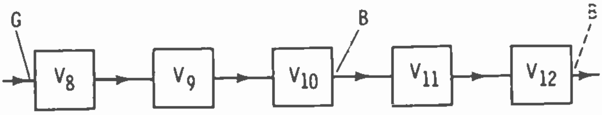
The diagram shows circuits following each other in a line. Such an arrangement is known as a **linear signal path.** Marks



on the diagram show a good input and a bad output. The concept of Step 4 is to isolate the one faulty circuit among the five with the fewest tests.

To minimize the number of circuit tests required, the first check with the oscilloscope is made at either the input or output of V_{10}. V_{10} is the middle tube in the group; a good or a bad indication eliminates the necessity of checking about half of the circuits. It is usually acceptable to check the output of V_9 or the input of V_{11}, since the waveforms at these points are essentially the same as the input or output of V_{10}, respectively.

This procedure of dividing a linear string of circuits for testing purposes is known as the **half-split method.** If the test is made at the output of V_{10} and reveals an improper or nonexistent waveform, the bad indicator should be moved to that point.

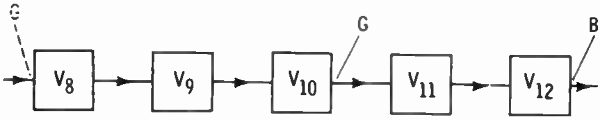


Q10. What is the concept of Step 4?

Your Answer Should Be:

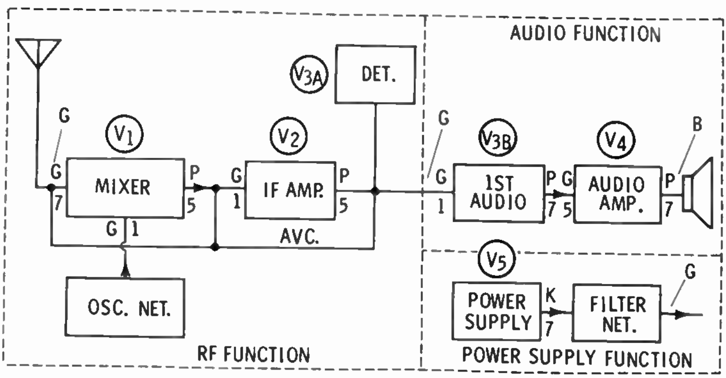
A10. The concept of Step 4 is to **isolate the one faulty circuit** among the many in the suspected function.

The faulty circuit is now located between the input of V_8 and the output of V_{10}. If the scope test is properly made, V_{11} and V_{12} are considered good. If the test reveals a proper waveform, the **good** mark is moved as shown below. With the **good** mark at the output of V_{10}, circuits V_8 through V_{10} are no longer suspects; the faulty circuit is thus V_{11} or V_{12}.



By moving either the **good** or **bad** mark, depending on the result of the test, the faulty circuit is restricted to a smaller enclosure. By half-splitting again between the new G and B marks, the enclosure is made even smaller. In the second example, a test at the output of V_{11} identifies the faulty circuit. Depending on the results of the test, G or B is moved to that point, and either V_{11} or V_{12} is pinpointed as the faulty circuit.

Take a dead receiver as a practical example. The only symptoms obtained in Step 1 are no sound output or electrical power reaching the power supply. In Step 2 all functions are listed as probables. Step 3 reveals the following information.



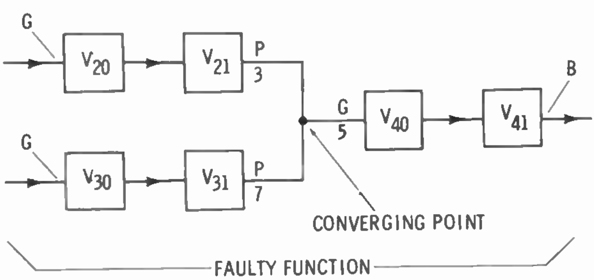
Good test indications are made at the input of V_1, the input of V_{3B}, and the output of the filter network in the power supply. A bad test is identified at the speaker input.

The audio function is therefore suspected of being faulty. The first test of Step 4 should be made at the grid (pin 5) of V_4 or the plate (pin 7) of V_{3B}.

Convergent Circuits

There are circuit combinations other than linear. One of these is called **convergent.** As the name implies, a convergent circuit is one in which the outputs of two or more circuits converge (join) to feed a single circuit.

CONVERGENT CIRCUIT



The diagram above shows the test results of Step 3. Inputs to both channels of the function are good, but the single output is bad. The decision of where to make the first Step-4 test depends on the nature of the bad output.

First, assume that there is no output signal of any kind. After checking the function of V_{40}, it is learned that this circuit does not operate unless the outputs of both channels are received. This is called a **gating** circuit. To minimize the number of tests, where should the first check be made?

The first test should be made at the converging point. A waveform reading at the input of V_{40} will reveal the nature of the outputs from V_{21} and V_{31}. If both waveforms were there and of the proper shape, the G could be moved to the converging point, thus limiting the remainder of the search to V_{40} and V_{41}.

Q11. What is a convergent circuit?

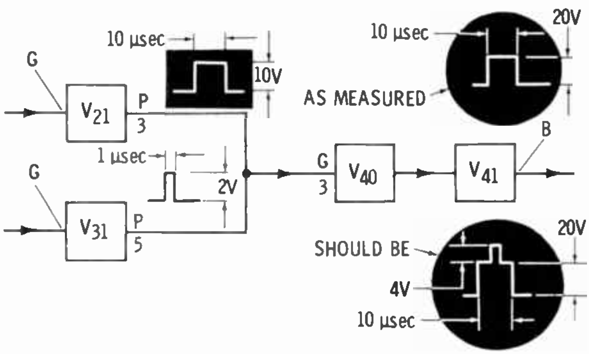
Q12. What is meant by gating?

Your Answers Should Be:

A11. A convergent circuit is one in which the **outputs of two circuits join at a point** to supply a signal to one subsequent stage.

A12. Gating refers to certain circuits that have **one output but two or more inputs.**

It is not probable that both output signals are missing or improper. Therefore, the check at the converging point, if not good, identifies which channel is bad. B is then moved to that output, reducing the number of faulty circuits to one. In cases where the convergent circuit passes either output signal as long as it appears on the grid, the approach to testing is a little different. Note these output waveforms:

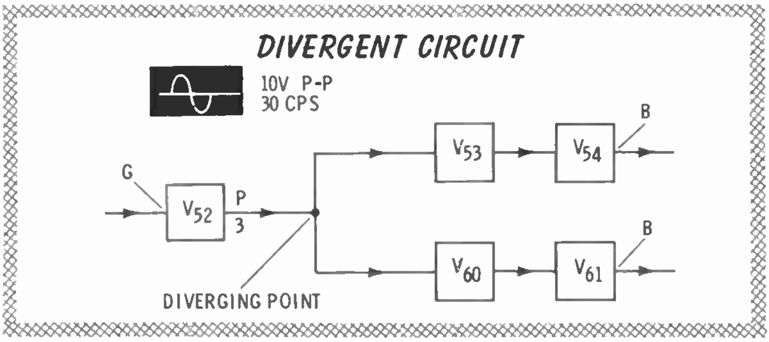


The first test should be made at the converging point (G_3 of V_{40}). A comparison of the two output waveforms—the measured waveform and the correct waveform—indicates that the 1-microsecond pulse is missing. A proper deduction shows that the small pulse does not leave V_{31}, therefore it is correct to make a test at the output of V_{31}.

If the above deduction is verified, B is moved to the output of V_{31}. A single circuit is enclosed, and Step 4 is satisfactorily completed. But, if the test is good, the lower G is moved to the converging point, leaving V_{40} and V_{41} as probables. It is already known that the square wave from V_{21} is passing through the complete functional group. One more test between V_{40} and V_{41} isolates the faulty circuit.

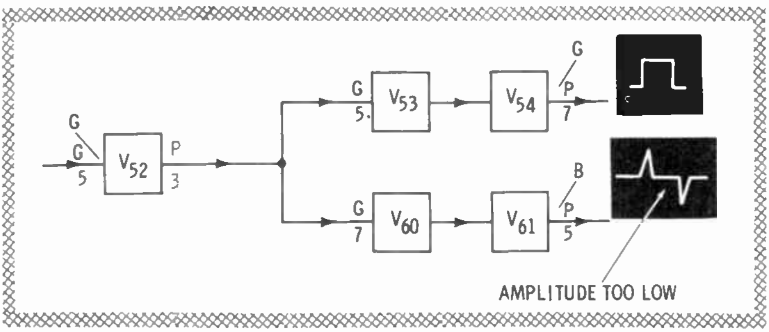
Divergent Circuit

A divergent circuit is the opposite of a convergent circuit: the output of a single circuit feeds into inputs of two or more other stages.



The illustration shows that the input to the divergent circuit (V_{52}) is good and that the output should be a 30-cps sine wave at 10 volts peak-to-peak. If the B indicates no output at either point, the first test should be made at the output (pin 3) of V_{52}. If there is no output at this point, enclose V_{52} with a G and a B, and Step 4 is concluded.

Suppose that the divergent circuit conditions were the following. Actual measured waveforms are shown at the appropriate points as a result of Step-3 testing.



Q13. What are the operating conditions of V_{53} and V_{54}?

Q14. Is V_{52} in good or bad operating condition?

Q15. Based on the conditions shown in the diagram, where should the first Step-4 test be made?

Your Answers Should Be:

A13. The output G of that channel indicates that V_{53} and V_{54} are **operating properly.**

A14. Since the output of V_{54} is a good signal, V_{52} is probably in **good** operating condition.

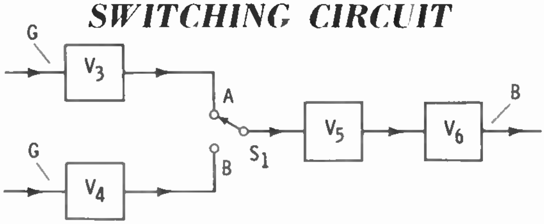
A15. The first Step-4 test should be made at the **output of V_{60}** or the **input of V_{61}.**

If the test mentioned in A15 is favorable, the G is moved up, and V_{61} is enclosed with a G and a B. If the test requires that a B be moved to the output of V_{60}, a second test at this input encloses either V_{60} or V_{52} as the faulty circuit. If it is found that V_{52} is producing the improper waveform, then the G analysis of the square-wave output from V_{54} is not very accurate, or the faulty output of V_{52} is sufficient as an input to that channel.

Switching Circuits

In many types of equipment, two or more circuits or channels may be switched individually to another channel.

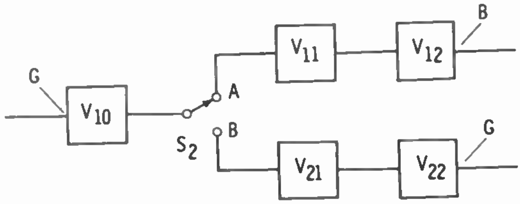
SWITCHING CIRCUIT



With switch S_1 in position A, Step-3 tests reveal good inputs to V_3 and V_4 but a bad output from V_6. The first test to make in Step 4 is a reading at the output of V_6 with S_1 in position B. If the reading is what it should be, V_5 and V_6 are good and the B can be moved to the output of V_3.

If the V_6 output is found to be bad, none of the enclosing marks can be moved, but additional information has been obtained about the probable location of the fault. It is improbable that both V_3 and V_4 would go bad simultaneously. This conclusion is verified by making the next test at the input of V_5. If, as suspected, the check is good, then either V_5 and V_6 is faulty, and the obvious enclosing test is made.

The switching-circuit channels also appear in reverse order, such as a single channel capable of being switched into one of two or more channels.

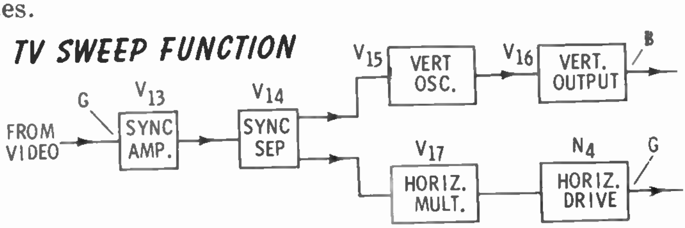


In the diagram above, when S_2 is switched to position B, the conditions indicate that V_{10}, V_{21}, and V_{22} are good. This leaves V_{11} and V_{12} in the circuit group as the only suspects. The quickest way to determine which is bad is by testing between them.

These are the typical circuit combinations that you will encounter while troubleshooting. You have seen that by combining technical knowledge with common sense, the number of enclosing tests to isolate a faulty circuit in a functional group can be kept at a minimum.

Enclosing a TV Receiver Function

Assume that the vertical and horizontal function of a TV receiver has proven to be faulty. Circuit conditions are shown below. Horizontal- and vertical-sync pulses appear at the grid of V_{13}, where they are amplified. The sync separator separates the vertical-sync pulses from the horizontal-sync pulses.



The vertical and horizontal channels generate waveforms of the proper frequency, shape, and amplitude to cause the electron beam in the CRT to sweep the required horizontal lines on the screen. Oscillations continue whether sync pulses are received or not. This is the reason for the raster appearing on the screen when a station is not tuned in.

The purpose of the sync pulses is to time the start of each line with corresponding events in the TV camera. If this were not done, the picture on the screen would be greatly distorted and unrecognizable.

The symptom noted in Step 1 of the troubleshooting procedure was a thin horizontal line across the face of the screen. Sound was good, and the condition repeated itself on all channels.

Steps 2 and 3 earmarked the vertical and horizontal function as being faulty. In the testing process, the input of sync pulses to V_{13} appeared good. So did the output of the horizontal channel. (N_4 is a network of capacitors and resistors that sharpen the shape of the waveform.) There is no measurable waveform at the output of V_{16}. Appropriate enclosure marks are shown on the diagram.

V_{13} and V_{14} are apparently operating properly in accordance with the tests shown. At least the horizontal portion of V_{14} appears to be good. The first test should be made at the input to V_{15}. This allows the G or B to be moved to that point, depending on test results. From there, only one more test must be made to isolate the single faulty circuit. If the input to V_{15} or the corresponding output from V_{14} is good, the next test should be made at the V_{15} output or V_{16} input.

Step 4 Review

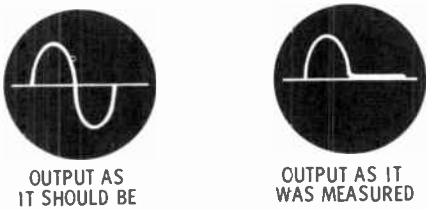
When picking out the faulty stage of a circuit group, symptoms and data from the first three steps are used in making deductions from a study of a servicing block diagram. Enclosure marks employing pencil, weights, or memory are placed at function inputs and outputs to show whether previous tests were good or bad. The enclosure marks are moved in accordance with circuit input or output tests made as the result of a technical and common-sense analysis of the circuit types, which are linear, convergent, divergent, or switching.

STEP 5. SEEK OUT AND VERIFY THE CAUSE OF THE TROUBLE

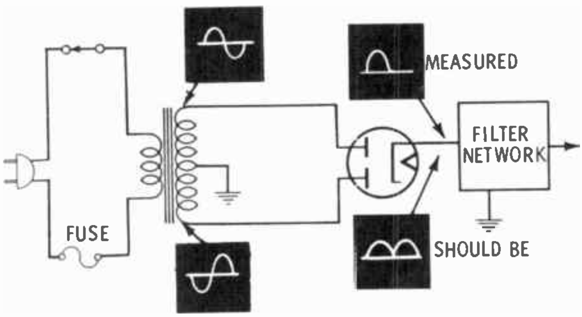
The troubleshooting procedure thus far has narrowed the trouble to a single circuit, consisting of a few electronic parts. The **seek-out** portion of the final step suggests that the faulty part be found and verified as the cause of the trouble symptoms.

Analyzing the Output Waveform

The trouble can be narrowed down by analyzing the output waveform of the circuit, making voltage or resistance checks, and/or substituting a good part for one that is suspected of being bad.



Comparing the output waveform actually measured against that of the proper waveform often provides clues as to the location and/or cause of the trouble. The above illustration, for example, shows the good and bad outputs of an amplifier. From your knowledge of how an amplifier circuit works, the trouble seems to be in the grid or cathode sections. Thus, examine that portion of the circuit.



Shown above is a faulty full-wave rectifier circuit with measured input and output waveforms. The proper output waveform is also included. Half of the output cycle is missing. A study of the schematic diagram and the waveforms reveal that you should concentrate your search in the lower plate section of the diode.

Q16. What does Step 4 enable you to do?

Q17. What is the purpose of Step 5?

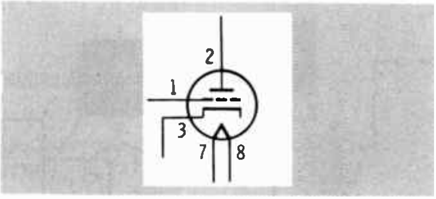
Your Answers Should Be:

A16. Step 4 enables you to determine in **which circuit** of the equipment the malfunction is located.

A17. Using Step 5, you can find the **component** that is causing the trouble in the suspected circuit.

This type of waveform analysis in most cases will help you limit your search to a small area of a circuit. Of equal or even greater importance, a knowledge of the nature of the distortion in an improper waveform will assist you in verifying that the located fault is the actual cause of the trouble.

Making Voltage and Resistance Checks—If an analysis of the output waveform provides a probable location, or if there is no waveform to be analyzed, the next procedure involves making voltage and resistance checks. Some schematics provide both voltage and resistance readings in chart form. If the measured values of a suspected part are not reasonably close to those indicated in the diagram or chart, you have narrowed down the trouble.



In nearly all examples the elements of a tube are marked with their pin numbers, as shown above. Transistor leads are identified by the elements shown in the schematic. A notation on the diagram identifies the type of instrument used in making the measurements. For example, DC voltage **measurements are taken with a 20,000-ohms-per-volt meter, and AC voltages with a 1,000-ohms-per-volt meter.**

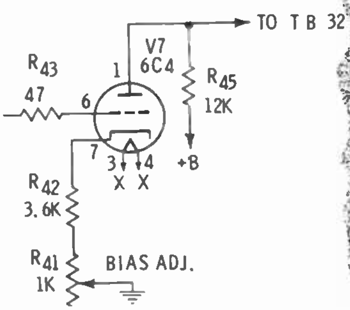
The diagram may also include the following notations:

Pin numbers are counted in a clockwise direction when viewed from the bottom of the tube socket.

Measured values are from pin socket to ground unless otherwise indicated.

Controls are set for normal operation.

Component values are given in ohms and micromicro-farads, unless otherwise stated.



ELEMENT	PIN NO.	VOLTAGE	RESIS-TANCE
PLATE	1	+250V	130K
FILAMENT	3	3.15VAC	0
FILAMENT	4	3.15VAC	0
GRID	6	+72V	80K
CATHODE	7	+76V	5K

It is generally better to take voltage readings first and resistance readings second, if they are required. If voltages are to be read at all pin numbers, it is best to take them in sequence of voltage values rather than pin numbers. For example, start with a high scale on the voltmeter and measure the pin having the highest voltage. In this case it would be the plate, pin 1. Use a scale that will permit a higher reading than the 250V shown; this will prevent damage to the meter in case the actual voltage is much higher. Next, measure pins 6 and 7, since they are supposed to have voltage values relatively close together. Finally, pins 3 and 4 can be measured on an AC voltage range.

If you are able to determine suspected sections of the circuit from an analysis of the improper output waveform, take voltage readings at these sections first. For example, if your deduction indicated that the waveform was being distorted by improper grid-to-cathode bias, these would be the pin voltages to check first. If the pin-6 measurement is the proper 72V but pin 7 is 80V, your deduction would be confirmed and the trouble fairly well isolated.

Q18. How would you determine which components are included in the resistance reading from pin to ground?

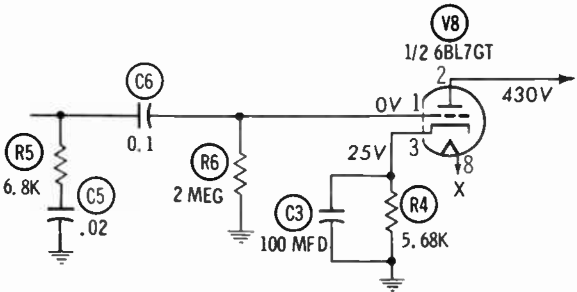
Q19. If you measured zero volts at pin 3 in the diagram, what would be your conclusion?

Your Answers Should Be:

A18. All the parts included in the resistance being measured from a pin to ground can be determined by **tracing them out on the schematic diagram,** making sure you will find all the parallel paths.

A19. If zero volts were measured on the heater pin, the conclusion would be that **voltage is not available at this pin.**

In another type of presentation for voltage and resistance readings, voltages are placed near the tube elements, and resistance measurements are shown in chart form.



RESISTANCE MEASUREMENTS

STAGE	TUBE	PIN 1	PIN 2	PIN 3	PIN 4	PIN 5	PIN 6	PIN 7	PIN 8
V8	6BL7GT	2 MEG	3.5K	920	2.4 MEG	2.6 MEG	0	0	0.1

As in the previous example, part numbers and their values are shown on the schematic. If the trouble is isolated to one section of the circuit, the individual parts can then be measured. If, for example, something other than 25V and 920 ohms were read from pin 3 to ground, either C_3 or R_4 would be suspected of causing the trouble.

If R_4 is to be measured, one of the capacitor leads must be separated from the resistor. Otherwise, if ohmmeter test leads were placed across the resistor, they would still measure the parallel resistance of the two parts. In this case a capacitor lead could be unsoldered from ground or the tube-socket pin. If R_4 does not measure close to 5.68K, it may be the cause of the trouble.

Part Substitution

It is often necessary to substitute a known good part for one suspected of being faulty. C_3 in the example on the opposite page could be such a case. Replacing it with a new capacitor of the same value will confirm whether it is good or bad. The same reasoning applies to other parts, including tubes and transistors. As you recall from a preceding chapter on tube testers, one of the only valid methods of checking a faulty tube is by substituting a good one.

Verifying the Cause

Although a faulty part can actually be located by the preceding methods, Step 5 is not completed. The nature of the fault must be compared with and verified by the trouble symptoms obtained in preceding steps. If an open resistor, shorted capacitor, weak tube, etc., adequately explains the improper waveforms and trouble symptoms, then you can feel reasonably sure that you have found the cause of the trouble and can make the necessary repair.

However, if the nature of the trouble does not substantiate the distorted waveforms or other trouble symptoms, you have not found the faulty component or, in some cases, you have found only one of the faulty components. For example, a slight change in the value of a plate resistor does not explain the loss or flattening of a half cycle in an amplified sine wave.

The faulty component you have isolated may have been the result of a fault in another part of the circuit or even in an adjacent circuit. The narrowing-down procedure may have uncovered a cathode resistor whose measured resistance deviates greatly from its rated value. In addition, if the resistor is badly charred it is evident that the resistor has been passing an excessive amount of current. The cause could have been a gradual decrease in resistance over a period of time, allowing more and more current to pass until the charred condition resulted. However, the increase in current could also have been caused by a faulty component in another part of the circuit. A decrease in the plate or screen resistance would also cause excessive current to flow and damage the cathode resistor.

If, in such a case, the cathode resistor were replaced without verifying the cause of the trouble, the same trouble symptoms would repeat themselves after a period of time. Always verify that the isolated fault explains the trouble symptom(s) and that it is the actual cause of the malfunction.

Repair

You may have noted that the word **repair** was not included in the troubleshooting steps. Replacing a part, resetting an adjustment, or restoring a connection is actually not a part of troubleshooting. Troubleshooting includes all the processes required to isolate the faulty condition. Once the trouble is found and verified, then the repair can be made.

WHAT YOU HAVE LEARNED

1. Troubleshooting is the process of locating a fault in a piece of equipment.
2. To become a good troubleshooter, you must:
   (a) Know enough about electronic principles to use them in determining how equipment operates.
   (b) Know enough about the use of test equipment to make and interpret test readings properly.
   (c) Know enough about electronics to extract desired information from a technical manual or service folder.
   (d) Know enough about the logical troubleshooting procedure, **STEPS**, to apply it well.
3. A good method of troubleshooting is a systematic, orderly process called logical troubleshooting.
4. The logical troubleshooting procedure consists of five parts. The initial letters of these parts spell the word **STEPS**.

   STEP 1. Search for all trouble symptoms.

   STEP 2. Trace out all probably faulty functions.

   STEP 3. Expose the single faulty function.

   STEP 4. Pick out the faulty circuit.

   STEP 5. Seek out and verify the cause of the trouble.

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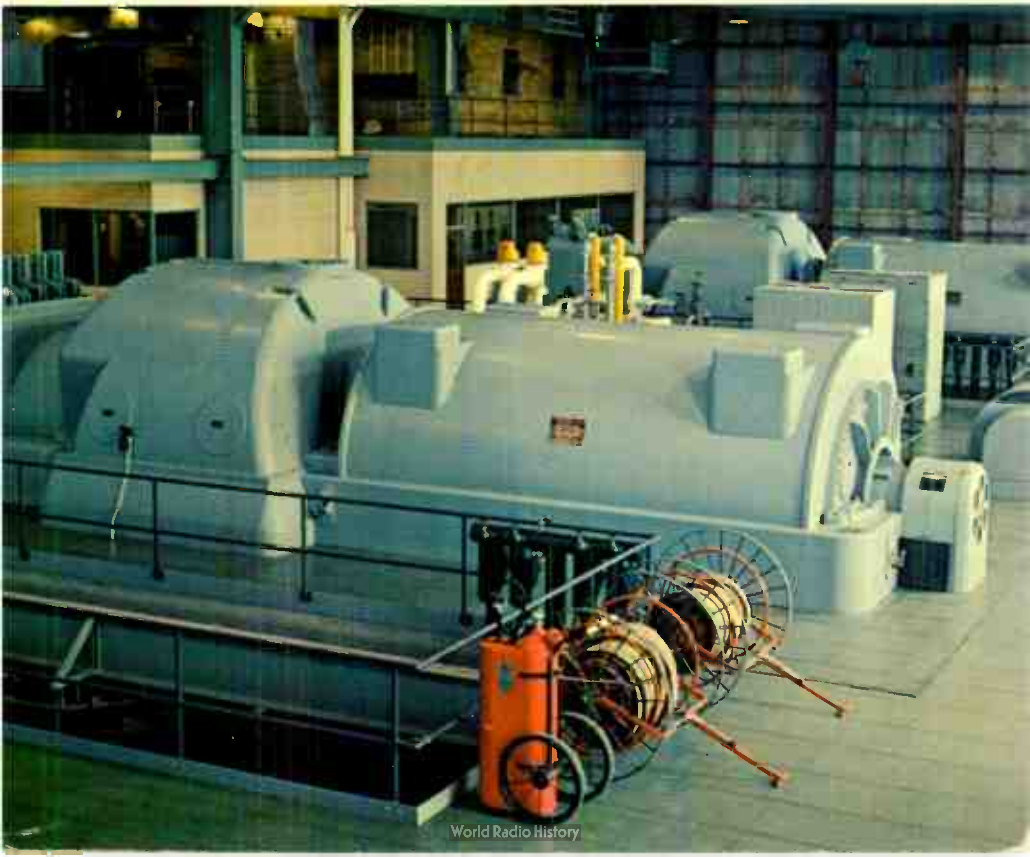

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MOTORS & GENERATORS— HOW THEY WORK

By Training & Retraining, Inc.

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SEYMOUR D. USLAN, *Editor-in-Chief,*
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Introduction

This volume, the fifth and last in the series, is concerned with the principles of AC and DC motors and generators. The text is designed to provide the reader with a sound understanding of the fundamentals of motors and generators. The characteristics of each type of machine are presented so that the student can relate each type to actual applications. In this way, reader interest is maintained, and the information presented is of practical value.

WHAT YOU WILL LEARN

You will be shown how the operation of motors and generators depends on the basic electrical principles you have already learned. You will see how these principles are put to work to perform specific tasks with electrical machines.

First you will be introduced to the ways in which mechanical energy can be transformed into electrical energy, and vice versa. Such terms as commutator, slip rings, torque, left-hand rule, brush, armature, and many others are explained.

DC generators are discussed in detail. Construction details are given, including bearings, armature cores, etc. Wave windings as well as simplex, duplex, and triplex lap windings are explained. The characteristics of separately excited, shunt, series, and compound generators are described, along with losses (copper loss, eddy-current loss, and hysteresis loss). You will learn about armature reaction and the methods used to counteract it. The methods of paralleling DC generators are given, and maintenance techniques are described.

You will learn that DC motors are similar in construction to DC generators. Counter emf and armature reaction are discussed in addition to the characteristics of shunt, series, and compound motors. Several types of DC motor starters are covered, and the most common methods of motor speed control are listed.

The text on AC generators explains synchronous, induction, single-phase, and polyphase types. Armature reaction, frequency control, and voltage regulation are discussed. Methods of connecting several AC generators in parallel are described.

The application of three-phase electromagnetic fields to motor operation is explained. You will learn about polyphase synchronous and induction motors. You will also learn about several types of single-phase motors, including shaded-pole, split-phase, capacitor, repulsion, repulsion-induction, and universal motors.

The generation and distribution of electrical power by three-phase systems along with the relationships of voltage, current, and power in both wye- and delta-connected systems are described.

You will learn about devices used to convert electric power from one form to another (AC to DC, DC to DC of a different voltage, etc.). Finally, you will learn about servo control systems. Open and closed servo systems, servomotors, AC and DC servo amplifiers, and synchromechanisms are included in this discussion.

WHAT YOU SHOULD KNOW BEFORE YOU START

Before you study this book, it is essential that you have a good background in the principles of electricity and electronics, including the fundamentals of tube and transistor circuits and test equipment. This background can be obtained by studying the first four volumes of this series. With the proper background, however, you should have no trouble understanding this text. All new terms are carefully defined. Enough math is used to give precise interpretation to important principles, but if you know how to add, subtract, multiply, and divide, the mathematical expressions will give you no trouble.

WHY THE TEXT FORMAT WAS CHOSEN

During the past few years, new concepts of learning have been developed under the common heading of programmed instruction. Although there are arguments for and against each of the several formats or styles of programmed textbooks, the value of programmed instruction itself has been proved to be sound. Most educators now seem to agree that the style of programming should be developed to fit the needs of teaching the particular subject. To help you progress successfully through this volume, a brief explanation of the programmed format follows.

Each chapter is divided into small bits of information presented in a sequence that has proved best for learning purposes. Some of the information bits are very short—a single sentence in some cases. Others may include several paragraphs. The length of each presentation is determined by the nature of the concept being explained and the knowledge the reader has gained up to that point.

The text is designed around two-page segments. Facing pages include information on one or more concepts, complete with illustrations designed to clarify the word descriptions used. Self-testing questions are included in most of these two-page segments. Many of these questions are in the form of statements requiring that you fill in one or more missing words; other questions are either multiple-choice or simple essay types. Answers are given on the succeeding page, so you will have the opportunity to check the accuracy of your response and verify what you have or have not learned before proceeding. When you find that your answer to a question does not agree with that given, you should restudy the information to determine why your answer was incorrect. As you can see, this method of question-answer programming insures that you will advance through the text as quickly as you are able to absorb what has been presented.

The beginning of each chapter features a preview of its contents, and a review of the important points is contained at the end of the chapter. The preview gives you an idea of the purpose of the chapter—what you can expect to learn. This helps to give practical meaning to the information as it is presented. The review at the completion of the chapter summarizes its content so that you can locate and restudy those areas which have escaped your full comprehension. And, just as important, the review is a definite aid to retention and recall of what you have learned.

HOW YOU SHOULD STUDY THIS TEXT

Naturally, good study habits are important. You should set aside a specific time each day to study in an area where you can concentrate without being disturbed. Select a time when you are at your mental peak, a period when you feel most alert.

Here are a few pointers you will find helpful in getting the most out of this volume.

1. Read each sentence carefully and deliberately. There are no unnecessary words or phrases; each sentence presents or supports a thought which is important to your understanding of electricity and electronics.

2. When you are referred to or come to an illustration, stop at the end of the sentence you are reading and study the illustration. Make sure you have a mental picture of its general content. Then continue reading, returning to the illustration each time a detailed examination is required. The drawings were especially planned to reinforce your understanding of the subject.

3. At the bottom of most right-hand pages you will find one or more questions to be answered. Some of these contain "fill-in" blanks. Since more than one word might logically fill a given blank, the number of dashes indicates the number of letters in the desired word. In answering the questions, it is important that you actually do so in writing, either in the book or on a separate sheet of paper. The physical act of writing the answers provides greater retention than merely thinking the answer. Writing will not become a chore since most of the required answers are short.

4. Answer all questions in a section before turning the page to check the accuracy of your responses. Refer to any of the material you have read if you need help. If you don't know the answer even after a quick review of the related text, finish answering any remaining questions. If the answers to any questions you skipped still haven't come to you, turn the page and check the answer section.
5. When you have answered a question incorrectly, return to the appropriate paragraph or page and restudy the material. Knowing the correct answer to a question is less important than understanding why it is correct. Each section of new material is based on previously presented information. If there is a weak link in this chain, the later material will be more difficult to understand.
6. In some instances, the text describes certain principles in terms of the results of simple experiments. The information is presented so that you will gain knowledge whether you perform the experiments or not. However, you will gain a greater understanding of the subject if you do perform the suggested experiments.
7. Carefully study the review, "What You Have Learned," at the end of each chapter. This review will help you gauge your knowledge of the information in the chapter and actually reinforce your knowledge. When you run across statements you don't completely understand, reread the sections relating to these statements, and recheck the questions and answers before going to the next chapter.

This volume has been carefully planned to make the learning process as easy as possible. Naturally, a certain amount of effort on your part is required if you are to obtain the maximum benefit from the book. However, if you follow the pointers just given, your efforts will be well rewarded, and you will find that your study of electricity and electronics will be a pleasant and interesting experience.

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1

Understanding Basic Principles

What You Will Learn

In this chapter you will learn about the basic principles of motors and generators. You will learn how generators convert mechanical energy into electrical energy. You will find that generators can provide an AC or DC output depending on whether the generated current is taken from the generator through slip rings or a commutator. You will also learn how AC and DC motors convert electrical energy into mechanical energy.

SOURCES OF ELECTRICITY

Earlier you learned that electrical energy is usually supplied by batteries or electrical power plants. Batteries are generally used where portability is desired and small amounts of current are needed. The voltage and current that can be developed by one cell are small. To increase the voltage, a number of cells must be connected in series. To increase the current capacity, either the cell must be made larger, or a number of cells must be connected in parallel. A battery that supplies both high current and high voltage is bulky and expensive.

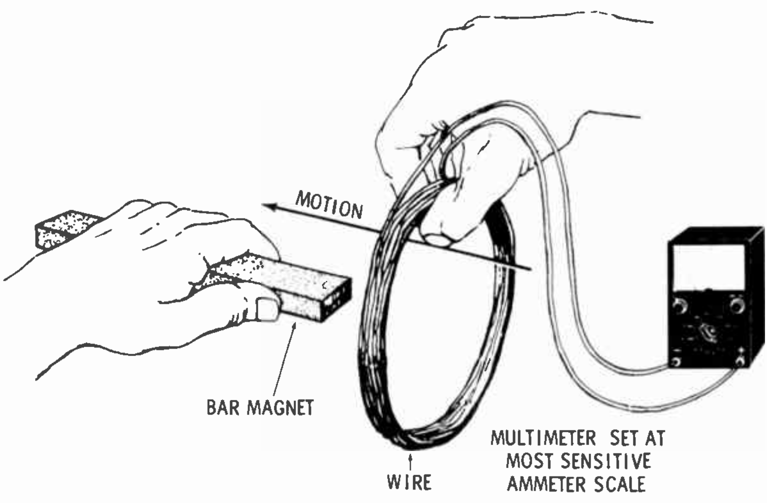
A voltage drop occurs when DC is transmitted over long distances, so batteries must be located near the place where the electrical energy is used. Batteries are usually used when a portable source of small values of DC is needed.

PRODUCTION OF ELECTRICAL ENERGY

Large amount of electrical energy are usually supplied by **generators** in power plants. A generator is defined as **a machine that converts mechanical energy into electrical energy.**

Mechanical energy is converted into electrical energy by **induction.** The following example shows how a voltage is generated by induction. Your hand supplies mechanical energy to move the coil, and the multimeter detects the electrical energy produced.

GENERATING A VOLTAGE BY INDUCTION



If an electric conductor is moved through a magnetic field in such a way that it cuts the lines of force, a voltage is generated, or induced, in the conductor. The induced voltage is greatest when the conductor moves at right angles to the magnetic field, and is zero when the conductor moves parallel to the lines of force.

If the moving conductor is connected to a complete electric circuit, an electric current will flow in the conductor and the circuit. This means that the **mechanical energy** used in moving the conductor through the magnetic field is converted into **electrical energy** which moves the current through the circuit.

Factors Determining Voltage

The amount of voltage generated is determined by: (1) **The speed at which the conductor passes through the magnetic field.** Greater speed causes the conductor to cut more lines of force per second. (2) **The strength of the magnetic field.** A stronger field provides more magnetic lines of force. (3) **The number of loops of wire.** Each additional loop of wire increases the number of conductors in which a voltage may be induced. Since the loops are in series, the generated voltages in each are additive.

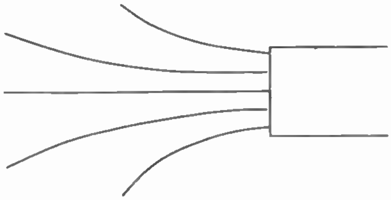
Conditions for Generating a Voltage

Voltage is generated by induction when a conductor is moved through a magnetic field, or when a magnetic field moves in relation to a stationary conductor in the field. In other words, **voltage is generated when a conductor and a magnetic field move relative to each other.**

In a generator the conductor can move, the field can move, or both can move. All of these possibilities as used in practical generators are discussed in this volume.

The amount of voltage induced in a conductor by a magnetic field depends, among other factors, on the distance between the magnetic pole and the conductor. When the distance between the magnetic pole and the conductor de-

FIELD STRENGTH IS GREATEST NEAR A POLE



creases, the magnetic field through which the conductor is moving is stronger. The conductor then cuts through more magnetic lines of force per given distance of movement, and a higher voltage is produced.

Q1. A generator converts mechanical energy into electrical energy by the principle of ---------.

Q2. The amount of voltage generated by induction increases as the ----- between the conductor and the magnetic pole increases.

Q3. Name three ways to generate an emf by induction.

Your Answers Should Be:

A1. A generator converts mechanical energy into electrical energy by the principle of **induction.**

A2. The amount of voltage generated by induction increases as the **speed** between the conductor and the magnetic pole increases.

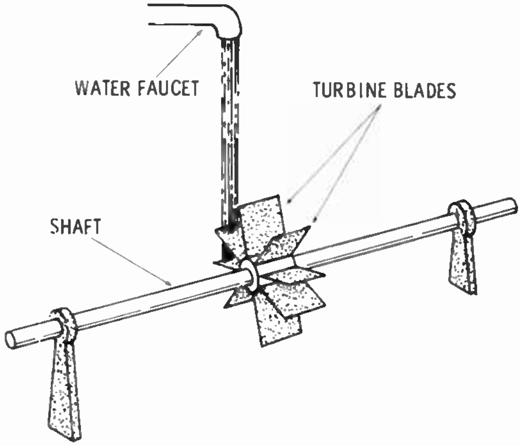
A3. Three ways to generate an emf by induction are:

1. **Moving a conductor through a stationary magnetic field.**
2. **Moving a magnetic field past a stationary conductor.**
3. **Moving a magnetic field and a conductor relative to each other.**

Transmission of Mechanical Energy to the Generator

Mechanical energy is usually transmitted to a generator by a shaft. When a coil, called the **armature,** is mounted on the shaft and the assembly is rotated in a magnetic field, an **emf** (voltage) is induced in the armature.

Energy from waterfalls, wind, tides, or high-pressure steam can be used to turn a **turbine** that will rotate the shaft. A turbine is a machine that converts water or steam pressure into rotation of a shaft.



A SIMPLE TURBINE

POWER-PLANT LOCATION

The location of power plants depends on the availability of a plentiful source of energy that can be used to rotate the generator shaft.

In steam power plants, high-pressure steam is directed against the blades of a turbine which rotates the generator shaft. Coal or oil is used to boil water and create the high-pressure steam. This type of power plant requires large amounts of water, as well as fuel, in order to produce steam.

Hydroelectric plants are located at the base of waterfalls or dams. Water flowing over the waterfall or released by the dam is directed against the turbine blades, causing the generator shaft to rotate.

WHAT IS A MOTOR?

Electrical energy produced by generators is used in many ways, but one of the most important is to turn motors that operate machinery and appliances.

A **motor** is a machine that converts **electrical energy** into **mechanical energy.** This definition is the inverse of the definition of a generator

When electrical energy is supplied to a motor, current flows through the armature. The current flow creates a magnetic field surrounding the armature. This field interacts with a stationary magnetic field. The interaction of the two magnetic fields creates a twisting force, or **torque,** that causes the shaft of the motor to rotate.

Q4. Name three methods that are used to turn a generator shaft.

Q5. When water or high-pressure steam is directed against the turbine blades, the generator shaft will ______.

Q6. What will happen if the force with which the water strikes the turbine blades is increased?

Q7. A twisting force is called ______.

Q8. A motor is a machine that converts ___________ ______ into ___________ ______.

Q9. A water wheel is a simple example of a _______.

Your Answers Should Be:

A4. Some methods that are used to turn a generator shaft are: **turbines** turned by water or high-pressure steam, **windmills**, and **gasoline or diesel engines.**

A5. When water or high-pressure steam is directed against the turbine blades, the generator shaft will **rotate.**

A6. If the force with which the water strikes the turbine blades is increased, the turbine will **rotate at a higher speed.**

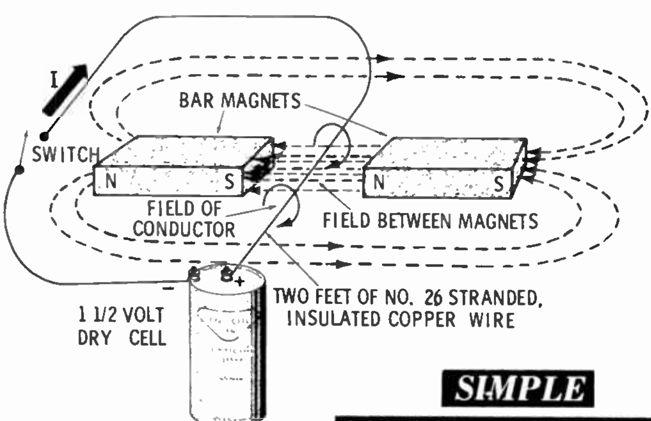
A7. A twisting force is called **torque.**

A8. A motor is a machine that converts **electrical energy** into **mechanical energy.**

A9. A water wheel is a simple example of a **turbine.**

Converting Electrical Energy Into Mechanical Energy

The following experiment demonstrates how forces are created in a motor. If you try the experiment, be careful not to close the switch until you are ready to observe the results. When you close the switch, you should do so for only a few seconds. This is because the battery is short-circuited when the switch is closed. If the switch is not

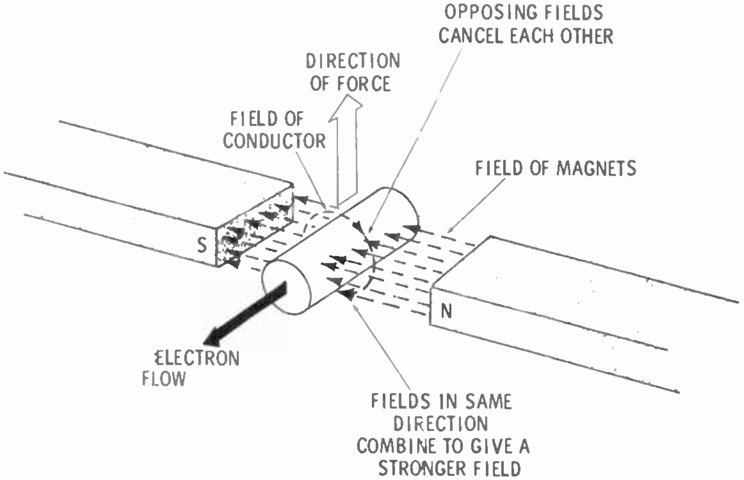


SIMPLE MOTOR PRINCIPLE

reopened quickly, the battery will be drained of its electrical energy. When the switch is closed, the conductor should jump. When the switch is opened, the conductor should return to its original position.

The conductor jumps from between the magnets when the switch is closed because a magnetic field is created by the flow of current through the conductor. The magnetic field around the conductor causes the main magnetic field to be strengthened on one side of the conductor and weakened on the other. This creates a force which pushes the wire away from the stronger part of the field.

CONDUCTOR IN A MAGNETIC FIELD



The direction of the magnetic field surrounding the conductor can be determined by applying the **left-hand rule** for straight conductors. Wrap the fingers of your left hand around the conductor so that your thumb points in the direction of electron flow through the conductor. Your fingers then show the direction of the magnetic field surrounding the conductor. External magnetic fields are considered to flow from the north pole to the south pole.

Q10. State the left-hand rule for straight conductors.

Q11. The difference in the strength of the magnetic field above and below the conductor results in a _____.

Your Answers Should Be:

A10. The left-hand rule for straight conductors is applied by wrapping the fingers of your left hand around the conductor so that your **thumb** points in the **direction of the electron flow.** Your **fingers** then show the **direction of the magnetic field surrounding the conductor.**

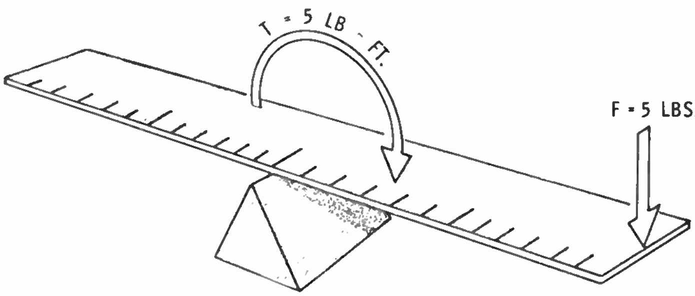
A11. The difference in the strength of the magnetic field above and below the conductor results in a **force.**

What Is Torque?

Torque (pronounced "tork") is a turning force. In a motor, the conductor is formed into a coil and placed on a shaft that is free to rotate. When current flows through the coil, a magnetic field is produced. This magnetic field around the coil reacts with the stationary magnetic field, developing a torque and causing the shaft to turn.

Torque is calculated by multiplying the force times the distance from the center of rotation. The illustration below shows a two-foot ruler balanced at its center. When a force

CALCULATION OF TORQUE

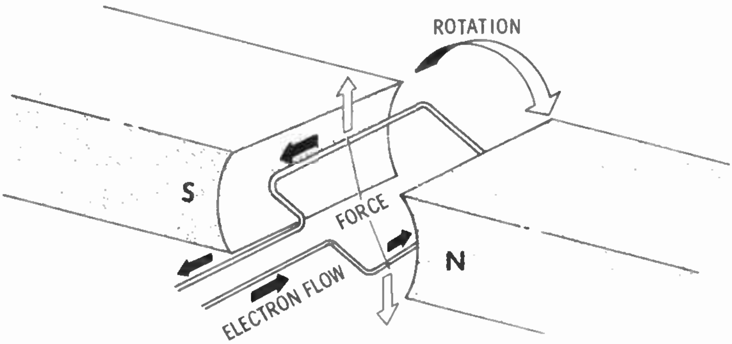


of five pounds is applied to the right end of the ruler, the resulting torque is calculated as follows:

$$\begin{aligned} \text{Torque} &= \text{Force} \times \text{Distance from center of rotation} \\ &= 5 \text{ pounds} \times 1 \text{ foot} \\ &= 5 \text{ pound-feet} \end{aligned}$$

Shown below is a coil that is free to rotate in a magnetic field. The flow of current out of the left side of the coil

PRODUCTION OF TORQUE



causes the magnetic field below the conductor to be strengthened and the field above to be weakened. This results in an upward force on the left side of the coil and a clockwise direction of rotation. The flow of current into the right side of the coil causes the magnetic field below the conductor to be weakened and the field above to be strengthened. This results in a downward force on the right side of the coil and a clockwise rotation.

The amount of torque generated depends on the strength of the two magnetic fields and on the distance of the sides of the coil from the center of rotation. The strength of the magnetic field around the coil depends on the number of turns in the coil, the current through the coil, the core material of the coil, etc.

Q12. If the ruler shown on the opposite page were six feet long and a force of ten pounds were applied to the right end, how much torque would be developed?

Q13. What factors determine the amount of torque on the coil shown in the figure on this page?

Q14. What factors determine the strength of the magnetic field around the coil shown in the figure at the top of this page?

Q15. Torque is calculated by multiplying ----- times the --------- from the center of rotation.

Your Answers Should Be:

A12. The torque developed is calculated as follows:

Torque = Force × Distance from center of rotation
= 10 pounds × 3 feet = **30 pound-feet**

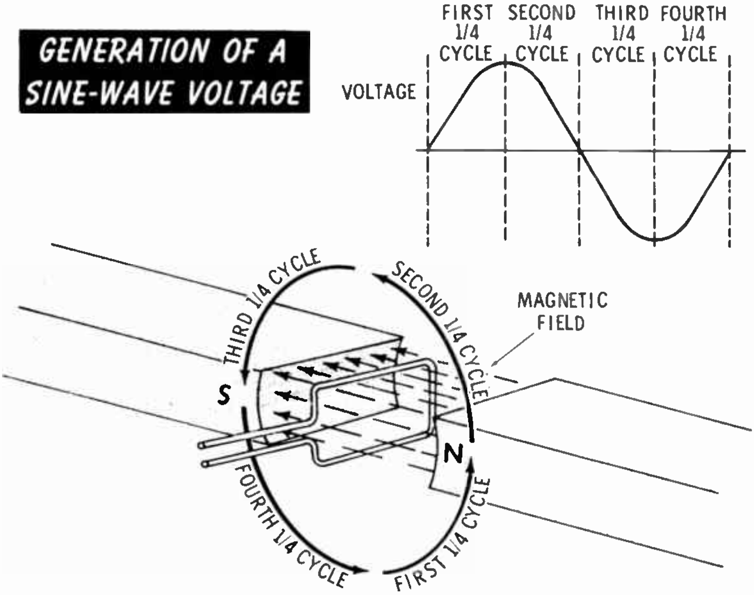
A13. The amount of torque on the coil shown on the preceding page is determined by the **strength of the two magnetic fields** and the **distance** of the sides of the coil **from the center of rotation.**

A14. The strength of the magnetic field around the coil depends on the **number of turns** in the coil, the **current** through the coil, and the **core material,** etc.

A15. Torque is calculated by multiplying **force** times the **distance** from the center of rotation.

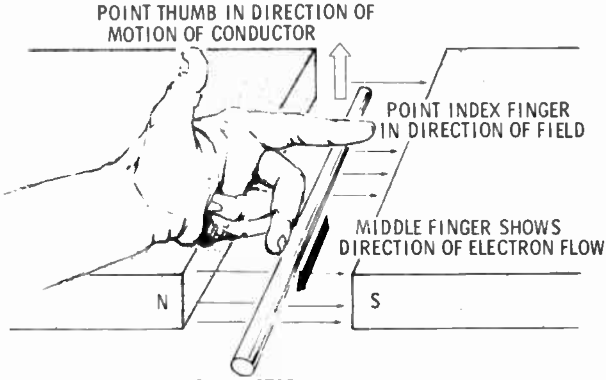
AC AND DC GENERATORS

The output from the armature coil of any generator is an AC voltage. As the coil shown below rotates at constant speed, it cuts more or fewer magnetic lines of force per sec-



ond, depending on its position at any particular instant. When it is moving at right angles to the magnetic field, it is cutting a maximum number of lines of force per second. Therefore, the voltage induced in the coil increases until, when the coil is moving at right angles to the field, the voltage is maximum. Then, as the coil continues to rotate, it cuts fewer and fewer lines of force per second until it is moving parallel to the magnetic field. At that point, no voltage is induced. In the third quarter cycle, the conductor cuts the lines of force in the opposite direction, so the induced voltage has the opposite polarity and again rises to a maximum. In the fourth quarter cycle, the voltage again decreases to zero.

LEFT-HAND RULE FOR GENERATORS



The **left-hand rule** for generators is shown above. This is an easy way of remembering the relationship between the direction of the magnetic field, the direction of motion of the conductor, and the direction of the induced current.

In a generator, the shaft rotation determines the direction that the conductor moves. The direction of the magnetic lines of force is from the north pole to the south pole. If the polarity of a magnet is unknown, it can be determined by using a compass. The south end of the compass needle will point to the north pole of the magnet.

Q16. A(an) __ voltage is induced in a rotating generator coil.

Q17. Describe the left-hand rule for generators.

Your Answers Should Be:

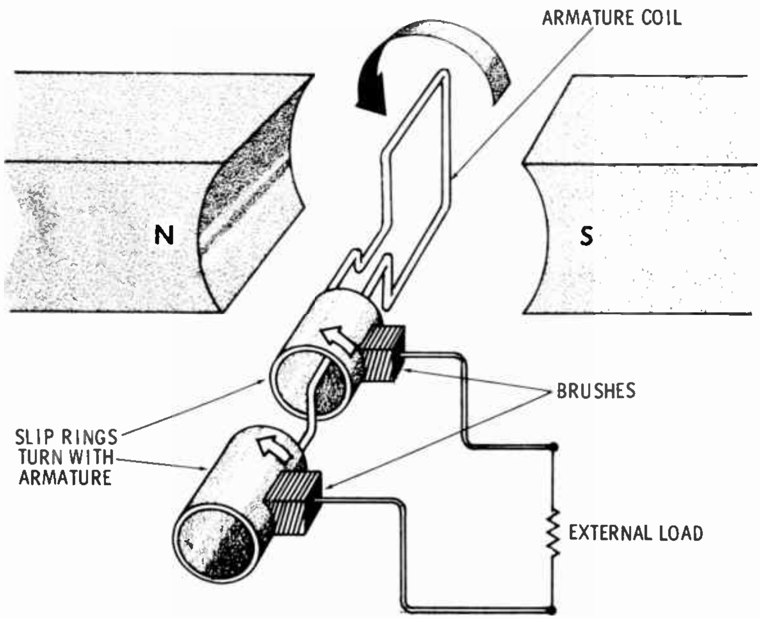
A16. An AC voltage is induced in a rotating generator coil.

A17. In the left-hand generator rule, the thumb, index finger, and middle finger of the left hand are held at right angles to each other. The **thumb** is made to point in the **direction of motion** of the conductor, and the **index finger** is made to point in the **direction of the magnetic** field. The **middle finger** will then point in the **direction of electron flow.**

The AC Generator

The output from the armature coils of any generator is AC. In order to take the AC output of the generator from

SIMPLE AC GENERATOR

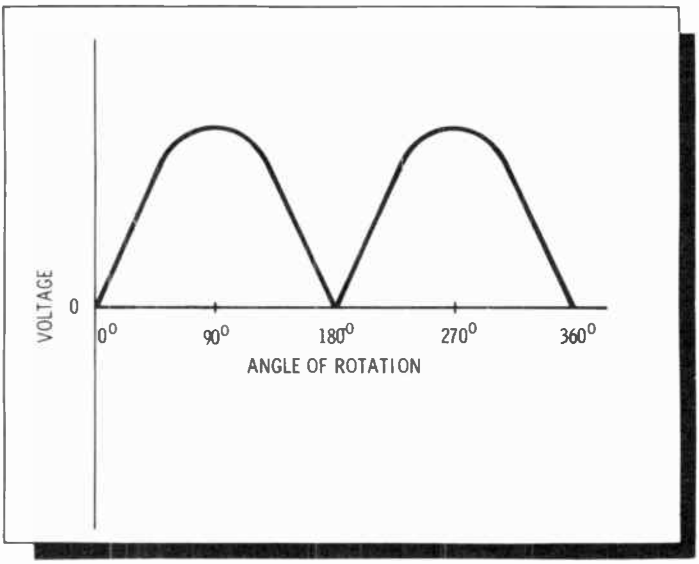


the armature coils, the ends of the coils are connected to **slip rings** which rotate with the armature. Stationary conductors called **brushes** provide a sliding contact on the rotating slip rings. In this way, the brushes and slip rings provide a connection between the armature coils in the generator and any external load that is being furnished power by the generator.

The DC Generator

In a DC generator, the AC output of the armature coils is converted to pulsating DC by the use of a **commutator** in the place of slip rings. The output of a basic DC generator is shown in the figure below. This pulsating DC output is

OUTPUT OF A BASIC DC GENERATOR



obtained because the connections to the armature coil are reversed every half cycle when the voltage is zero and is about to change polarity.

Q18. In an AC generator ____ _____ are used to take the output of the generator from the coils.

Q19. _______ are used to make a sliding contact on the rotating slip rings.

Q20. In a DC generator a __________ is used to convert the AC output of the armature coils into pulsating DC.

Your Answers Should Be:

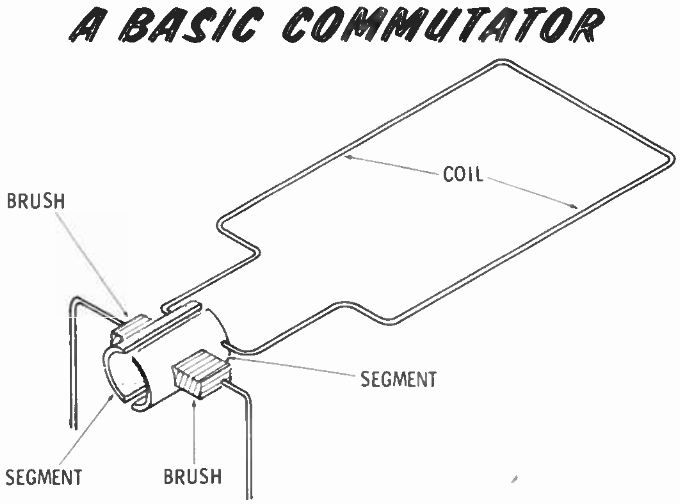
A18. In an AC generator **slip rings** are used to take the output of the generator from the coils.

A19. **Brushes** are used to make a sliding contact on the rotating slip rings.

A20. In a DC generator a **commutator** is used to convert the AC output of the armature coils into pulsating DC.

What Is a Commutator?

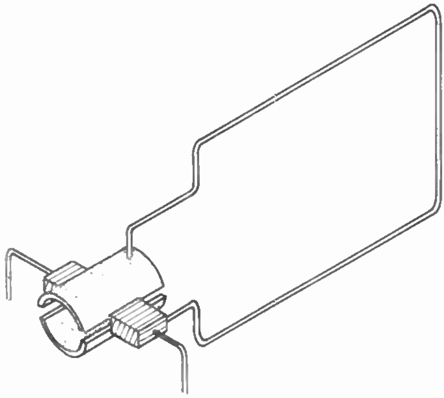
A basic commutator is simply a slip ring split into two semicircular halves, called **segments.** The segments are insulated from each other and from the shaft. One end of the armature coil is connected to one segment and the other end



of the coil is connected to the other segment. Two brushes touch opposite sides of the commutator. As the commutator turns, the two sides of the coil are short-circuited for a moment as the brushes touch both segments of the commutator at once. Then the connections are reversed.

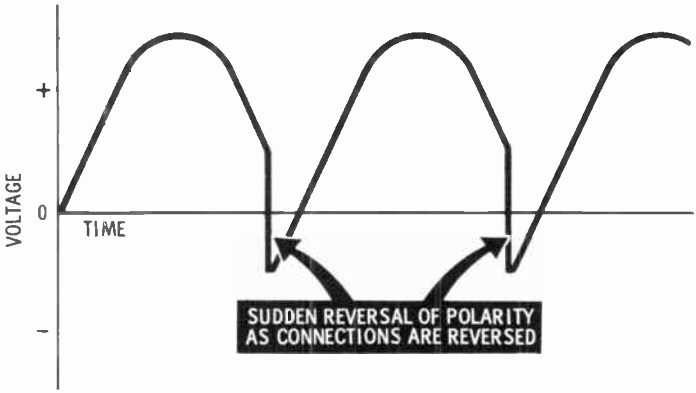
If the armature coil is short-circuited by the brushes while an emf is being induced in the coil, a heavy current will flow in the armature coil. This is because the circuit formed by the coil and the brushes has a very low resistance. This excessive current may cause serious damage to the armature

COIL SHORT-CIRCUITED BY BRUSHES



coils. Also, if the commutator of a DC generator is not adjusted to reverse the armature coil connections at the moment when the induced emf is zero, the output of the generator will not be DC. Instead, it will be AC as shown in the figure below.

GENERATOR OUTPUT WHEN SWITCHING OCCURS AT THE WRONG TIME



Q21. At what point in the AC cycle should the commutator reverse the coil connections?

Q22. Give two reasons why proper adjustment of a commutator is important.

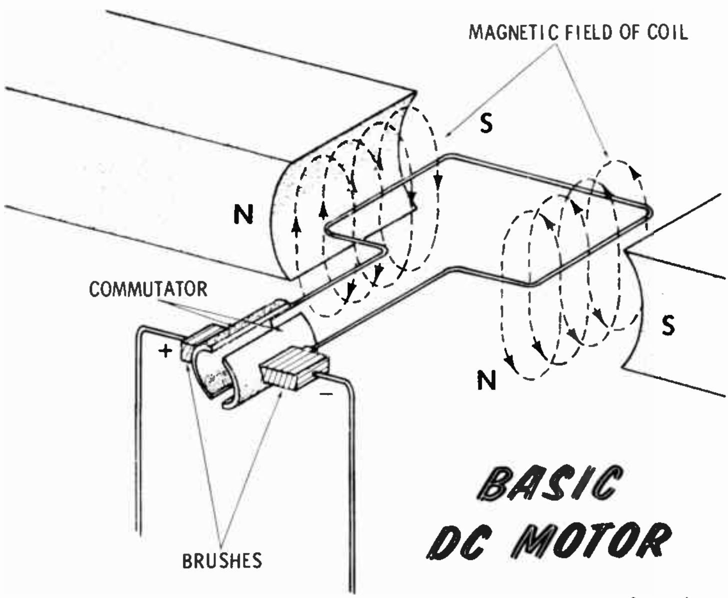
Your Answers Should Be:

A21. The commutator should reverse the coil connections when the **induced emf is zero.**

A22. If the commutator is not properly adjusted, the **generator coils may be damaged** by a heavy current through the short circuit created when the brushes touch both segments. Also, the output of the generator will **not** be **pure DC**, but will reverse polarity periodically.

DC MOTORS

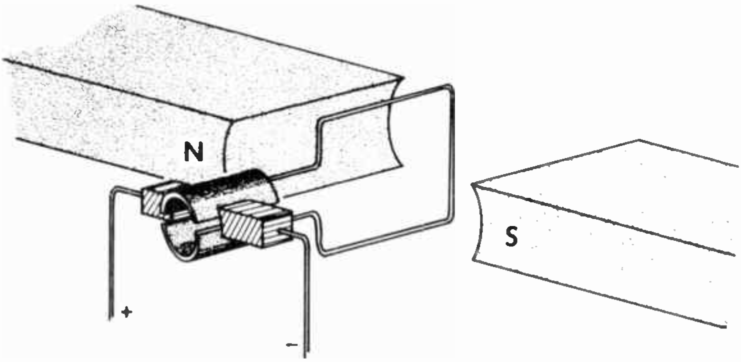
DC motors also have commutators. In fact, a basic DC generator can also act as a DC motor. When a DC current passes through the coil, the current creates a magnetic field. The north pole of the coil is attracted to the south pole of the outside magnetic field, and the south pole of the coil to the north pole of the outside field. Thus, the coil rotates.



You can analyze the magnetic forces acting on the simple coil by using the left-hand rule for straight conductors. The figure above shows the field around the coil.

When the coil reaches the position shown in the figure below, the brushes touch both commutator segments at the same time. No current flows in the coil, and there is no turning force on the coil. However, the coil is turning and

MOTOR COIL AT DEAD CENTER



its inertia, tending to keep it turning, carries it past dead center. As the coil rotates past dead center, the commutator reverses the direction of current flow through the coil. The polarity of the magnetic field around the coil is reversed, and the pole of the coil next to the south pole of the external field now becomes the south pole of the coil. The new south pole of the coil is now attracted toward the north pole of the external field, so the coil keeps on rotating. The same switching process is repeated when the coil has rotated another 180°.

In the figure above, the commutator causes a momentary short circuit across the power source when the coil is at dead center. You can see why this simple commutator-brush arrangement is not used in practical motors. The basic principle of all commutators is the same, however. As you have seen, the commutator in a DC motor converts the DC power supplied to the motor into AC for the armature coil.

Q23. Would the motor just described rotate if you supplied AC to the coil through slip rings?

Q24. The commutator in a DC motor changes DC into __.

Q25. There is no magnetic field developed around the coil when it is at ____ ______.

Your Answers Should Be:

A23. **Yes.** If the motor is supplied with AC, it does not need a commutator.

A24. The commutator in a DC motor changes DC into AC.

A25. There is no magnetic field developed around the coil when it is at **dead center.**

WHAT YOU HAVE LEARNED

1. A generator is a machine that converts mechanical energy into electrical energy by induction.
2. For induction to occur there must either be a conductor moving in a stationary magnetic field, a moving magnetic field surrounding a stationary conductor, or a moving magnetic field containing a moving conductor.
3. The strength of the induced emf depends on how fast magnetic lines are being cut by conductors, the strength of the magnetic field, the number of conductors in which an emf is being induced, and the distance between the source of the magnetic field and the conductor.
4. The direction of the induced emf depends on the direction of motion of the conductor and the direction of the field through which it is moving.
5. AC is generated in the armature coils of all generators.
6. The output of a generator will be AC if the output of the rotating armature coils is removed through slip rings and brushes.
7. The output of a generator will be DC if the output of the rotating armature coils is removed through a commutator and brushes.
8. Motors are machines that convert electrical energy into mechanical energy.
9. A DC motor is supplied with DC voltage and current which is converted into AC by the commutator for use in the armature coils.
10. An AC motor does not need a commutator.

2

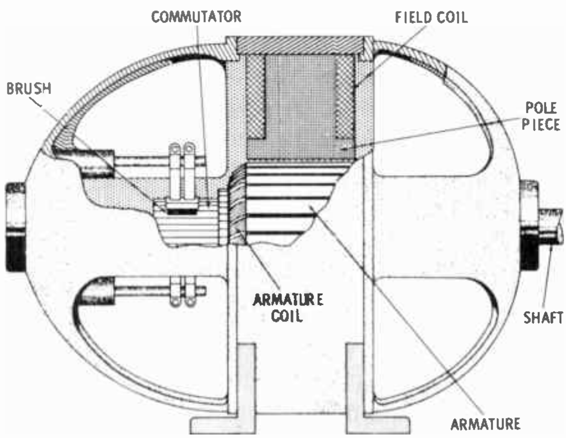
DC Generators

What You Will Learn

In this chapter you will learn about DC generator construction. You will learn to recognize each part and to know its function. You will be able to recognize effects within the generator that waste power, and how to minimize them. You will also learn the characteristics of the various kinds of DC generators.

CONSTRUCTION

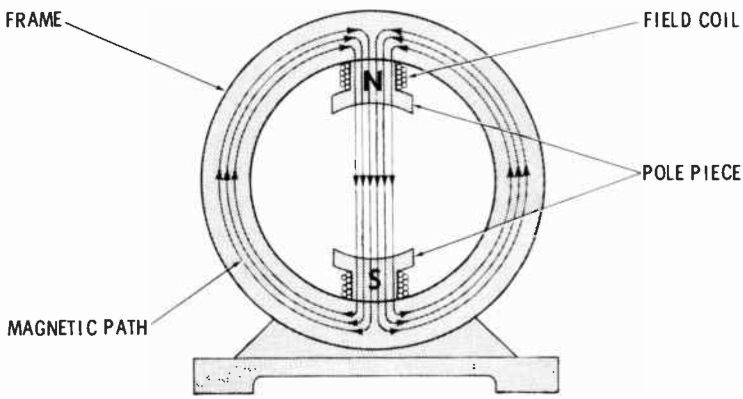
The major parts of a DC generator are the frame, end bells, pole pieces, shaft, armature assembly, commutator assembly, and brush assembly. The illustration below shows the construction of a DC generator.



Frame (Yoke)

The **frame**, or yoke, supports the generator. The frames of most modern generators are constructed of steel because this metal is an excellent conductor of magnetic lines of force. When the magnetic circuit is completed through a good magnetic conductor, as shown below, the field between the poles is stronger.

MAGNETIC PATH IN A GENERATOR FRAME



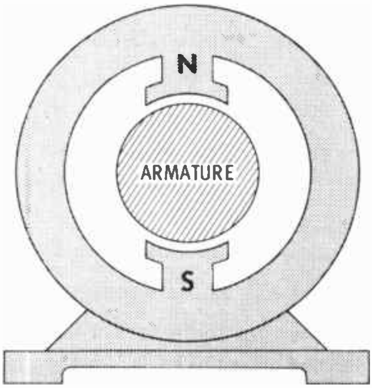
At one time, most generator frames were made of cast iron. Cast iron is heavier than steel and has a poorer **permeability** (ability to conduct magnetic lines of force), so it is used less frequently now. The frames of large generators are made of steel castings; those of smaller generators are made of rolled sheet steel. The frame of the generator also includes a base or mounting brackets.

There are three types of frames: open, semiclosed, and closed. An **open frame** has the ends open so that air can circulate freely through it. A **semiclosed frame** has a wire screen or a metal grille in its end bells to prevent foreign matter from entering the machine. A **closed frame** has solid end bells, and the machine is airtight.

Pole Pieces

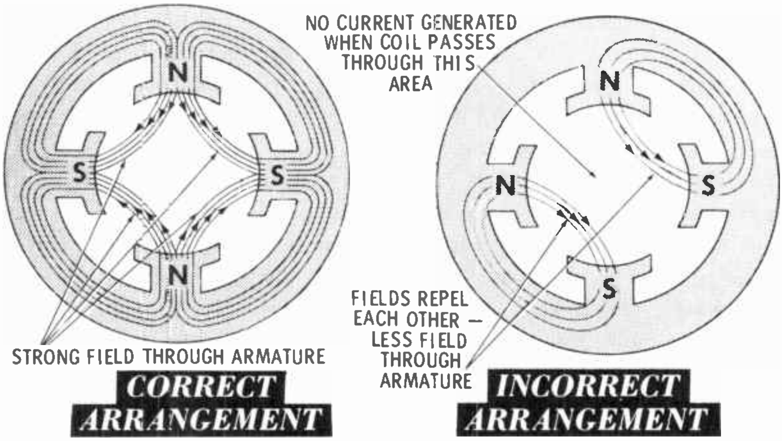
The **pole pieces** (also called pole shoes) of a generator are always used in pairs and are bolted to the frame. They support the field windings which are used to produce a north pole facing the armature on one side, and a south pole directly opposite on the other side.

ARRANGEMENT OF TWO GENERATOR POLES



More than one pair of poles are sometimes used in order to produce a stronger magnetic field. When this is done, opposite poles are always next to each other. You can see from the following illustration how this arrangement creates the strongest magnetic field through the armature.

ARRANGEMENT OF FOUR GENERATOR POLES



Q1. The permeability of a material refers to how well the material conducts _________ _______ _____.

Q2. Magnetic pole pieces are placed in a generator so that poles of (the same, opposite) polarity are next to each other.

Your Answers Should Be:

A1. The permeability of a material refers to how well the material conducts **magnetic lines of force.**

A2. Magnetic pole pieces are placed in a generator so that poles of **opposite** polarity are next to each other.

End Bells and Bearings

The **end bells** are bolted to each end of the frame and contain the bearings that support the armature shaft. The three types of bearings most commonly used in generators are: **ring-oiled** (sleeve), **yarn-packed,** and **ball** bearings.

The ring-oiled, or sleeve, bearing contains an oil ring that rides on the shaft. As the shaft turns, oil is carried from a reservoir to the top of the shaft for distribution to the bearing surface.

The yarn-packed bearing consists of a bundle of wool yarn looped on the armature shaft. Both ends of the yarn loop are in the oil reservoir. Oil soaks into the yarn and lubricates the revolving shaft.

Both oil-ring and yarn-packed bearings are provided with oil seals at each end of the bearing in order to prevent oil from escaping and causing damage to the parts of the generator carrying electricity.

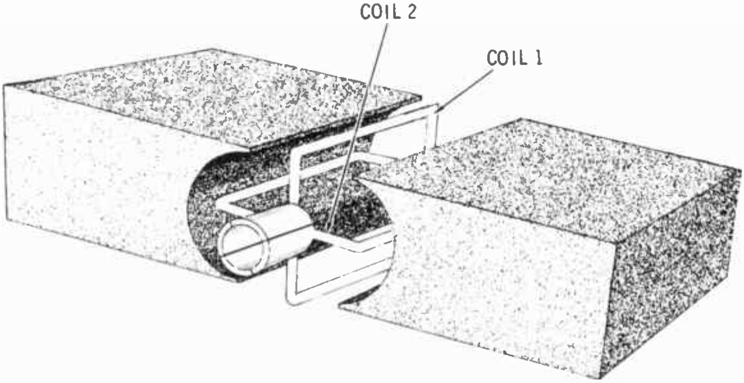
Ball bearings may be either the open or closed type and are packed with their own grease or lubricant. This type of bearing contains an outer ring, or race, and an inner ring. The outer ring does not move and is firmly held in position by the frame. The inner race rotates with the turning shaft. Between the inner and outer races are a number of very finely machined steel balls packed in grease. This arrangement provides an almost friction-free rotation of the inner race while the outer race is stationary.

Armature and Commutator

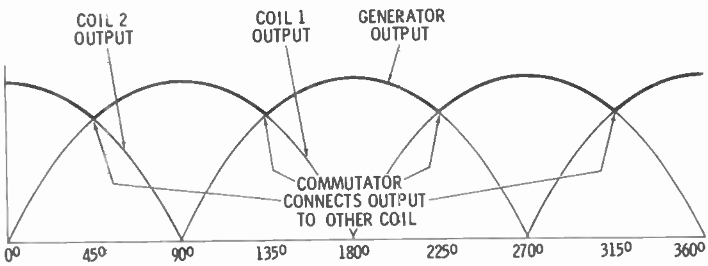
As you learned in Chapter 1, the commutator used with a single coil produces a pulsating DC output. By using more coils and combining their output, a smoother waveform can be obtained.

When a second coil is added to the armature and placed perpendicular to the first coil, the resulting output will be as shown below.

OUTPUT OF A TWO-COIL DC GENERATOR



COIL ARRANGEMENT



OUTPUT WAVEFORM

Notice that an emf is induced at all times. Although the DC still pulsates, the output is smoother. In practical generators, many coils are added to the armature to produce a still smoother DC output.

Q3. Which type of bearing is usually lubricated with grease rather than oil?

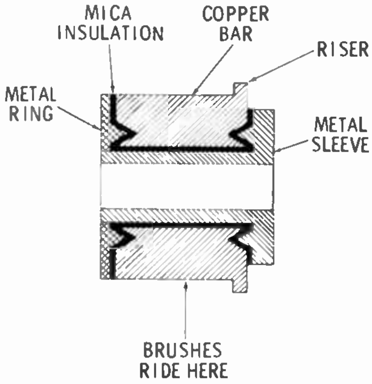
Q4. A generator using two coils (does, does not) have a smoother output than one using one coil.

> **Your Answers Should Be:**
>
> A3. **Ball bearings** are usually lubricated with grease rather than oil.
>
> A4. A generator using two coils **does** have a smoother output than one using one coil.

Commutator Connections

Each armature coil in a DC generator is connected to two commutator segments, one segment for each end of the coil. A generator with many coils will also have many commutator segments.

In a practical commutator, the segments are usually made of copper. Mica is used to insulate the commutator segments from each other and from the commutator sleeve. The ends of the armature coils are connected to the raised portions of



CROSS SECTION OF A COMMUTATOR

the segments. The raised part of the segment is called a **riser** and is slotted to hold the coil ends. The brushes ride on the lower portions of the commutator segments.

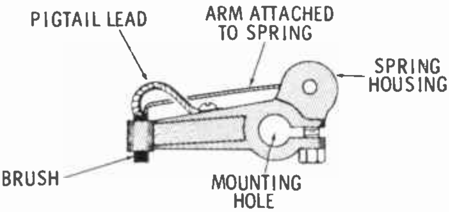
Brush Assembly

The brush assembly shown in the illustration on the opposite page consists of the brush, brush holder, adjustable brush-holder springs, and pigtailed connections.

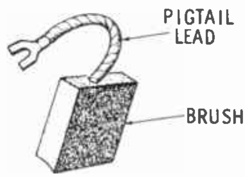
In normal operation, both the commutator segments and the brushes wear. The adjustable brush-holder spring allows the brush pressure on the commutator to be adjusted to compensate for this wear. The spring should apply only enough pressure to make a good connection between brush and commutator.

The pigtailed connections are braided copper wires that provide a low-resistance and flexible connection between the brush and the brush holder.

BRUSH ASSEMBLY



COMPLETE ASSEMBLY



BRUSH

Brush Materials

The type and operating conditions of a generator determine the material used for brushes. **Graphite brushes** are easily distinguished by their silvery appearance and soft, flaky texture. This type of brush is for general-purpose use. **Carbon brushes** are used on generators that have both low rotation speeds and low current output.

Electrographitic brushes are made from the same material as carbon brushes but are processed at high temperatures in an electric furnace. This process increases the ability of the brush to conduct both electrical and heat energy. These brushes are nonabrasive and cooler running. They have very low friction and a higher current capacity than carbon brushes.

Copper-graphite brushes are made from a mixture of powdered copper and powdered graphite pressed together and baked at low temperatures. This type of brush is used on low-voltage generators.

Q5. Normal wear of the commutator segments and the brushes of a generator is adjusted with the ______ ______ ______.

Q6. ______ ________ brushes are used in low-voltage generators.

Your Answers Should Be:

A5. Normal wear of the commutator segments and the brushes of a generator is adjusted with the **brush-holder spring.**

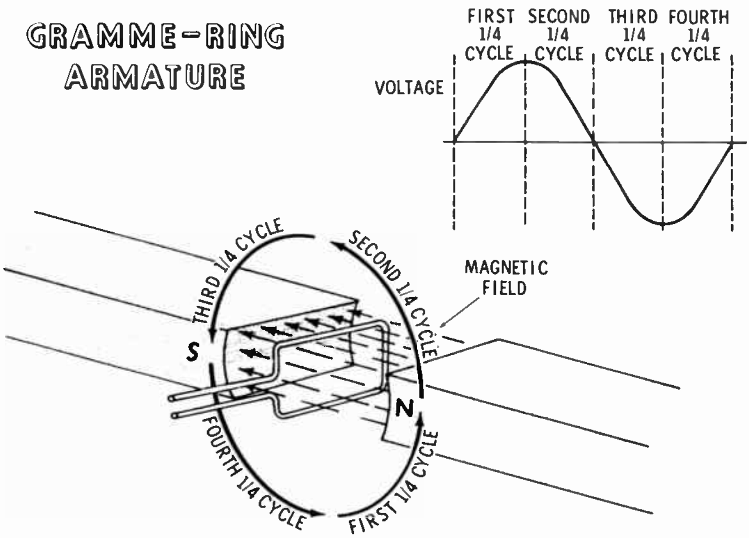
A6. **Copper-graphite** brushes are used in low-voltage generators.

THE ARMATURE CORE

Armature coils are wound on cores of either the **Gramme-ring** or **drum** type. The Gramme-ring armature core is an older type and is usually not found on newer machines.

Gramme Ring

In a Gramme-ring armature, the windings are wound on the surface of an iron or steel ring. The armature winding is tapped at regular intervals for connection to the commutator.



Since the armature windings of the Gramme-ring core are wound on the surface of the core, the distance between the core and the pole pieces must be great enough that there is no danger of the armature windings touching the pole pieces. This causes a reduction in the strength of the magnetic field. The weakened field results in reduced output from the generator.

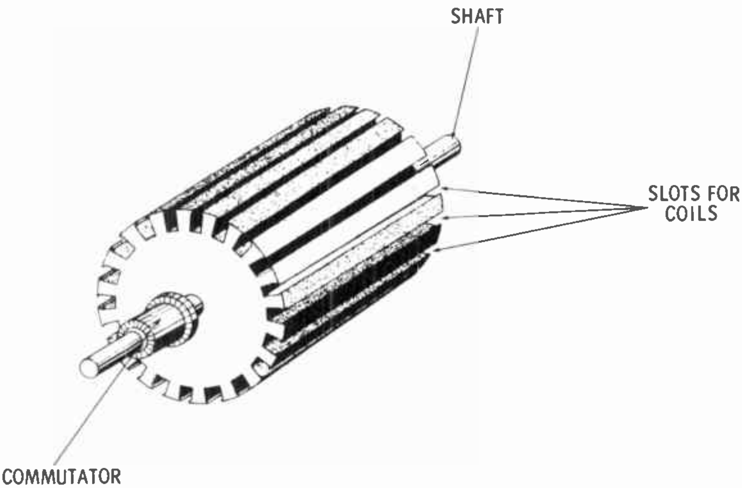
The Gramme-ring core offers a lower **reluctance** (magnetic equivalent of resistance) to the lines of force than the air gap inside the ring. The magnetic lines of force follow the circular path of the core and do not cross the center air gap. Thus they are not cut by the conductors on the inside surface of the core and, therefore, do not induce an emf in these conductors.

For these and other reasons the Gramme-ring armature is rarely used. Nearly all modern DC generators use drum-type armatures.

Drum

The drum armature core is newer and more efficient. Coils are placed in slots and are generally a fraction of an inch below the outer surface of the core. This type of construction and coil placement eliminates the danger of the armature coils rubbing against the pole pieces while the armature is rotating.

DRUM ARMATURE CORE



Q7. What are two disadvantages of the Gramme-ring armature?

Your Answer Should Be:

A7. The Gramme-ring armature core must be kept **farther from the pole pieces** than the drum type. This results in reduced magnetic field strength. Only the parts of the conductors on the **outside of the core** have voltages induced in them.

Advantages of the Drum Armature Core

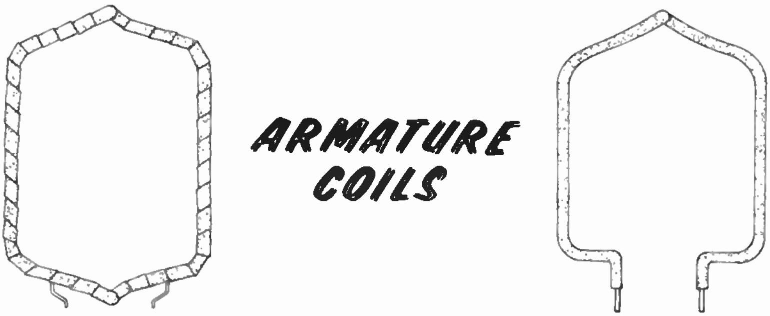
One of the advantages of the drum armature core is that a smaller air gap exists between the armature and the pole pieces. The smaller air gap permits the armature coils to cut through a magnetic field of greater density, and thus a greater emf is induced in the armature coils.

Since the drum armature core is more compact than the Gramme-ring armature core, the drum armature can be rotated at a higher speed, thus producing a greater emf.

THE ARMATURE COIL

The coils used on drum armature cores are usually preformed. That is, they are wound in their final shape before being put on the armature.

The sides of the preformed coil are placed in the slots of the drum armature core. The two slots for each coil are usually the same distance apart as adjacent magnetic poles. This distance is called the **pole pitch**, or **pole span.** As you recall, adjacent magnetic poles are of opposite polarity, so that the emf induced in one side of the armature coil is reinforced by the emf induced by the opposite pole on the second side of the armature coil.



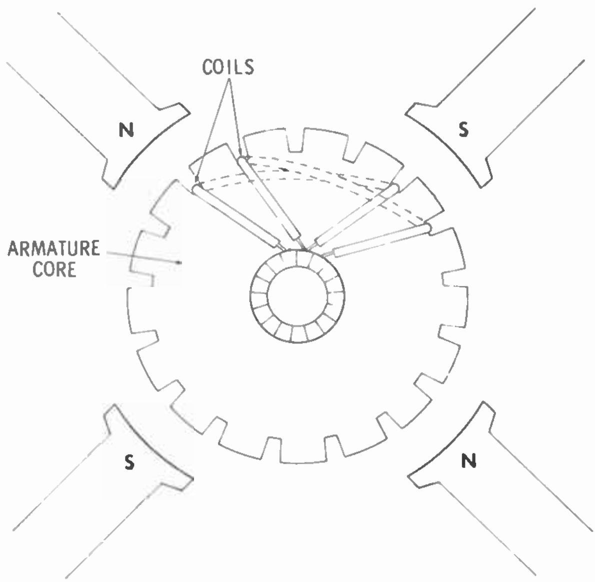
Sometimes the distance between the two sides of an armature coil is not equal to the distance between the adjacent magnetic poles. When this distance is less than the pole pitch, the coil is called a **fractional-pitch winding.**

Fractional-pitch windings are used when it is necessary to save copper. The emf induced in a fractional-pitch coil is not as great as the emf induced in a coil whose pitch is equal to the pole pitch. This is because the voltages induced in the two coil sides do not reach their maximum values at the same time.

Lap and Wave Windings

There are two ways the coils can be connected—**lap winding** and **wave winding.** In a **simplex lap winding,** the ends of each coil are connected to adjacent commutator segments. In this way, all the coils are connected in series. This is shown in the figure below.

SIMPLEX LAP WINDING



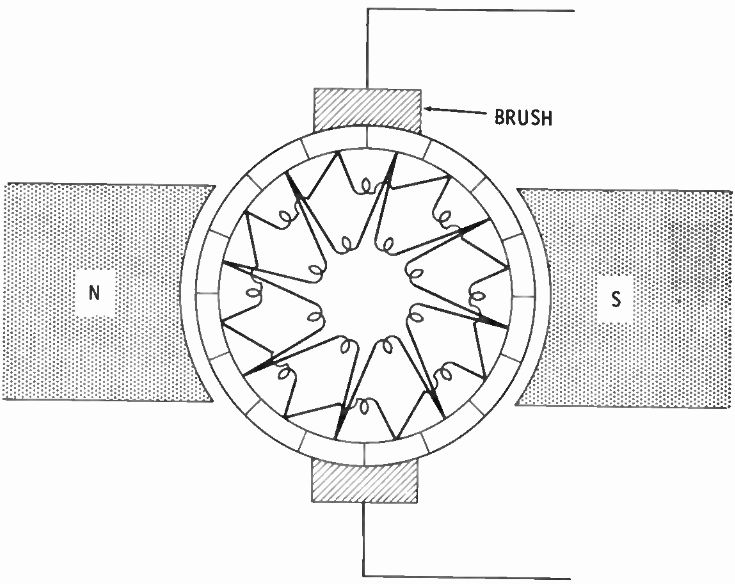
Q8. What are some advantages of the drum armature core?

Your Answer Should Be:

A8. The drum armature core makes possible a **smaller air gap.** The drum armature can be **rotated at a higher speed** than the Gramme-ring type. Both these effects make possible a **higher induced voltage.**

In a **duplex lap winding,** there are in effect two separate sets of coils, each set connected in series. The two sets of coils are connected to each other only by the brushes.

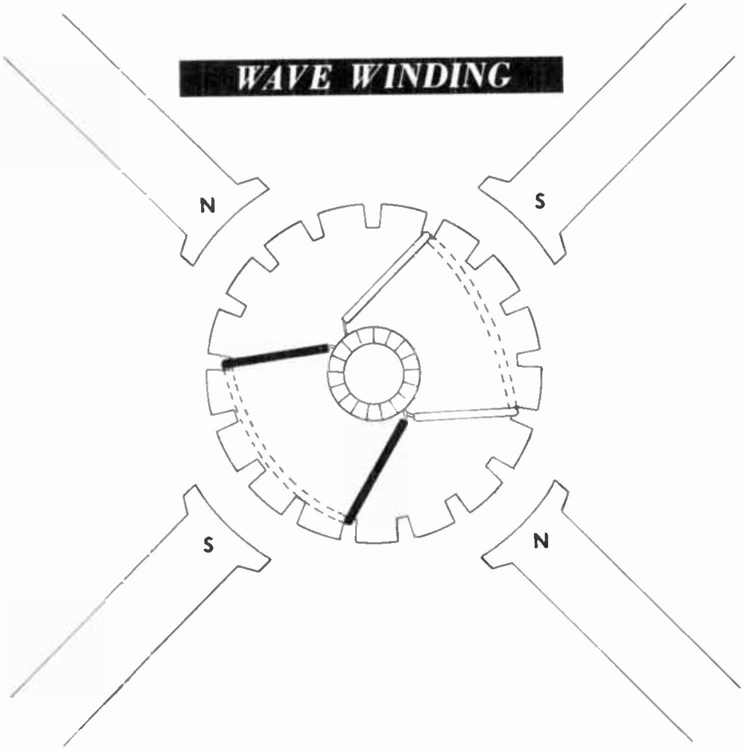
DUPLEX LAP WINDING



Similarly, a **triplex lap winding** is in effect three separate sets of series-connected coils. In a simplex lap winding, a single brush shorts the two ends of a single coil.

In a **wave winding,** the ends of each coil are connected to commutator segments two pole spans apart. Instead of shorting a single coil, a brush will short a small group of coils in series. There will be as many coils in the group as there are **pairs** of magnetic poles.

The figure below shows part of a wave winding.



The Neutral Plane

The area in the generator where no emf can be induced in an armature coil is called the **commutating, or neutral, plane.** This plane is midway between adjacent north and south field poles (somewhat shifted from this position under load). In this plane the moving armature coils cut no lines of force and so generate no voltage. The brushes are always set so that they short-circuit the armature coils passing through the neutral plane while, at the same time, the output is taken from the other coils.

Q9. In a wave winding, the coil ends are connected to commutator bars two ---- ----- apart.

Q10. Of what does a duplex winding consist?

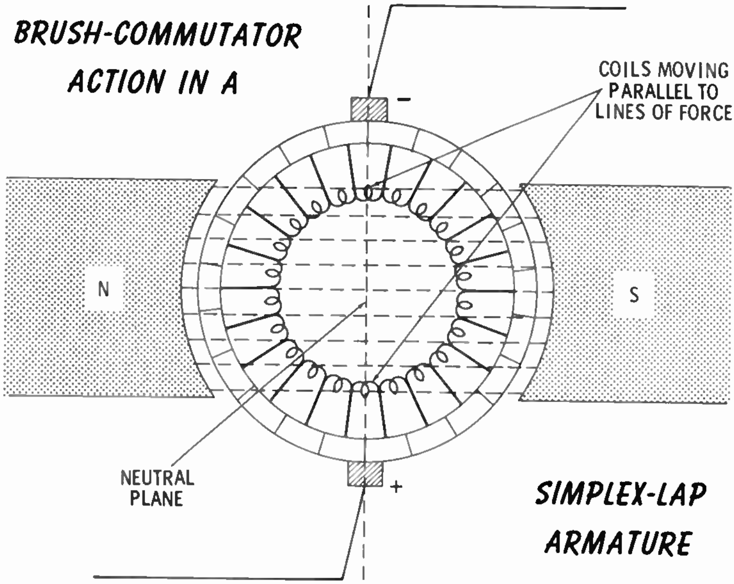
Your Answers Should Be:

A9. In a wave winding the coil ends are connected to commutator bars two **pole spans** apart.

A10. A duplex winding consists of two **separate sets of coils.**

Commutator Output

While the brush is short-circuiting one armature coil, it is receiving the emf and current induced in the other armature coils. This is accomplished by connecting one end of two different coils to the same commutator segment.

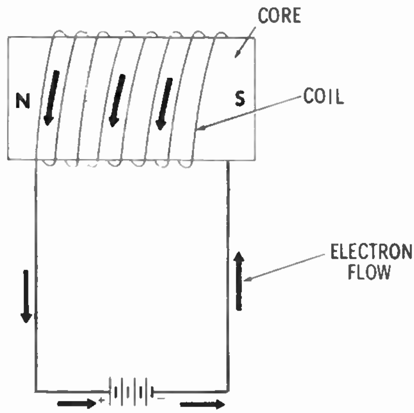


The illustration above shows an armature with 22 coils connected to 22 commutator segments. There are two brushes. The positive brush is short-circuiting armature coil 11 while the negative brush is short-circuiting armature coil 22. There is no emf being induced in either of these coils. The two coil groups, 1 through 10 and 12 through 21, are connected in parallel by the brushes. This is possible because the voltages in both coil groups have the same polarity. The brushes also connect the generated emf to the load.

POLE PIECES

Permanent magnets can only produce magnetic fields of limited strength and are used mainly in small generators called **magnetos.** Most generators use electromagnets to produce the magnetic field. Electromagnets consist of a metal core with a coil of wire wrapped around it.

AN ELECTROMAGNET



When a current flows through the coil, a magnetic field is produced around the coil. If the core conducts the magnetic lines of force easily, it becomes a temporary magnet when current flows through the coil. The current supplied to an electromagnet is DC, since AC would cause the polarity to constantly change.

To find the polarity of the core when current is flowing through a coil, imagine that you wrap the fingers of your left hand around the coil in the direction of the electron flow through the turns. Your thumb then points to the north pole of the core.

The electromagnetic poles are mounted on the frame of a DC generator. This enables the frame to complete the magnetic circuit.

Q11. The magnetic field of most electromagnets is (stronger, weaker) than the magnetic field of a permanent magnet.

Q12. Why is there no large flow of current in a generator coil shorted by a brush?

Your Answers Should Be:

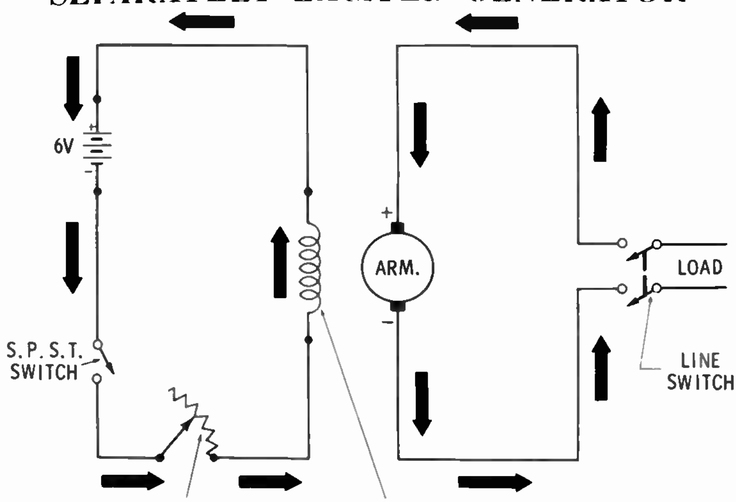
A11. The magnetic field of most electromagnets is **stronger** than the magnetic field of a permanent magnet.

A12. There is no large flow of current in a generator coil when shorted by a brush because, by proper adjustment, **no emf is induced** in the coil during that time.

THE SEPARATELY EXCITED GENERATOR

The current for the electromagnetic field of a generator may be generated by a separate source of DC. This source could be a battery or a separate DC generator. With either source, the generator is said to be **separately excited.**

SEPARATELY EXCITED GENERATOR



Notice that the separately excited magnetic-field circuit is completely independent of the generator circuit. The strength of the externally excited magnetic field depends directly on the amount of current supplied by the external DC source. A rheostat is used to vary the strength of the magnetic field. This provides a very sensitive control of the generator output.

THE SELF-EXCITED GENERATOR

The current for the electromagnetic field of a DC generator may be developed in the armature coils of the generator itself. The current is taken from the commutator by the brushes and then fed to the field coils. The three types of circuits used to feed current to the field coils are the series, shunt, and compound.

The electromagnetic field of a self-excited DC generator depends on current induced in the armature coils of the generator by an electromagnetic field. Since a field is required to produce current, how can a self-excited DC generator build up a voltage?

An electromagnet has a small amount of magnetism even when the electromagnetic coil is not energized. This small amount of magnetism is called **residual magnetism.** Usually, the residual magnetism in the electromagnetic core is strong enough that a weak voltage is induced in the armature coils. This voltage causes a small amount of current to flow in the field windings. The current causes the magnetic field to increase. This increases the voltage which again increases the current, and so on. In this way the generator voltage builds up to its maximum value. This process is called **building up.**

When there is not enough residual magnetism in the field core, the generator will not build up. In this case the electromagnetic field must be excited temporarily from an external DC source. This is called **flashing the field.** Reversing the connections to the field windings can also cause a generator to fail to build up.

Q13. A generator that has a separate source of current for its field windings is said to be ---------- --------.

Q14. A -------- is used to control the amount of current flowing in the field winding.

Q15. A rheostat provides (poor, sensitive) control of the output of a generator.

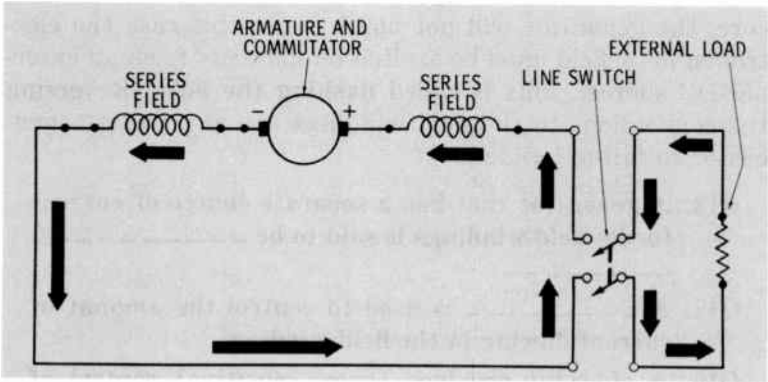
Q16. The small amount of magnetism that remains in the core of an electromagnet when the current is removed is called -------- ---------.

> **Your Answers Should Be:**
>
> A13. A generator that has a separate source of current for its field windings is said to be **separately excited.**
>
> A14. A **rheostat** is used to control the amount of current flowing in the field winding.
>
> A15. A rheostat provides **sensitive** control of the output of a generator.
>
> A16. The small amount of magnetism that remains in the core of an electromagnet when the current is removed is called **residual magnetism.**

The Series Generator

In a series generator the field windings, armature windings, commutator, brushes, and the external load are all connected in series. In order for a self-excited series generator to produce voltage, the external load must be connected. Without the external load connected, the series circuit is incomplete, and the small generator voltage is due only to residual magnetism.

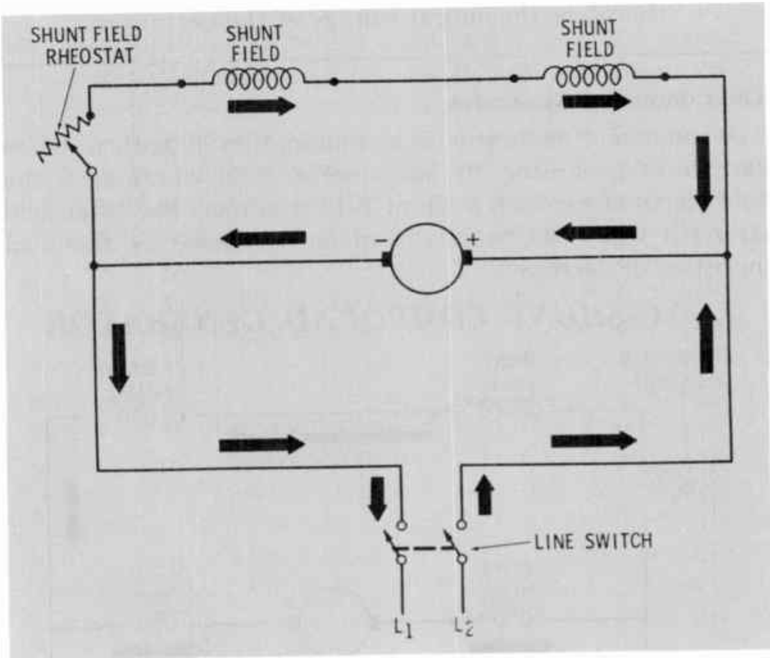
A SERIES GENERATOR



The Shunt Generator

The shunt generator is connected as a parallel (shunt) circuit. The parallel circuit is used to provide separate paths for supplying current to the electromagnetic field and to the external load. In the shunt generator, the DC current induced in the armature coils is taken from the commutator by the brushes. From the brushes, part of the current is supplied to the electromagnetic field windings, while the main current flow is delivered to the external load.

A SHUNT GENERATOR



Building up in a self-excited shunt generator does not require that the external load be connected to the generator because the current supplied to the electromagnetic field does not flow through the external load. This means the generator can be started, and the full strength of the magnetic field and the induced emf reached before the external load is connected.

Q17. How will an increase in the current drawn by the load affect the current through the field coils of a series generator?

Q18. What will be the effect of varying the resistance of the shunt-field rheostat?

Your Answers Should Be:

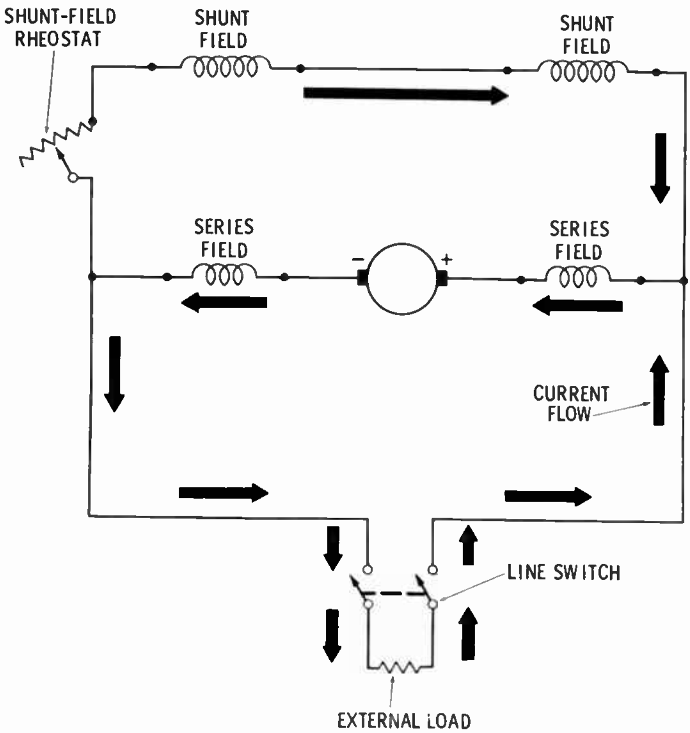
A17. An increase in load current will **increase the current through the field coils,** which tends to **increase the output voltage.**

A18. Varying the resistance of the shunt-field rheostat will vary the **strength of the magnetic field** and therefore the **output voltage** of the generator.

The Compound Generator

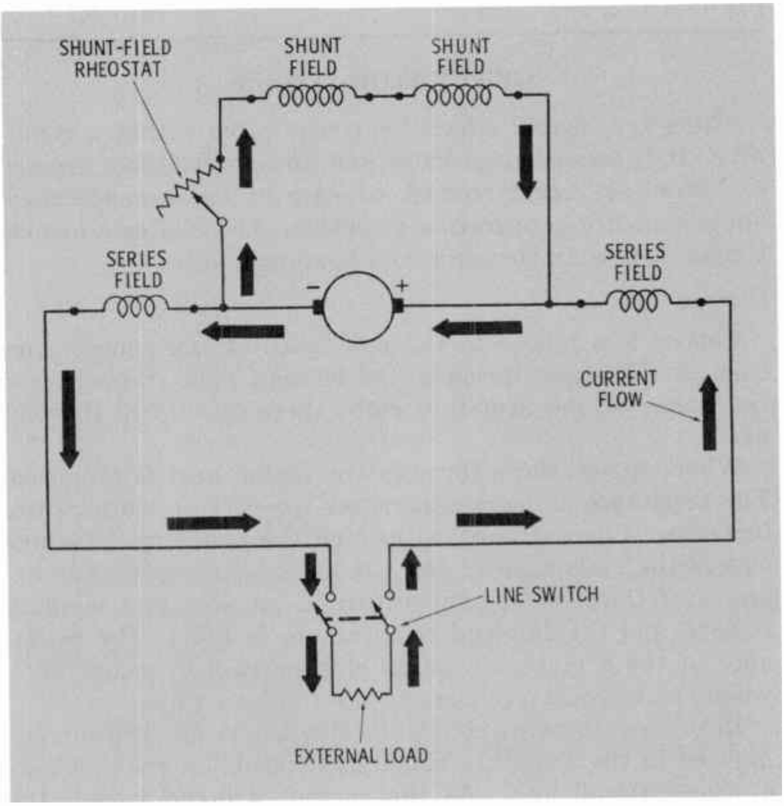
A compound generator is a combination of both a series and shunt generator. It has a series field winding on the pole pieces along with a shunt field winding. The total field strength will thus be increased or decreased as the load increases or decreases.

LONG-SHUNT COMPOUND GENERATOR



In a **long-shunt** compound generator, the shunt field winding is connected to the ends of the series field windings away from the armature. In a **short-shunt** compound generator, the ends of the shunt field winding are connected between the series field windings and the armature.

SHORT-SHUNT COMPOUND GENERATOR



There is no difference between the short- and long-shunt compound generators as far as the operation and output are concerned. The only difference is in the point where the series field is connected.

Q19. Compound-generator pole pieces have both ______ and _____ field windings.

Q20. Name the three types of circuits used to supply current to the field of a self-excited generator.

Your Answers Should Be:

A19. Compound-generator pole pieces have both **series** and **shunt** field windings.

A20. **Series, shunt,** or **compound** circuits may be used to supply current to the electromagnetic field of a self-excited DC generator.

GENERATOR LOSSES

There are several effects that take place within a generator. It is necessary to know how these effects are created and how they are corrected in order to maintain electrical equipment in top operating condition. These effects include copper loss, eddy currents, and hysteresis loss.

Copper Loss

Copper loss is due to the resistance of the copper wire used in the armature coils. As current flows through the resistance of the armature coils, there is an I^2R (power) loss.

When current flows through any metal, heat is produced. The resistance of metals increases when their temperature increases. Current flowing through the armature windings causes the resistance of the windings to increase. For example, if the no-load temperature of an armature winding is 68°F and the full-load temperature is 122°F, the resistance of the armature winding will increase by about 20% when the temperature rises to the full-load value.

Most generators are constant-voltage devices. The current induced in the armature windings depends on the demands of the external load. As the current demand varies, the copper loss in the armature will vary also.

Eddy Currents

When the conductors of the armature coils rotate through the magnetic field, an emf is induced. Current is caused to flow in the armature coils as determined by the requirements of the external load.

The armature core is also a conductor and rotates in the same magnetic field. Therefore, an emf and current are produced in the armature core. These are called **eddy currents.**

The power used in generating eddy currents comes from the generator power source and represents a loss of output power. This is because it is power taken from the power source but not converted into the desired output; it lowers the efficiency of the generator. (Besides being a waste of power, this energy results in undesirable heating of the iron.) Eddy currents are reduced by **laminating** the core. That is, the core is made of a number of thin layers of metal, all insulated from each other. Lamination reduces the length of the conductor in which the eddy currents flow and therefore reduces the amount of I^2R (power) loss in the armature core.

Hysteresis Loss

Hysteresis loss is a heat loss due to the magnetic properties of the armature. This also is a power loss since this energy, too, is taken from the prime mover. When the armature core is rotating, the magnetic particles of the core tend to line up with the magnetic field. Since the core is rotating, the magnetic field keeps changing direction. The movement of the magnetic particles as they keep trying to align themselves produces friction which, in turn, produces heat. This heat result in an increase in armature resistance and an additional copper loss. Hysteresis loss varies with the speed of the armature and the amount and type of iron in the core.

To limit hysteresis loss, an armature-core material is used in which the magnetic particles line up with the constantly changing direction of the magnetic field with relative ease. The most commonly used material is dynamo sheet steel. Using this material **reduces** the hysteresis loss but does not eliminate it completely.

Q21. What two types of power loss are limited by constructing an armature core of dynamo sheet-steel laminations?

Q22. What happens to the temperature of the armature as the load increases?

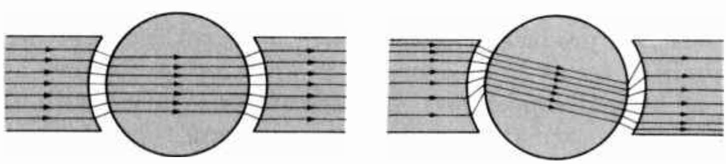
Q23. What effect will this change in temperature have on copper loss in the generator?

> **Your Answers Should Be:**
>
> A21. **Eddy-current and hysteresis losses** are limited by constructing armature cores of dynamo sheet steel.
>
> A22. As the load increases, the temperature of the armature will **increase.**
>
> A23. An increase in temperature will increase the resistance of the armature coils and therefore **increase the copper loss.**

ARMATURE REACTION

Armature reaction is the result of the magnetic field surrounding the armature due to the electric current flowing through the armature coils. This field acts on the main magnetic field of the generator and distorts it. This effect is called **cross magnetization.** It only occurs when current is flowing through the armature.

Distortion of Magnetic Field



No Armature Reaction ***With Armature Reaction***

You have learned that the best place to take the output from an armature is from commutator bars in the **neutral,** or commutating, plane. When there is no current flowing through the armature, the neutral plane is at right angles to the main generator field. With armature current flowing, the distorted magnetic field due to cross-magnetization will cause the neutral plane to shift to a new position. The position of the neutral plane will shift with every change in current flow in the armature.

Identifying and Correcting Armature Reaction

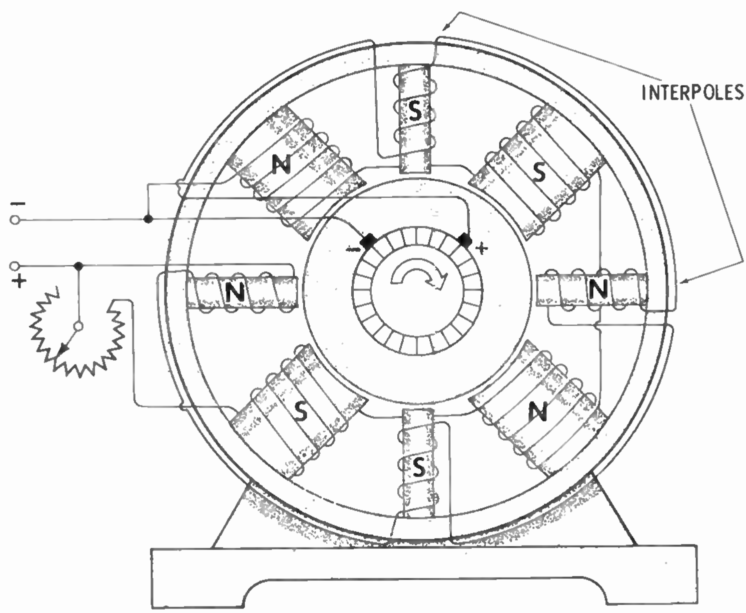
When sparking occurs between the commutator and brushes, you should suspect armature reaction. The neutral plane may be found by moving the brushes on the commutator until sparking stops. The neutral plane will, of course, shift each time the current changes.

One way of compensating for armature reaction is to cancel the armature field with an opposing magnetic field. Interpoles and compensating windings operate on this principle.

Interpoles

Interpoles, or **commutating poles,** are narrow auxiliary poles located midway between adjacent main magnetic poles. Interpoles tend to neutralize the armature reaction created by the magnetic field of the armature. This effect takes place only within the area of the interpole magnetic field.

SHUNT-FIELD GENERATOR WITH INTERPOLES



Interpole windings are connected in series with the armature windings and are wound in such a direction that the polarity of the interpole always has the same polarity as the nearest main-field pole in the direction of rotation.

Q24. What causes armature reaction?

Q25. What symptom indicates armature reaction?

Your Answers Should Be:

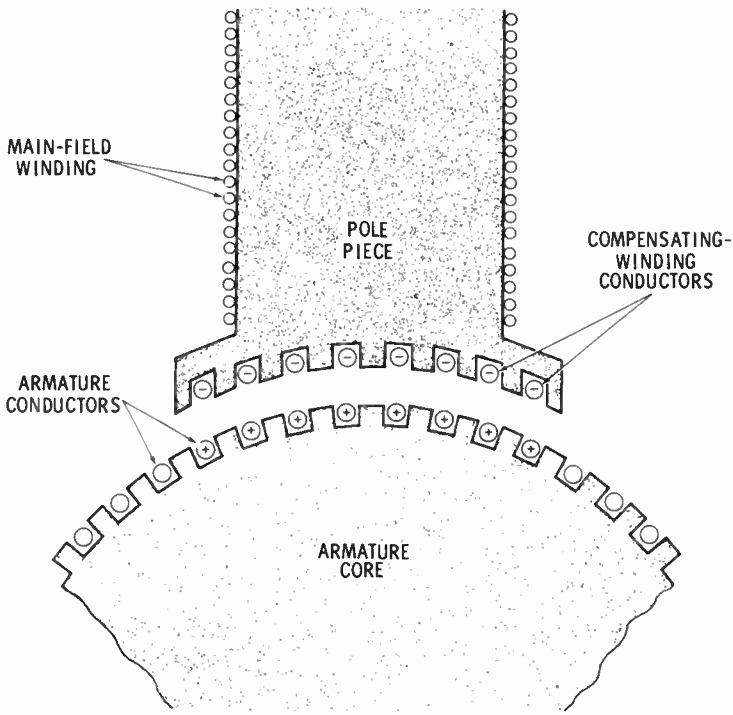
A24. Armature reaction is caused by the **magnetic field around the armature due to the flow of armature current.**

A25. The symptom of armature reaction is **sparking between the commutator and brushes.**

Compensating Windings

When a generator must operate at high efficiency under varying external load demands, **compensating windings** are used. The compensating windings are normally embedded

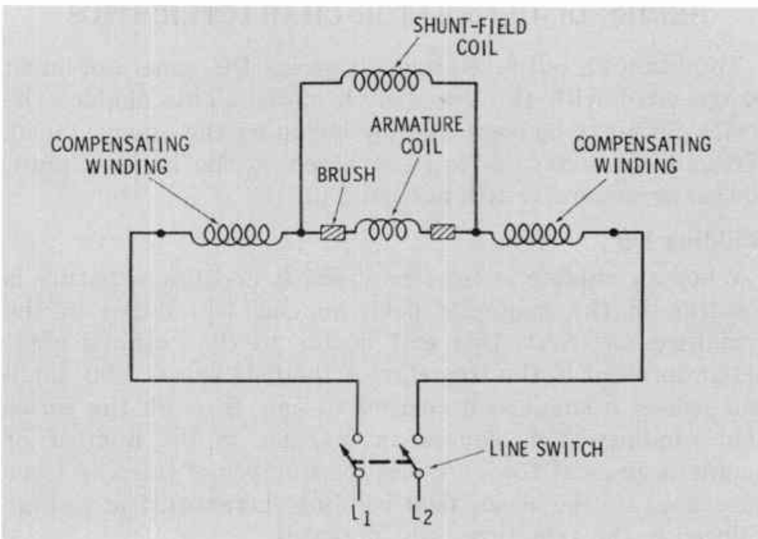
LOCATION OF COMPENSATING WINDINGS



in the faces of the pole pieces. They are connected in series with the armature coils, like interpoles, but are wound in the opposite direction from the armature coils. The field of the compensating windings completely cancels the field of the armature that would tend to distort the main field of the generator.

Compensating windings are a very efficient but expensive method for eliminating armature reaction. The use of compensating windings is limited almost exclusively by their high cost.

SHUNT-FIELD DC GENERATOR WITH COMPENSATING WINDINGS



Motor Reaction in a Generator

When current flows in the armature coils, a generator will tend to act as a motor. The magnetic field surrounding the armature coils weakens the main magnetic field on one side of the coil, but strengthens it on the other side. As a result, a torque is developed that opposes the rotation of the generator shaft. This is why the rotating armature presents a mechanical load to the prime mover. Due to this reaction, the prime mover "feels" an opposition to turning the generator shaft.

Q26. Why are compensating coils wound in a direction opposite that of the armature coils?

Your Answer Should Be:

A26. Compensating coils are wound in a direction opposite that of the armature coils because **the magnetic field of the armature will be opposed by compensating coils wound in the opposite direction.** The fields will vary **the same amount** when the coils are fed the same current in series.

SERIES DC-GENERATOR CHARACTERISTICS

To obtain an output voltage, a series DC generator must be operated with the line switch closed. This enables the series circuit to be completed by including the external load. Without the external load connected to the series circuit, the series generator will not build up.

Building Up

When a complete series circuit exists and the armature is rotating in the magnetic field, an emf is induced in the armature. At first, this emf is due to the residual magnetism present in the iron core of the field poles. This small emf causes a small load current to flow through the series field winding. This causes an increase in the number of magnetic lines of force. When the number of lines of force generated by the series field winding increases, the voltage induced in the armature coils increases.

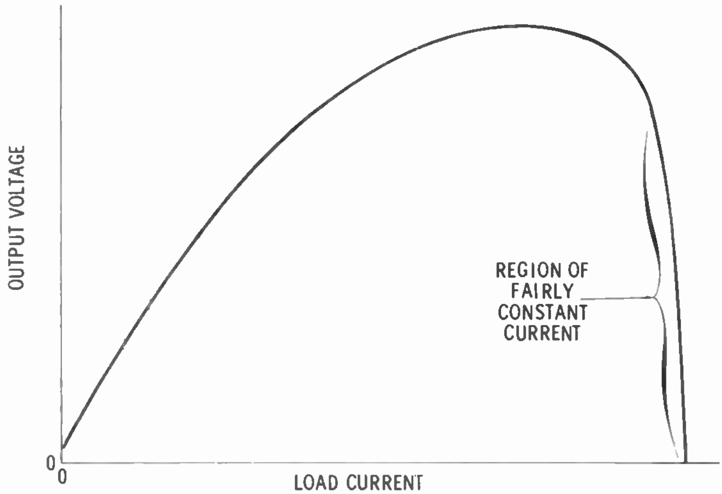
The output voltage in the series machine continues to rise until the iron core of the series field becomes **saturated;** that is, it cannot contain any additional lines of force. When the magnetic field reaches saturation, the output voltage will be maximum, and any additional current required by the external load will not increase the output voltage.

Characteristics Under Load

Drawing more current from the armature than required to achieve maximum voltage output will create a drop in the output voltage of the generator. This decrease in voltage is due to armature reaction and the voltage drop across the resistances of the armature and the field. A graph of the output of a DC generator is shown on the next page.

The most important conclusion that can be reached about the series-wound DC generator is that it is best suited for **constant-current applications.**

Output-Voltage Characteristics of a Series Generator



As more current is demanded (within practical limits) from a series-wound DC generator, the output voltage increases. When the practical limit of current is reached, a further demand has a reverse effect. The practical limit is reached when the magnetic field strength reaches its maximum value.

Examining the characteristic curve of the series-wound DC generator shows that the voltage drops off sharply. Therefore, it is possible to obtain a fairly constant current for a wide voltage range.

Q27. In order to obtain output voltage, a series generator must be operated with the ____ connected.

Q28. The series DC generator is best suited for _________ ________ applications.

Q29. The output voltage of a series generator first __________ and then __________ as the output current increases.

Your Answers Should Be:

A27. In order to obtain output voltage, a series generator must be operated with the **load** connected.

A28. The series DC generator is best suited for **constant-current** applications.

A29. The output voltage of a series generator first **increases** and then **decreases** as the output current increases.

SHUNT DC-GENERATOR CHARACTERISTICS

The field coils of a shunt-wound DC generator are connected in parallel with the armature and the external load. The number of magnetic lines of force produced by the pole pieces does not depend directly on the load current. However, the load current does have an indirect effect. As the load current increases, the generator output voltage decreases. This is due to increased armature reaction and the voltage drop across the resistance of the armature coils. When the generator output voltage decreases, the current through the shunt field coils also decreases. This causes an additional decrease in the output voltage. The output voltage is therefore less than it would be if the field windings were connected to a source of constant voltage.

A rheostat is usually placed in series with the shunt field windings. By adjusting the rheostat, the current through the windings can be controlled. In this way, the strength of the magnetic field can be changed to make up for a decrease in output voltage.

Building Up

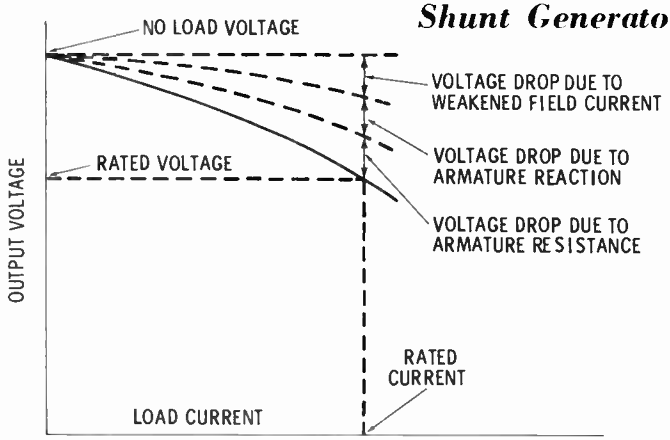
The line switch to a shunt DC generator can be left open since it is not necessary for the external load to be connected during buildup. When the generator is turning, the armature coils cut the weak, residual magnetic field of the iron shunt-field core. The weak magnetic field causes a weak voltage to be induced in the armature coils. This voltage, in turn, causes a weak current to flow from the armature coils, through the shunt-field rheostat, and through the shunt field coils. The weak shunt field current generates additional lines of force which strengthen the magnetic field. The strength of the electromagnetic field and the voltage induced in the armature coils increase until the terminal voltage of the generator reaches its no-load voltage.

Characteristics Under Load

In order for the shunt DC generator to deliver power to the external load, the line switch is closed. The load requirements are met by adjusting the shunt-field rheostat.

As the amount of current required by the external load increases, the output voltage of the generator decreases as shown in the following characteristic curve.

Output-Voltage Characteristics of a Shunt Generator



The shunt DC generator is well suited for **constant-voltage applications** at a specified rated output. When an additional load (beyond a critical limit) is placed on the generator, the output voltage falls off almost to zero. Any attempt to force a shunt DC generator to deliver more than its rated output could cause it to break down.

Q30. A shunt DC generator is used mainly for constant _______ applications.

Q31. When more current is required by the external load than the critical limit of a shunt generator, the additional load will cause the output voltage to ____.

Your Answers Should Be:

A30. A shunt DC generator is used mainly for constant-**voltage** applications.

A31. When more current is required by the external load than the critical limit of a shunt generator, the output voltage **drops.**

COMPOUND DC-GENERATOR CHARACTERISTICS

You have learned that there are two types of compound DC generators, the long shunt and the short shunt. The build-up, loading, and general characteristics of the two are very similar. The short-shunt generator is in wider use because of its simpler circuitry. On the next few pages the compound DC generator will be discussed in terms of the short-shunt design. The series field of a short-shunt, compound DC generator is connected between the load and the parallel shunt field and armature. Basically, the compound DC generator takes advantage of the characteristics of both the series and shunt DC types.

Building Up

One of the advantages of the shunt generator is also present in the compound generator. It is not necessary to start a compound generator with the external load connected. The building-up process is similar to that of the shunt type.

Characteristics Under Load

When the no-load terminal voltage has been reached, the line switch is closed. The output voltage is then adjusted with the shunt-field rheostat which controls the resistance of the shunt field circuit. As described before, this varies the strength of the magnetic field. The output voltage changes directly with the strength of the magnetic field controlled by the shunt-field rheostat.

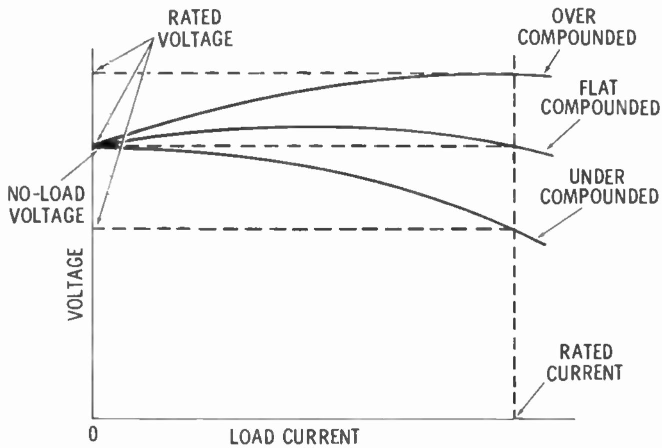
The purpose of the series field windings in a compound generator is to control the output voltage of the generator in relation to the external load. The series field windings help to offset the voltage decrease that occurs when a shunt field alone is used.

Compounding Effects

When the effect of the series winding produces the same terminal voltage at rated load as at no load, the generator is said to be **flat compounded.**

When the effect of the series winding produces a smaller terminal voltage at rated load than at no load, the generator is said to be **undercompounded.**

Compound-Generator Characteristics



When the effect of the series winding produces a greater terminal voltage at rated load than at no load, the generator is said to be **overcompounded.** Compound generators are usually wound so that they are slightly overcompounded.

In some generators, the degree of compounding is controlled by a variable resistor in parallel with the series field. This resistor is called a **diverter.** It determines the fraction of the load current that flows through the series field. This gives the same effect as changing the number of turns in the winding.

Q32. A compound generator most resembles a _____ generator in its operation.

Q33. A compound generator in which the rated-load voltage is equal to the no-load voltage is said to be ____ ___________.

Your Answers Should Be:

A32. A compound generator most resembles a **shunt** generator in its operation.

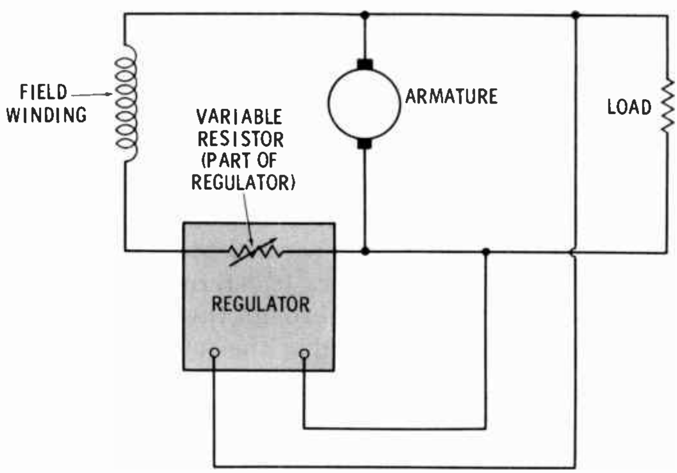
A33. A compound generator in which the rated-load voltage is equal to the no-load voltage is said to be **flat compounded.**

AUTOMATIC VOLTAGE REGULATION

It is possible to use an automatic device to keep the output voltage of a shunt generator nearly constant, even if the load changes. Such a device is called a **voltage regulator.** These regulators automatically change the current through the shunt field winding every time the output voltage starts to vary.

Some regulators have a variable resistance in series with the field winding. If the output voltage decreases, the resistance is decreased, and the voltage is brought back almost to its original value. If the voltage increases, the resistance increases, and the voltage again is returned almost to normal.

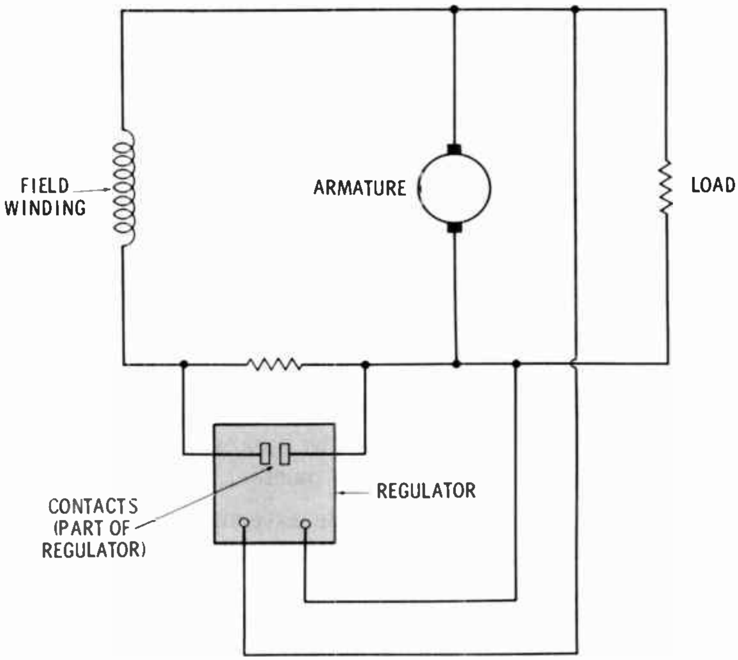
VOLTAGE REGULATION BY VARYING FIELD RESISTANCE



In another type of regulator, a pair of contact points is used to short-circuit a fixed resistor in the field circuit.

When the contacts are open, the resistor limits the field current and keeps the output voltage below the desired value. When the contacts short-circuit the resistor, the voltage rises above the desired value. In operation the regulator causes the contacts to vibrate (open and close rapidly). The average current through the field winding depends on how rapidly the contacts vibrate. This, in turn, is determined by the value of the output voltage.

VOLTAGE REGULATION BY USING VIBRATING CONTACTS



More complicated arrangements are sometimes used to regulate the voltage of shunt generators. However, they all operate by controlling the amount of current flow in the shunt field winding.

Q34. The voltage of a shunt generator is regulated by varying the _____ _____ current.

Q35. A device that automatically keeps the output voltage of a generator nearly constant is called a _______ __________.

Your Answers Should Be:

A34. The voltage of a shunt generator is regulated by varying the **shunt-field** current.

A35. A device that automatically keeps the output voltage of a generator nearly constant is called a **voltage regulator.**

PARALLEL OPERATION OF DC GENERATORS

At times it is necessary for more than one generator to supply electrical energy to the same load. This may be due to peak load demands or the need for continuous service should one generator become disabled.

In order to have more than one generator supply the external load, it is necessary to connect them in parallel. The same general precautions should be taken when connecting DC generators in parallel as are used when connecting batteries in parallel. Polarity and voltage must be the same. It is important to remember that **different paralleling procedures are used for AC than for DC generators.**

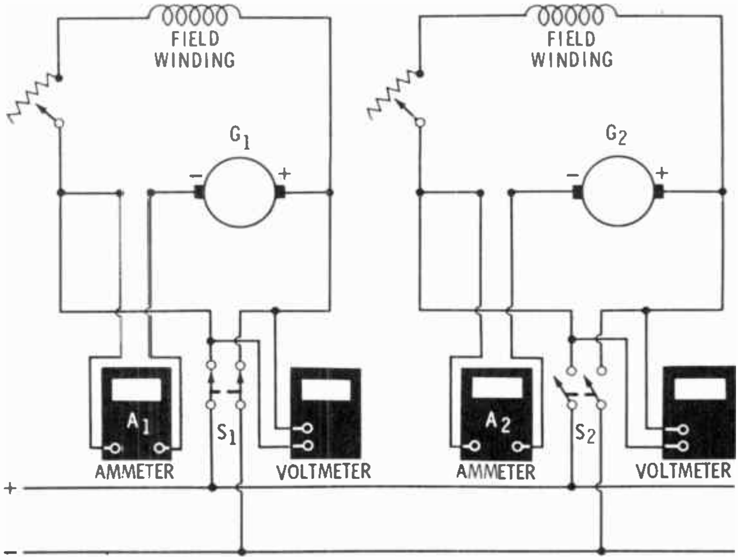
Paralleling Two DC Generators

The figure on the opposite page shows two generators that can be connected to the same load by means of switches. The procedure for connecting them in parallel is as follows.

1. Generator G_1 is supplying the external load; generator G_2 is to be placed into parallel operation with G_1.
2. Switch S_2 must be open to prevent generator 1 from trying to operate generator 2 as a motor.
3. Adjust the shunt-field rheostat of generator 2 to the lowest position.
4. Bring generator 2 up to its rated speed.
5. Adjust the shunt-field rheostat so that generator 2 is supplying slightly more voltage than generator 1. The polarity must be as shown.
6. Close switch S_2 to bring generator 2 into parallel operation with generator 1. NOTE: Generator 2 should be carrying a small portion of the external load.
7. Adjust the shunt-field rheostat of generator 2 to dis-

tribute the load equally. At the same time the shunt-field rheostat of generator 1 is adjusted to maintain the normal voltage.

TWO DC GENERATORS CONNECTED IN PARALLEL



Removing a DC Generator From Parallel Operation

1. Weaken the field of the generator to be removed from operation and at the same time strengthen the field of the remaining generator.
2. When the outgoing generator is no longer carrying any of the load, open the switch so that the generator is removed from operation.

Q36. Are the same procedures used in paralleling AC and DC generators?

Q37. When paralleling DC generators, the positive terminal of one generator must be connected to the _________ terminal of the other.

Q38. The load is transferred from one generator to the other by adjusting the _____ _____ __________.

Your Answers Should Be:

A36. A **different** procedure is used for paralleling AC generators than for paralleling DC generators.

A37. When paralleling DC generators, the positive terminal of one generator must be connected to the **positive** terminal of the other.

A38. The load is transferred from one generator to the other by adjusting the **shunt-field rheostats.**

MAINTENANCE

In order to operate any machine properly, you must be familiar with the construction details and maintenance procedures for the machine. Maintenance should not be confined to the repair and replacement of units that have failed in operation. Regular checks on operating equipment aid in detecting many problems before they become serious.

The nameplate on the generator should list the **maximum temperature rise** for the machine. This is the maximum amount by which the machine should be warmer than the surrounding air.

Check for generator hot spots by touching with the palm of your hand. Check for faulty bearing operation by feeling the bearing caps on the end bells. Naturally, you must be careful to avoid injury when touching the generator. The table on the next page lists some causes and remedies of hot spots.

When the bearings are checked for overheating, you should also test for any vibration. Vibration may be caused by excessive speed of the rotating shaft, and is usually quite loud. If not corrected, this can result in permanent damage to the machine. Excessive speed, if maintained for any length of time, can result in the machine tearing itself apart. Vibration may also be caused by poorly balanced rotating parts or by worn bearings.

It is important to follow the manufacturer's instructions for lubrication and maintenance of bearings. This information is usually contained in the manual that accompanies the equipment. **Follow the manufacturer's instructions exactly.**

Pointers About Lubrication

Remember these things about lubrication. Improper lubrication, either too little or too much, can cause serious damage to moving and electrical parts. Too little lubrication causes friction and wear of moving parts. Excessive lubrication can cause electrical damage—shorting the commutator segments, fouling the commutator brush assembly, or soaking the armature coils.

GENERATOR HOT SPOTS—CAUSES AND REMEDIES

Possible Causes	Remedy
1. Insufficient lubrication.	1. Lubricate.
2. Excessive load on generator.	2. Check ammeter reading with current rating of the generator. If overloaded: a. Reduce generator load. b. Place a second generator in parallel to share the load.
3. Clogged cooling vents.	3. With generator off, blow out with clean, dry air at low pressure.

Q39. How would you determine the allowable temperature rise for a generator?

Q40. What could cause a generator bearing to become too hot?

Q41. What are some causes of vibration in a generator?

Your Answers Should Be:

A39. The allowable temperature rise for a generator is usually given on its **nameplate.**

A40. A generator bearing can become too hot because of **too little lubrication.**

A41. Vibration in a generator can be due to **excessive speed, poorly balanced rotating parts,** or **worn bearings.**

WHAT YOU HAVE LEARNED

1. The main parts of a DC generator are the frame, end bells, pole pieces, shaft, armature, commutator, and brushes.
2. The armature contains a number of coils in order to produce a relatively smooth output.
3. Various types of carbon and graphite brushes are used to take voltage and current from the commutator segments.
4. Most armatures consist of a drum-type iron core with windings set in slots in the core.
5. Armature coils are connected to the commutator in simplex, duplex, or triplex patterns.
6. Coils can be connected in a lap-wound or wave-wound pattern. In a lap-wound pattern, a single coil is shorted by a brush; in a wave-wound pattern, a small group of coils in series is shorted.
7. The neutral plane is the plane where no emf is induced in a coil. The brushes should be set to this position.
8. The electromagnetic field of a DC generator can be either separately excited by an external DC source or self-excited from the generator output in a series, shunt, or compound circuit.
9. A self-excited generator can start with its own residual magnetism or, if necessary, it can be started by flashing the field with an external DC source.
10. Generator losses are copper loss (due to armature reresistance), eddy-current loss, and hysteresis loss.

11. Armature reaction results in the shifting of the neutral plane due to interaction of the magnetic field caused by current flow in the armature with the main magnetic field.
12. A series generator and its external load must be connected in order to obtain voltage from the generator.
13. The current flow in a series generator varies with the current required by the external load and causes the strength of the magnetic field to vary.
14. The series generator is best suited for constant-current applications.
15. The shunt generator does not require that the external load be connected during buildup of that generator.
16. The no-load terminal voltage of a shunt generator is greater than the rated voltage (voltage after external load is connected) because the load-current flow causes power losses within the generator.
17. The current supplied by a shunt generator varies with the external load requirements, but a fairly constant voltage is maintained.
18. The compound generator is basically a shunt generator with a series field used to offset the falling voltage when large amounts of current are required by the external load.
19. The ability of the series field of a compound generator to produce a greater, equal, or lesser terminal voltage than no-load voltage determines if the generator is over, flat, or undercompounded.
20. Regulators can be used to keep the output voltage of a shunt generator nearly constant.
21. A shunt generator can be connected in parallel with another shunt generator only when it has reached a voltage slightly above the voltage of the other generator.
22. Generators should be checked regularly for hot spots and vibration.
23. It is important to follow the manufacturer's instructions for the lubrication and maintenance of generators.

3

DC Motors

What You Will Learn

In this chapter you will learn about DC motors. You will see how they are constructed and find out what reactions occur inside them. You will be able to recognize the different types of DC motors and know the advantages and disadvantages of each. You will learn about starting devices for DC motors, why they are needed, and how they work. You will also learn about the various methods used to control the speed of DC motors.

BASIC DC-MOTOR CONNECTIONS

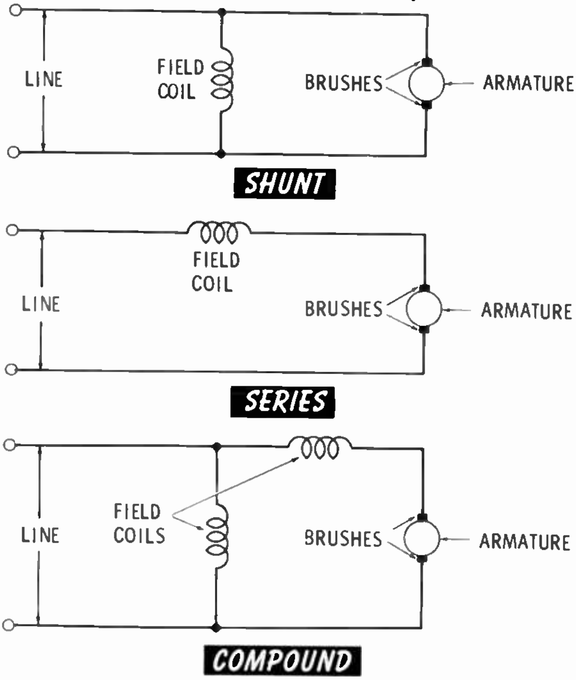
The parts of a DC motor are essentially the same as the parts of a DC generator. A DC motor consists of a frame, end bells, pole pieces, shaft, armature assembly, commutator assembly, and brush assembly. The construction of these parts is essentially the same as for the generator, with minor changes for practical reasons.

The field windings on the pole pieces (also called the **stator**) are supplied with DC. The commutator and armature (sometimes called the **rotor**) are also supplied with DC which is converted to AC, as you learned in Chapter 1. It would be possible, of course, to supply the two windings from different DC sources, but normally they are both supplied from the same source.

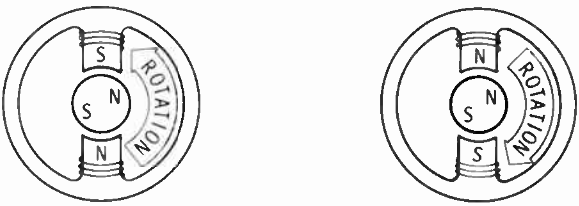
The two windings (stator and rotor) then become parts of the same circuit. The methods of connecting the two windings determine the different types of DC motors. The three basic types are **shunt, series** and **compound** motors.

Notice that the DC motors in the diagrams below are similar to the three types of DC generators.

TYPES OF DC MOTORS



The direction of rotation of any DC motor can be reversed by reversing the leads of the field coils but leaving the armature connections unchanged. If both the field-coil and armature leads are reversed at the same time, the motor will continue to run in the same direction.



EFFECT OF REVERSING FIELD CONNECTIONS IN A DC MOTOR

Reversing the leads of the field coils reverses the polarity of the magnetic field. The armature field remains unchanged. This causes the motor to run in the opposite direction, as shown in the figure at the bottom of the opposite page. The magnetic poles of the rotor and stator, as shown, attract each other until the field connections are reversed. Then the poles repel each other. If both the field and armature connections were reversed, the poles would continue to attract each other, and the motor would not reverse direction.

ARMATURE LOSSES

Armature losses occur in a DC motor for exactly the same reasons they occur in a DC generator. The losses in the armature of a DC motor are copper loss, hysteresis loss, and eddy-current loss. The same kinds of construction are used in DC motors to reduce the armature losses as in DC generators. Armature cores in motors are usually built of laminated steel.

ARMATURE REACTION

Just as in a generator, the interaction of the armature and main magnetic fields distorts the main field. This causes the commutating plane of the motor to shift. There will be excessive sparking when the brushes are not properly aligned in the commutating plane. Armature reaction in the motor can be limited by interpoles and compensating windings.

Q1. What happens to the direction of rotation of a DC motor if the leads of the field but not of the armature are reversed?

Q2. There are armature losses in a DC generator. Are there similar losses of power in a DC motor?

Q3. Armature reaction occurs in a DC generator. Is there armature reaction in a DC motor?

Q4. Another name for the stationary field assembly in a motor is the ______.

Q5. Another name for the rotating armature is the _____.

Your Answers Should Be:

A1. If only the field leads are reversed, the motor **reverses its direction of rotation.**

A2. **There are armature losses in a DC motor** just as there are in a DC generator.

A3. **Armature reaction distorts the main magnetic field** and shifts the commutating plane **in a DC motor just as it does in a DC generator.**

A4. Another name for the stationary field assembly in a motor is the **stator.**

A5. Another name for the rotating armature is the **rotor.**

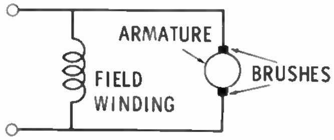
COUNTER EMF

When the armature conductors of a motor rotate in the main magnetic field, an emf is generated. This always happens when a conductor cuts magnetic lines of force. This emf opposes the applied line voltage. The faster the motor turns, the greater the **counter emf** becomes.

When a DC motor is started, a very large current will flow unless a starting resistor is used to limit this current. As the motor builds up speed, however, the counter emf increases and limits the current by reducing the effective voltage across the armature coils.

DC SHUNT MOTORS

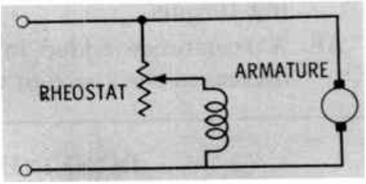
The shunt field winding consists of many turns of small wire and is connected in parallel with the armature winding, or across the line, as shown below.



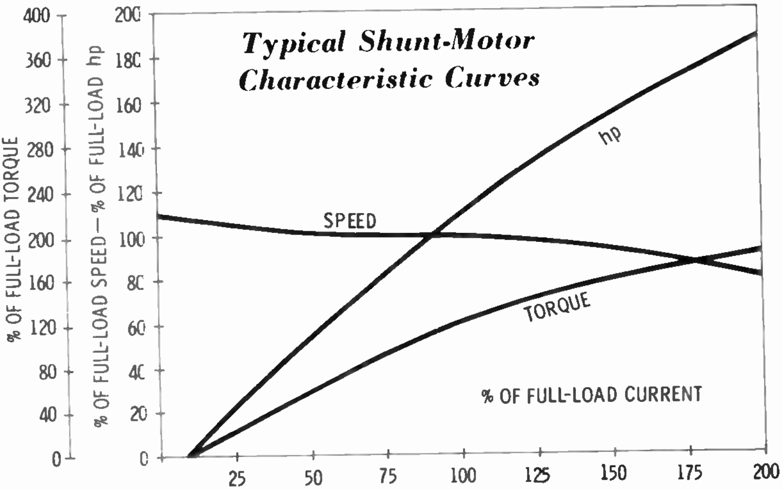
A DC SHUNT MOTOR

The shunt-type motor is used when it is desired to vary the rotational speed above and below the normal speed. Increasing the resistance in series with the shunt field will cause the motor to speed up. (If the field circuit is broken and voltage is still applied to the armature, the motor may run so fast that it damages itself.) A resistor connected in series with the armature will decrease the speed of the motor. The characteristics of any type of motor need to be

DC SHUNT MOTOR WITH FIELD RHEOSTAT



known so that the motor may be used properly. The following figure indicates typical characteristics for a shunt motor.



The main characteristics of a shunt motor are its constant speed and low starting torque. This means that DC shunt motors cannot be used for hard-starting loads.

Q6. The counter emf ---------- when armature speed increases.

Q7. What are the two main characteristics of a DC shunt motor?

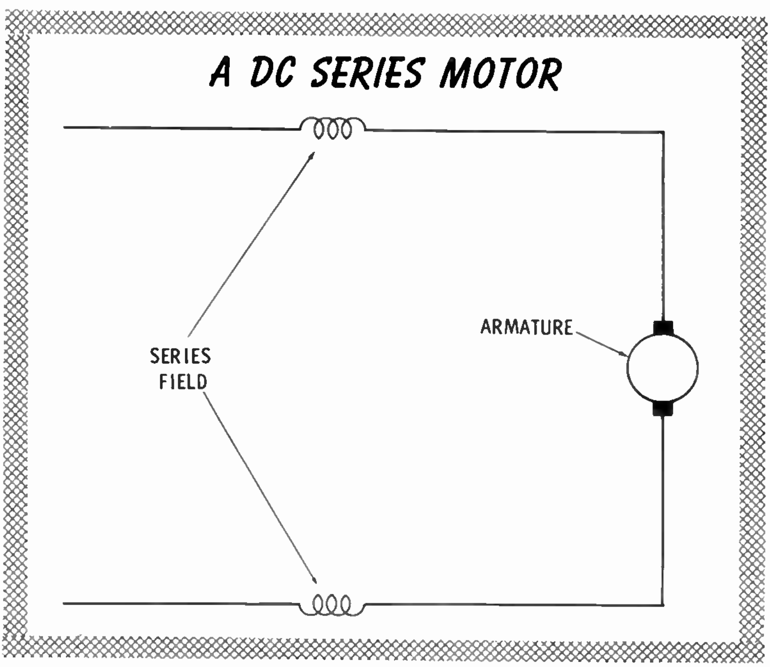
Q8. A resistance added in series with the shunt field ---------- the speed of the motor.

> **Your Answers Should Be:**
>
> A6. The counter emf **increases** when armature speed increases.
>
> A7. The two main characteristics of a DC shunt motor are its **relatively constant speed** and its **low starting torque.**
>
> A8. A resistance added in series with the shunt field **increases** the speed of the motor.

DC SERIES MOTORS

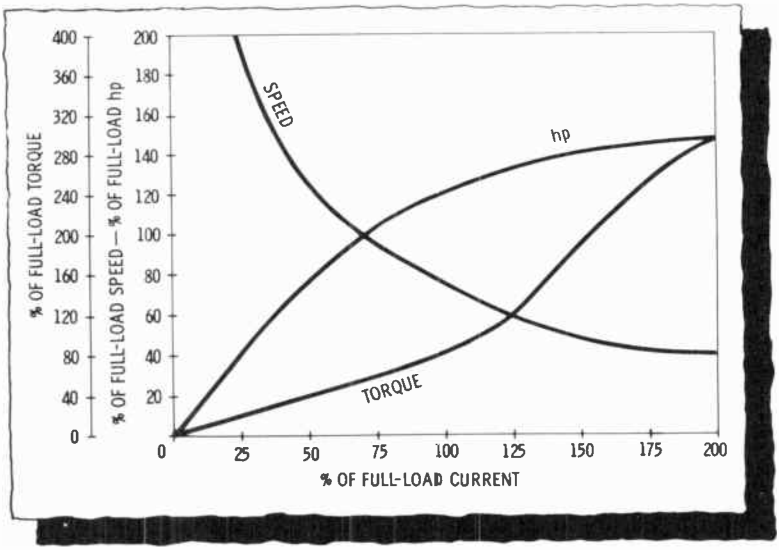
DC series motors have the field and armature windings connected in series. Both sets of windings therefore carry the same current.

The field coil, therefore, must be of much heavier construction than the field of a DC shunt motor in order to withstand the heavy currents. Below is a schematic diagram of a DC series motor.



The starting and stalling torque of a series motor is excellent. It will start and carry very heavy overloads. Speed regulation, however, is very poor. The speed decreases as the load increases. Therefore, the motor turns slower with

Typical Series-Motor Characteristic Curves



a heavy load and faster with a light load. If a DC series motor is run without any load, it may run so fast that it may damage itself. Series motors are seldom used in applications requiring belt coupling to the load; if the belt should break, the motor would be without a load. A typical use of a series motor is the automobile starter.

Q9. Why is the field winding of a series motor wound with larger wire than the field winding of a shunt motor?

Q10. A series motor has a (large, small) starting torque.

Q11. What happens to the speed of a series DC motor operated with no load connected to its shaft?

Q12. The armature current of a series motor (does, does not) flow through the field windings.

Your Answers Should Be:

A9. The field winding of a series motor is wound with larger wire than a shunt field winding because the **series field carries** a **much larger current.**

A10. A series motor has a **large** starting torque.

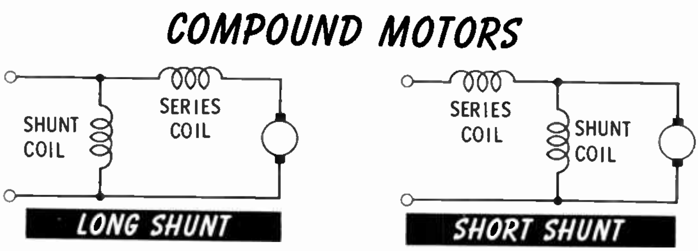
A11. If a series DC motor is operated without load, it runs at a **dangerously high speed.**

A12. The armature current of a series motor **does** flow through the field windings.

DC COMPOUND MOTORS

As the name implies, the DC compound motor is a combination of a DC shunt motor and a DC series motor. It has both a series and a shunt field winding. Its characteristics are a combination of the characteristics of the DC series motor and the DC shunt motor. When the shunt field coil and the series field coil act to aid each other, the machine is said to be a **cumulative-compound** motor. With the shunt field coil and the series field coil opposing each other, the machine is called a **differential-compound** motor.

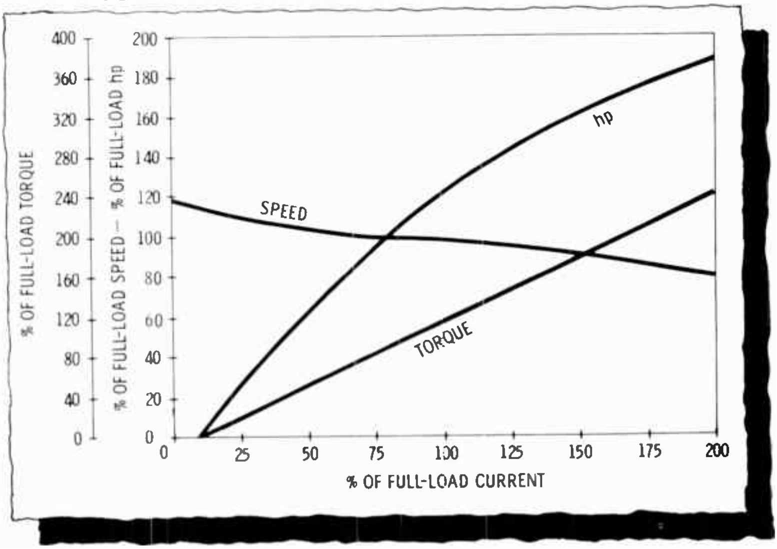
Compound motors are divided into two groups according to the manner in which the series field coil is connected with respect to the shunt field coil. These two groups are known as **short-shunt** and **long-shunt** compound motors.



By proper control of the relative strength of the two field coils, the compound motor may be used to meet any requirement that can be met by a pure series motor or a pure shunt motor. The characteristics shown on the opposite page apply to a typical compound motor, but not necessarily to every compound motor.

Examination of the chart below reveals that the speed of a compound motor is almost as constant as that of a shunt motor and the starting torque is almost as high as that of a series motor. A compound motor does not run dangerously fast even at no load. Compound motors can be designed to have different characteristics.

Typical Shunt-Motor Characteristic Curves



The compound motor has two field windings. For this reason, a compound motor is usually more expensive than either a series or shunt motor of the same capacity.

Q13. What type of DC motor has the highest starting torque?

Q14. What type of DC motor should never be started without a mechanical load connected?

Q15. What type of DC motor has a constant speed characteristic?

Q16. DC shunt motors have a ___ starting torque.

Q17. The same current flows through the armature and field coils in a DC ______ motor.

Q18. How does a short-shunt compound motor differ from a long-shunt compound motor?

Your Answers Should Be:

A13. A **series** DC motor has the highest starting torque.

A14. A **series** motor should always have a mechanical load.

A15. A **shunt** DC motor has a constant speed characteristic.

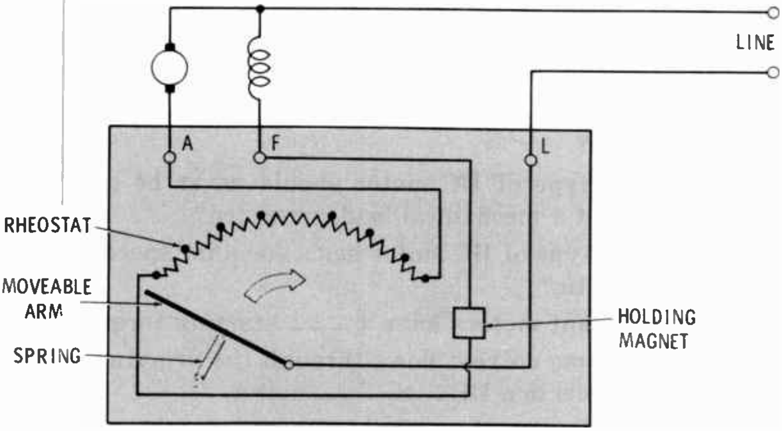
A16. DC shunt motors have a **low** starting torque.

A17. The same current flows through the armature and field coils in a DC **series** motor.

A18. A short-shunt motor has its shunt field connected **directly across the armature.** A long-shunt motor has the **series field between the armature and** the **connection to the shunt field.**

MANUAL STARTERS

A DC motor presents a very low resistance to a voltage source whenever the armature is at rest. For instance, a motor normally drawing 50 amperes at full load may have a starting current of 500 amperes or more. This inrush current could easily damage the motor. In order to prevent this condition, **starters** are often used. Starters are usually

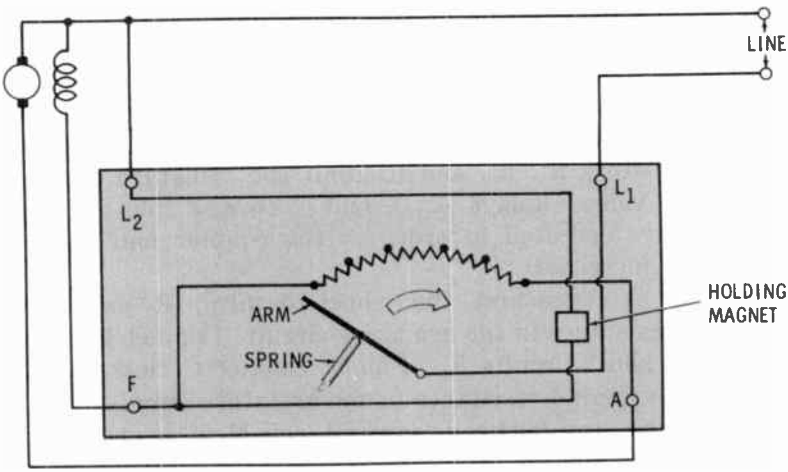


THREE-POINT STARTING BOX

required only with machines rated at more than ¼ horsepower. In most cases, the starters are rheostats connected in series with the armature. These rheostats are usually contained in an enclosure called a **starting box.**

In a **three-point** starting box the connections are made as shown in the figure on the opposite page. When the voltage is turned on, the rheostat in series with the armature limits the armature current to a reasonable level. As the motor gains speed, the operator turns the rheostat arm in the direction of the arrow, one step at a time. Some of the resistance is also in series with the shunt field, but is small enough to be neglected. The holding magnet is energized by the field current so that when the arm has been pushed across the entire rheostat, the holding magnet will hold it in this position. If the field circuit should become open, the arm is released and returns to the off position.

FOUR-POINT STARTING BOX



The operation of the **four-point** starting box is similar to that of the three-point starting box. However, the holding magnet releases the arm when the voltage, rather than the field current, is lost. The four-point box is the more common.

Q19. How many external connections are there on a three-point starting box?

Q20. When is the arm on a four-point starter released?

Your Answers Should Be:

A19. A three-point starting box has **three** external connections: line, armature, and field.

A20. The arm on a four-point starter is released when the **supply voltage is lost**.

AUTOMATIC STARTERS

Automatic starters are commonly used when frequent starting of DC machines is necessary. These starters can be operated by relatively inexperienced personnel since they involve only button pushing.

The motor in the figure on the opposite page is a compound motor, but the circuit would apply equally well to shunt motors (by removing the series field coil) or to series motors (by removing the shunt field loop).

As the starting push button is depressed, line voltage is applied to coil M. The coil closes the two normally open contacts, M_1 and M_2. M_1 causes continued current flow through coil M. M_2 causes the armature to receive voltage. The three series resistors R_1, R_2, and R_3 limit the armature current to a safe value. Relays A, B, and C (whose coils are not shown) are operated in order as the counter emf in the armature increases.

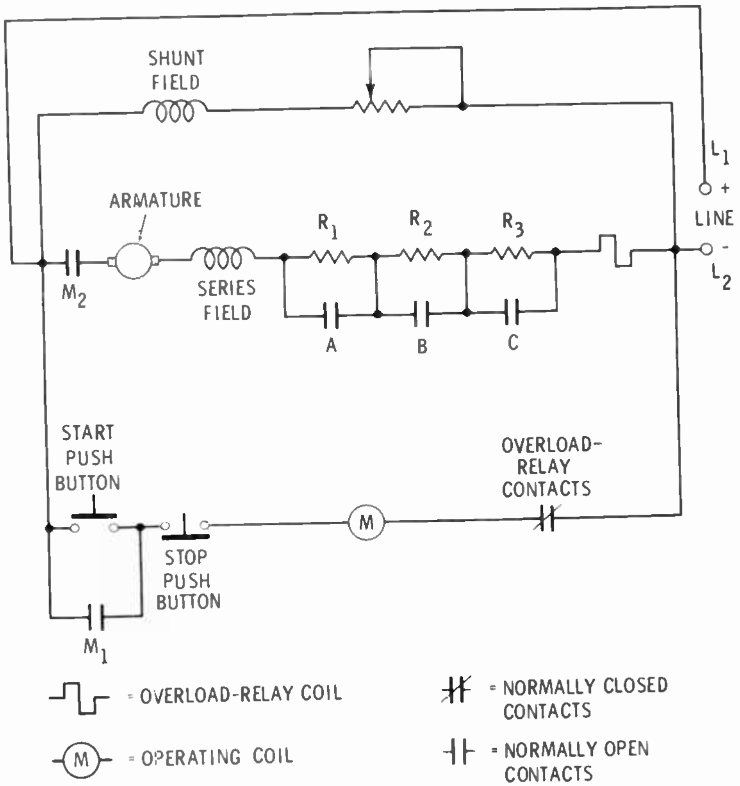
Contact A closes first, thus short-circuiting R_1 and leaving less resistance in the armature circuit. Contact B closes next and short-circuits R_2. Finally contact C closes. This leaves no external resistance in the armature circuit.

When the stop button is pressed, coil M is de-energized, and both M_1 and M_2 open. As the motor comes to a stop, contacts A, B, and C open.

If an overload occurs during normal motor operation, the heavy current will activate the overload relay and open its contacts. This is equivalent to pushing the stop button.

The short-circuiting of the resistances in series with the armature can be accomplished by time-delay relays, voltage-sensitive relays, or current-sensitive relays. The theory always remains the same—use series resistance to start and lower the resistance value as the motor picks up speed. Voltage-sensitive relays operate as the counter emf in the armature increases. Current-sensitive relays operate as the armature current **decreases.**

AUTOMATIC-STARTER CIRCUIT



Q21. What is the purpose of DC-motor starters?

Q22. Name the three types of relays that can be used to short-circuit resistors in an automatic starter.

Q23. Voltage-sensitive relays respond to the ---------- in the armature.

Q24. In a motor starter, current-sensitive relays act when the current ----------.

Q25. Under what conditions are automatic starters commonly used?

Your Answers Should Be:

A21. DC-motor starters are designed to **limit the starting current** to prevent damage to the armature.

A22. **Voltage-sensitive, current-sensitive,** and **time-delay** relays can be used to short-circuit resistors in an automatic starter.

A23. Voltage-sensitive relays respond to the **counter emf** in the armature.

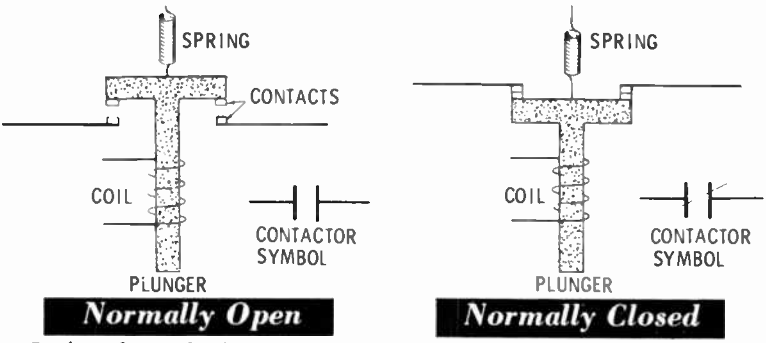
A24. In a motor starter, current-sensitive relays act when the current **decreases.**

A25. Automatic starters are commonly used when **frequent starting** is necessary.

RELAYS

There are several types of relays used in DC-motor controllers. The simplest is a switch closed or opened by an electromagnet when the current through the relay coil reaches a certain level.

SIMPLE RELAYS

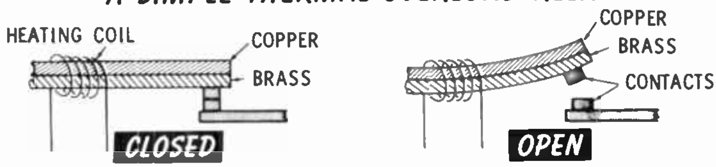


It is often desirable for a relay to operate only after a certain time delay. For example, the automatic starter just described may use time-delay relays to assure that the motor reaches its full load current after a given time, no matter what the load on the motor. Or it may not be desirable to have an overload relay disconnect the motor as a result of a momentary overload. A time-delay relay can be used for this purpose also.

Thermal Time Delay

Several types of relays can offer a time delay. One type often used for overload protection is the **thermal overload relay.** This relay is operated by heat rather than magnetism. A strip of brass and a strip of copper are fastened together to form a **bimetal strip.**

A SIMPLE THERMAL-OVERLOAD RELAY

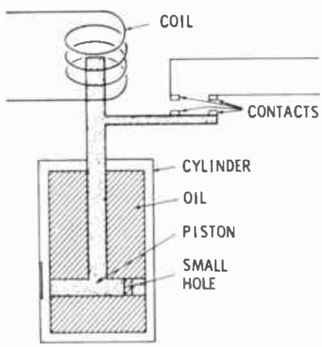


When the bimetal strip is heated, the brass expands more than the copper, and the strip bends away from the fixed contact and opens the circuit. The action of this relay depends on the heating effect of the current. That is, it depends on both the amount and the duration of the current. If a heavy current flows for a short time but not long enough to cause overheating of the motor, the relay will stay closed.

Dashpot Time Delay

Automatic starters generally use magnetic time-delay relays. One type, the **dashpot** timing relay, uses a cylinder containing oil (called a dashpot) to slow down the motion of a plunger.

A DASHPOT RELAY



Q26. Two types of time-delay relays depend on a _______ _____ or a _______ to determine the amount of time delay.

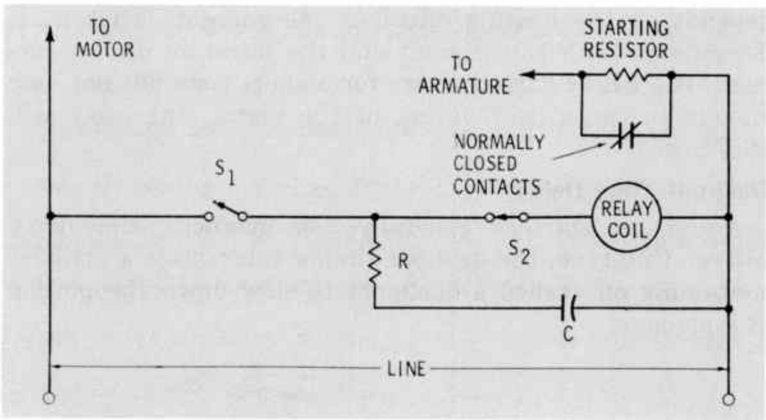
Your Answer Should Be:

A26. Two types of time-delay relays depend on a **bimetal strip** or a **dashpot** to determine the amount of time delay.

Resistance-Capacitance Time Delay

It is also possible to make use of the RC time constant of a resistor and capacitor to establish a time delay. For practical purposes, a current strong enough to operate a relay will flow from a discharging capacitor for a period equal to about five time constants.

A CAPACITOR TIME DELAY



In the simplified circuit shown above, S_1 is closed and S_2 is open when the motor is off. The capacitor becomes charged. When the motor is started, S_1 is opened and S_2 is closed. The capacitor discharges through resistor R and the relay coil. During the first moments after the motor is turned on, enough current flows through the relay to hold its contacts open. This causes the starting resistor to limit the armature current. When the capacitor-discharge current decreases below a certain value, the relay contacts close, short-circuiting the starting resistor. Armature current is no longer limited except by the counter emf which is now high enough to protect the armature.

MOTOR EFFICIENCY

Before motor efficiency can be discussed, the term efficiency must be thoroughly understood. **Efficiency** is the ratio of the amount of power obtained from a machine to the amount of input power required to operate it. Therefore, efficiency is a ratio of the power output to the power input of a system. This statement can be written as follows:

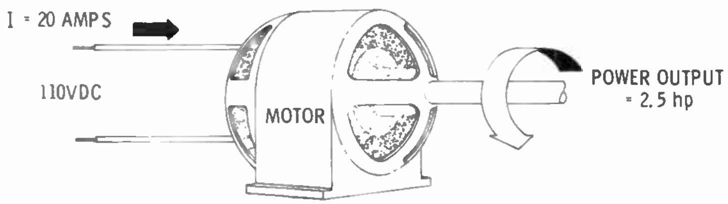
$$\text{Eff} = \frac{P_o}{P_i}$$

If a system requires 1,000 watts at the input while delivering 800 watts at the output, its efficiency is:

$$\text{Eff} = \frac{P_o}{P_i} = \frac{800}{1{,}000} = 0.80 \text{ or } 80\%$$

Efficiency is usually expressed as a percentage. In a motor, the output (mechanical power) is measured in horsepower (HP) while the input (electrical power) is measured in watts. The output is multiplied by 746 in order to obtain its equivalent in watts. For example, 1 HP = 746 W, so 2 HP = 2 × 746 = 1,492 W.

What is the Efficiency of This Motor?



To find the efficiency of the motor above, you must calculate the power input (in watts) and power output (in watts), and then use the formula to find efficiency.

$P_i = E \times I = 110 \times 20 = 2{,}200 \text{ W}$
$P_o = \text{hp} \times 746 = 2.5 \times 746 = 1{,}865 \text{ W}$
$\text{Eff} = \frac{P_o}{P_i} = \frac{1{,}865}{2{,}200} = 0.85\text{, or } 85\%$

Q27. If a motor requires an input of 30 amperes at 230 volts when its output is 8 HP, what is its efficiency?

Your Answer Should Be:

A27. $P_i = 230 \times 30 = 6{,}900$ W; $P_o = 8 \times 746 = 5{,}968$W

$$\text{Eff} = \frac{P_o}{P_i} = \frac{5{,}968}{6{,}900} = 0.86, \text{ or } 86\%.$$

Motor Losses That Affect Efficiency

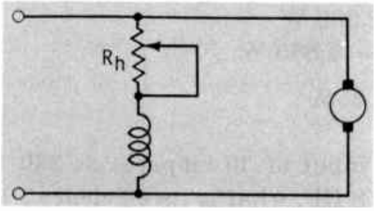
Now that you know how to calculate efficiency, the question of why the output power is smaller than the input power should be answered. A motor has several electrical losses. There are armature losses, losses in the field windings, and losses in the shunt-field rheostat.

There are also mechanical losses in the form of friction. The armature runs on bearings, and the brushes "rub" against the commutator. In addition, the entire armature has to overcome air friction while spinning. The power necessary to provide for these friction losses must be supplied from the input source. A fan is connected to one end of the armature to cool some motors. This amounts to an additional loss due to air friction. All these mechanical losses depend mainly on the speed.

Motor efficiency increases as the physical size of the motor increases. For fractional-horsepower motors, efficiencies are about 40-50%. In the 10-HP range the efficiency is about 85%. This is because the mechanical losses do not increase with the motor size at the same rate as power output.

SPEED CONTROL

One of the great advantages of DC motors over AC motors is that the speed of DC motors can be controlled easily. There are three basic methods for speed control. These make use of a **shunt-field rheostat, resistance in the armature circuit,** or **armature-voltage control.**



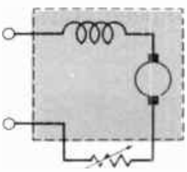
SPEED CONTROL WITH SHUNT-FIELD RHEOSTAT

Look at the figure at the bottom of the opposite page. As the rheostat (R_h) is changed to increase the resistance in the circuit, **less current** flows in the field coil, and the speed of the motor **increases.** When the resistance is completely short-circuited, the full voltage is impressed on the field coil, and the motor rotates at its lowest possible speed.

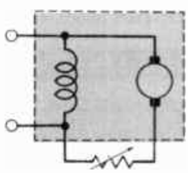
If the resistance of the rheostat is increased, the strength of the main field will decrease. The counter emf generated in the armature will also decrease. The current through the armature will then increase, and the speed of the motor will increase. When the resistance is decreased, the opposite action takes place, and the motor slows down.

As a motor speeds up, the commutator begins to spark (every commutator has a practical speed limit), and the mechanical stresses within the rotor increase sharply due to centrifugal force and vibration. If the speed continues to increase, the armature may fly apart.

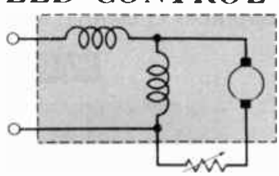
ARMATURE-RESISTANCE SPEED CONTROL



Series Motor



Shunt Motor



Compound Motor

Armature-resistance speed control is obtained by inserting an external variable resistance in series with the armature circuit, as shown above. Speed control for series motors is usually not required since they are used where varying speed is permissible. While this system meets the requirement of excellent speed control, the main disadvantage is the considerable amount of power loss in the control rheostat. This, in turn, makes the motor efficiency very low.

Q28. What are the mechanical losses in a DC motor?

Q29. Why is more power lost in an armature speed-control rheostat than in a shunt-field rheostat?

Q30. When the shunt-field resistance is increased, the speed of a motor ---------.

Q31. When the armature resistance is increased, the speed of a motor ---------.

Your Answers Should Be:

A28. Mechanical losses in a DC motor include **bearing friction, commutator friction,** and **air friction.**

A29. More power is lost in an armature speed-control rheostat than in a shunt-field rheostat because the **armature** normally **carries more current than the field coils.**

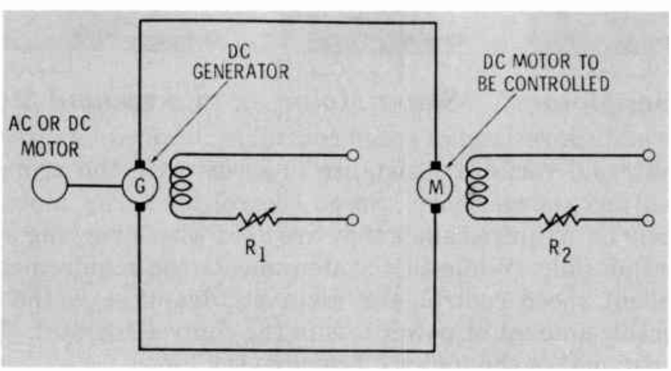
A30. When the shunt-field resistance is increased, the speed of a motor **increases.**

A31. When the armature resistance is increased, the speed of a motor **decreases.**

Ward Leonard Speed Control

The speed of a DC motor can be controlled by varying the armature voltage. This is done by the Ward Leonard system shown in the figure below. This system is the most accurate but also the most expensive method of motor-speed control.

WARD LEONARD SPEED CONTROL



The shunt fields of both the generator and motor are supplied from a constant-voltage source. The DC-generator output voltage is controlled by rheostat R_1. The voltage variation (out of G and into M) gives a wide range of speed control. In addition, by varying the motor rheostat (R_2), a wider speed range can be obtained.

This system requires three machines instead of one. A source of voltage for the field windings is also needed. In some cases this may be a fourth machine. However, in many cases the higher cost of this system is justified by the complete range of speed control it makes possible. With it the speed can be varied accurately from zero to maximum.

Q32. The Ward Leonard system controls the motor speed by varying the ________ _______.

Q33. Which type of speed control gives full-range control of speed?

WHAT YOU HAVE LEARNED

1. The main parts of a DC motor are the frame, end bells, pole pieces, shaft, armature assembly, commutator assembly, and brush assembly.
2. A DC motor has armature losses of the same sort as a DC generator: copper losses, eddy currents, and hysteresis losses.
3. Armature reaction occurs in a DC motor and can be limited by interpoles and compensating windings.
4. A motor, when it is turning, also acts as a generator and creates a counter emf that opposes the applied voltage and limits the flow of current through the armature.
5. There are three main types of DC motors—shunt, series, and compound.
6. Shunt motors have a low starting torque and a relatively constant speed regardless of load.
7. Shunt motors must not be operated without field current because the motor will then run at a dangerous speed.
8. Series motors have a high starting torque, but their speed varies greatly as the load changes.
9. Series motors must never be operated without a load because under that condition the speed will be so great that the armature may fly apart.
10. Compound motors combine the characteristics of both series and shunt motors in proportions that depend on the construction of the particular motor.
11. DC motors are started with a resistance in series with the armature to limit the starting current.

Your Answers Should Be:

A32. The Ward Leonard system controls the motor speed by varying the **armature voltage.**

A33. The **Ward Leonard** system gives full-range control of speed.

12. Two common ways of providing starting resistance for DC motors are the three-point and four-point starting boxes. In these devices, a contact is moved by hand to bypass the starting resistance as the motor gains speed. A magnet holds the contact in place while the motor is operating.
13. Automatic starting boxes perform the starting function automatically by using relays to bypass the resistance as speed builds up or after a time delay.
14. Thermal overload relays are operated by the heating effect of a current and can be used to protect motors from overheating.
15. Dashpot time-delay relays use an oil-filled piston to slow down the action of the relay.
16. An RC circuit can be used to provide a time delay for the operation of a relay.
17. Motor efficiency is found by dividing the output power by the input power. One horsepower is equal to 746 watts.
18. Motor speed can be controlled by use of a shunt-field rheostat.
19. Motor speed can also be controlled through the use of an armature speed-control rheostat. The disadvantage of this system is that it reduces motor efficiency considerably through power loss in the rheostat.
20. The most useful system of speed control is armature-terminal–voltage speed control (the Ward Leonard system), which uses an independent generator to provide voltage to the armature. This system allows a wide range of accurately controlled speeds, but it is complex and expensive.

4

AC Generators

What You Will Learn

The principles of AC-generator operation are presented in this chapter. You will learn the applications of the various generator types and how to recognize them. You will become familiar with the characteristics of AC generators and how they are regulated.

ALTERNATORS

AC generators are also known as **alternators.** They vary in size from no larger than a walnut to bigger than a house. Almost all electrical power for homes and industry is supplied by alternators in power plants. An AC generating system consists of the **armature, field,** and **prime mover.**

The Armature

The armature is that part of a generator in which the output voltage is induced. The current that flows to the load also flows through the armature. In an alternator, the armature is an assembly of coils, as in a DC machine. The armature may be either the rotating (rotor) or stationary (stator) member of an AC generator.

The Field

DC is supplied to the field winding in an alternator. This DC current creates a magnetic field which is cut by the armature winding. A separate DC source is usually used for the field. The field in alternators supplying up to 50 KW is usually the stationary part (stator). In larger machines the field is the rotating component (rotor). Electrically, it makes no difference whether a rotating winding cuts a stationary field or a rotating field cuts a stationary winding.

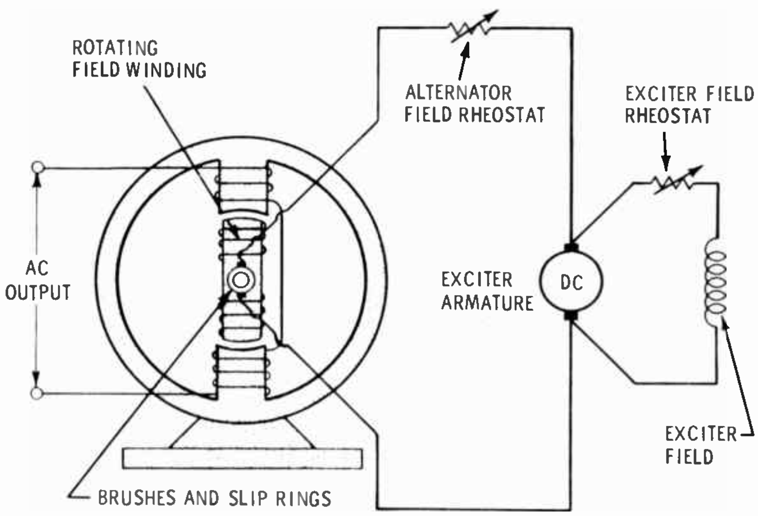
The field requires relatively low voltage and current compared to the high voltage and current generated in the armature of a large alternator. It is easier to connect this low voltage and current to a rotor through slip rings than it is to connect high AC voltage and current. This is why the field is the rotating part in large alternators.

The Prime Mover

The **prime mover** is the source of mechanical power which drives the rotor of the alternator. It can be a gasoline engine, a steam turbine, a water turbine, or any such source. The prime mover can even be an electric motor.

SYNCHRONOUS ALTERNATORS

The synchronous alternator is the basic and most common AC generator. The DC excitation is provided from an outside source, usually a small DC generator. The shaft of the alternator is driven at a constant speed, usually 1,800 or 3,600 rpm. As has been mentioned before, either the armature or the field of the alternator can be the rotor.



BASIC SYNCHRONOUS ALTERNATOR

Field Current

DC current can be supplied to the field in several ways. In most cases it is supplied by a DC generator called an **exciter.** The exciter may supply a DC line (called a **bus**) that is tapped to supply several loads. In other cases, the DC generator may be connected directly to the same shaft as the alternator, or it may be driven from the alternator shaft by a belt connection. Belt-connected exciters are used with relatively slow machines.

Since generators cannot operate without DC excitation, power plants usually have one or two spare exciters capable of taking over in case of an exciter failure. The exciter is usually a compound-wound DC generator that is flat compounded and rated at either 125 or 250 volts according to the size of the alternator. A flat-compound DC generator is used for excitation current because this type of machine gives the most constant voltage regardless of load.

Inductor Alternator

Inductor alternators are used to produce voltages at frequencies between 500 and 10,000 cycles per second. They are used for supplying power to induction furnaces for melting or heating metals.

In an inductor alternator both the armature and the field are stationary. The only rotating element is a toothed steel rotor which distorts the magnetic field of both the field and the armature. The motion of the steel teeth produces a rapidly vibrating magnetic field which induces a very high-frequency voltage in the armature winding.

Q1. What type of alternator is used to supply household current?

Q2. What type of alternator would be used to obtain a 5,000-cps AC current?

Q3. What is the minimum number of generators you could expect to find at an AC power-supply installation?

Q4. Why do large synchronous alternators have rotating fields and stationary armatures?

Q5. Why is a flat-compound generator used as an exciter for a synchronous alternator?

Your Answers Should Be:

A1. A **synchronous alternator** supplies household current.

A2. An **inductor alternator** would be used to obtain a 5,000-cps AC current.

A3. You would expect to find at least **two generators** at an AC power installation—an alternator and a DC exciter.

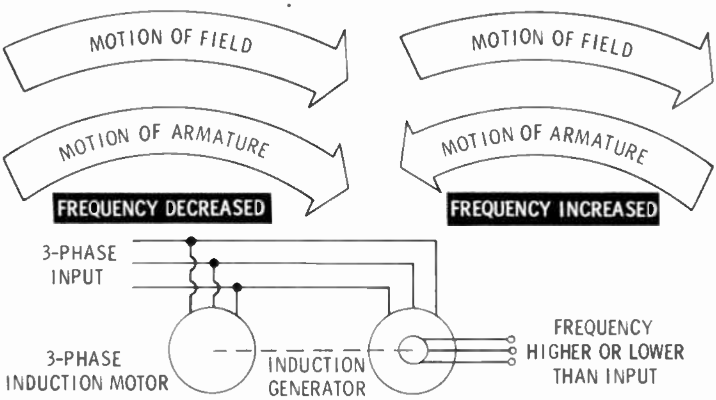
A4. Large synchronous alternators have rotating fields because the **field current and voltage are much smaller than the armature current and voltage.**

A5. A flat-compound generator provides a **constant output voltage** over a wide variation of load.

THE INDUCTION GENERATOR

The induction generator can be used to develop special frequencies for special applications. For example, some high-speed tools are operated by AC voltages at frequencies of 90, 100, 175, or 180 cps. Induction generators can also supply AC voltages at 25 or 50 cps. An induction generator may be considered a device for changing the frequency of AC, since it uses a three-phase AC power source.

PRINCIPLE OF FREQUENCY CHANGING



The power source is used to drive an AC motor. At the same time, it is used to establish a rotating magnetic field.

In the figure on the opposite page, the magnetic field itself rotates and the field coils remain stationary. (You will see how this is done in the following chapter when induction motors are discussed.) If the armature of the induction generator is standing still, the voltage induced in it will have the same frequency as the rotating magnetic field. The action is very similar to that of a transformer. However, if the armature is made to turn, the frequency of the induced voltage is no longer the same as the frequency of the field. If the armature turns in the same direction as the rotating field, the generated frequency will be lower. In fact, if the armature turns at the same speed as the rotating field, the induced frequency will be zero. When the armature is moving in a direction opposite from that of the rotating field, the relative speed is increased and the frequency is higher.

SINGLE PHASE AND POLYPHASE

Single phase refers to the type of generator discussed in Chapter 1. Single-phase alternators have only one armature winding whose leads deliver the output of the alternator. They deliver an AC output between two wires only.

Polyphase machines have more than one winding and deliver an output between several pairs of wires. The most common type of polyphase machine is the three-phase type. Two-phase machines are also sometimes used. Three-phase generators are widely used because large amounts of power can be transmitted more efficiently with a three-phase system than with a single-phase system.

Q6. What type of generator could be used to obtain a 120-cps output?

Q7. When an induction generator supplies an output frequency higher than the input frequency, is the rotor turning in the same direction as the magnetic field?

Q8. What is the advantage of a three-phase power system over a single-phase power system?

Q9. A single-phase generator delivers voltage between only ___ wires.

Your Answers Should Be:

A6. An **induction generator** could provide a 120-cps output.

A7. **No.** When the output frequency of an induction generator is higher than the input frequency, the rotor is turning in the **opposite** direction from the magnetic field.

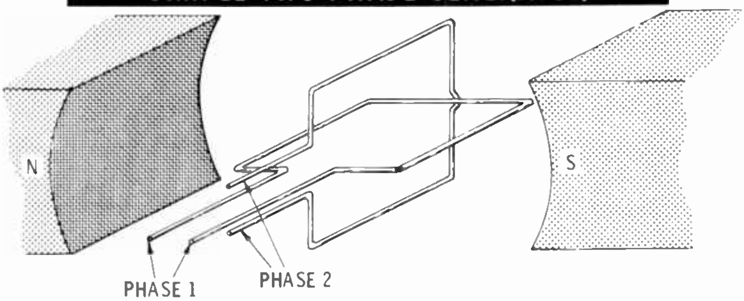
A8. Power is **transmitted more efficiently** in a **three-phase** system than in a **single-phase** system.

A9. A single-phase generator delivers voltage between only **two** wires.

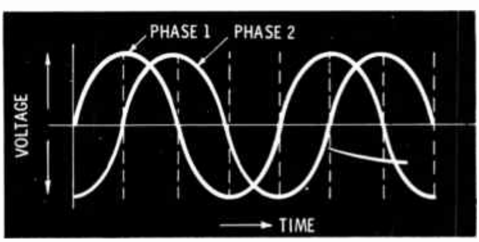
Two-Phase Alternator

The **two-phase alternator** is, as the name implies, a machine that has two separated windings on its armature. Usually the two windings are mounted 90 electrical degrees

SIMPLE TWO-PHASE GENERATOR



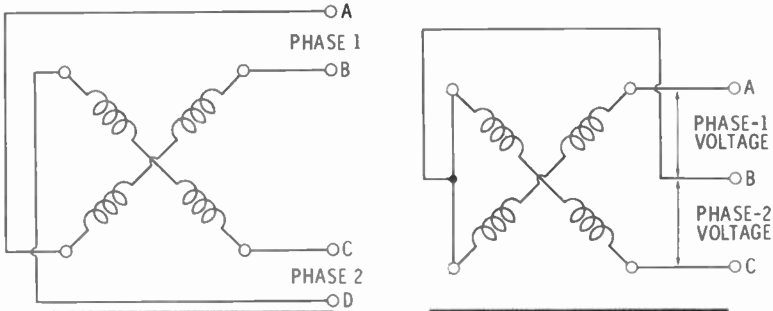
apart. Thus, when the voltage in one coil reaches its peak, the other one is at zero, and vice versa. The figure below indicates the phase relationships in a two-phase alternator.



PHASE RELATIONS IN A TWO-PHASE GENERATOR

The armature windings of a two-phase generator can be connected in two different ways. It is possible to simply make individual connections to the two separate windings. This arrangement gives four output connections and is called a **four-wire system.**

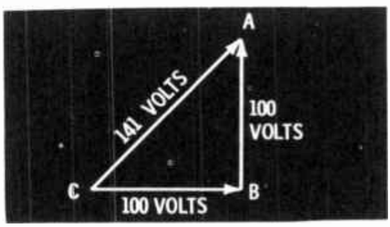
TWO-PHASE SYSTEMS



Four Wire | **Three Wire**

It is also possible, however, to combine two of the output connections to produce what is called the **three-wire system.** In this system the voltages of the two separate phases remain the same. Phase 1 appears between A and B. Phase 2 appears between B and C. But a third voltage is also available, the voltage between A and C. This voltage is the **vector sum** of the other two voltages.

VOLTAGE RELATIONSHIPS IN A TWO-PHASE GENERATOR



In the figure above, single-phase voltages of 100V exist between A and B and between B and C. The voltage between A and C is 1.41 times the single-phase voltage if the two phase voltages are equal.

Q10. In a three-wire, two-phase system, how can the combined voltage of the two phases be calculated if the individual phase voltages are equal?

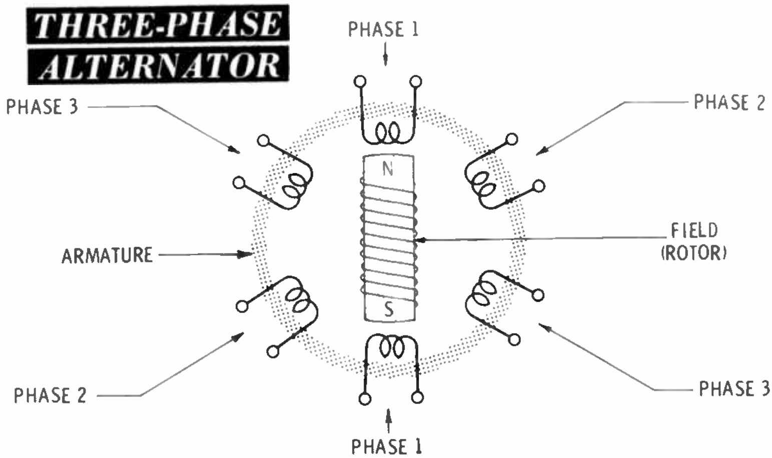
Your Answer Should Be:

A10. The combined voltage is **1.41 times the voltage of one phase,** provided the phase voltages are equal.

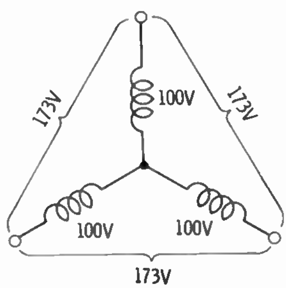
Three-Phase Alternator

A three-phase alternator has three separate armature windings connected in either a **delta** or **wye** (Y-shaped) pattern. A detailed discussion of these methods of connection is given in Chapter 6 of this volume. (In the figure below, each phase winding is made up of two parts.)

THREE-PHASE ALTERNATOR



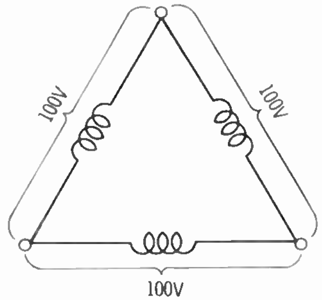
The three single-phase voltages of a three-phase alternator are usually 120 electrical degrees apart. As in the two-phase machine, it is possible to obtain single-phase voltages and also voltages between phases. The relationship



VOLTAGES IN A WYE-CONNECTED, THREE-PHASE ALTERNATOR

between these voltages depends on whether a delta or wye connection is used.

VOLTAGES IN A DELTA-CONNECTED, THREE-PHASE ALTERNATOR



As you will see in Chapter 6, three-phase power can be transmitted more economically than single-phase power can be transmitted.

GENERATOR RATINGS

The ratings of an AC generator are usually given on a nameplate attached to the outside of the frame of the machine. The following information is usually given:

1. Manufacturer's serial and type numbers.
2. Number of phases.
3. Speed (rpm).
4. Number of poles.
5. Maximum voltage ratings (output).
6. Frequency of output.
7. KVA (or KW) rating.
8. Armature current (in amps per phase).
9. Ambient temperature and temperature rise.
10. Field current (in DC amps).
11. Power-factor limits.

Additional information, such as whether the generator can be operated continuously, may be given.

Q11. If the single-phase voltage of a three-phase, wye-connected alternator is 120V, what is the voltage between phases?

Q12. How many between-phase outputs can be obtained from a three-phase machine?

Your Answers Should Be:

A11. 120V × 1.73 = 208V.

A12. You can obtain **three** between-phase outputs.

ARMATURE REACTION

Armature reaction occurs in an alternator just as it does in a DC generator. The magnetic field of the armature interacts with the main field. With a purely resistive load, this effect is similar to that in a DC machine. There is some distortion of the main magnetic field which changes the waveform of the output voltage.

However, current in an AC circuit is not always in phase with the applied voltage. This means, also, that current in the armature is not always in phase with the induced voltage. This fact gives rise to an interesting effect. When the load is highly inductive and the current lags behind the load voltage, the phase shift of the current causes the magnetic field of the armature to oppose the main field and partly cancel it. If an inductive load is applied to an alternator, there is a drop in output voltage. Exactly the opposite happens with a capacitive load. Here, the load current leads the load voltage, and the armature field now adds to the main field. The output voltage of an alternator will be higher with a capacitive load.

FREQUENCY

In all alternators the frequency is controlled by the speed of the rotor. The relationship between the speed of the rotor and the output frequency of an alternator is given by the following formula:

$$f = \frac{P \times S}{120}$$

where,

f is the frequency in cps,
P is the number of poles,
S is the speed in rpm.

This formula applies regardless of the number of phases.

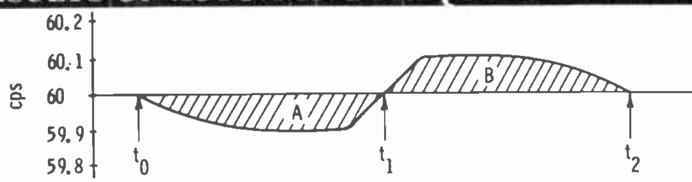
FREQUENCY CONTROL

Generators must maintain very steady frequencies since so many electrical devices require an accurate supply frequency. For example, all electric clocks depend on an accurate frequency to maintain the correct time. A variation of only 1 cycle per second would mean a change of 24 minutes every 24 hours. Many devices, such as timers, are operated by synchronous motors because of the constant speed of this type of motor. The constant speed of a synchronous motor depends directly on a constant-frequency input.

The frequency of an alternator depends on the speed of the prime mover. If the steam turbine, hydraulic turbine, or fuel engine driving the generator has a reliable speed regulation, the generator frequency will be constant.

In large power plants, very accurate frequency-recording instruments and means of compensating for any speed changes are maintained. Thus, if the frequency should drop for a short period, a control device will overspeed the shaft to make up for the loss. The following figure shows a frequency-time diagram for such automatic correction.

RESULTS OF AUTOMATIC FREQUENCY CONTROL



At time t_0 a situation such as a heavy load lowered the frequency to 59.9 cps. At time t_1 the automatic device sensed the loss and forced the frequency to 60.1 cps until time t_2. At that time the machine had caught up with itself. Shaded areas A and B on the diagram must be equal in order for the machine to be caught up.

Q13. What would be the frequency of a 4-pole alternator operated at a speed of 1,500 revolutions per minute?

Q14. Does the number of phases affect the frequency of the output? Why?

Q15. What happens to the output voltage of an alternator when the load is capacitive?

Your Answers Should Be:

A13. $f = \frac{P \times S}{120}$

$f = \frac{4 \times 1{,}500}{120} = $ **50 cps**

A14. No. One complete revolution generates one complete cycle in each winding.

A15. When a capacitive load is connected to an alternator, the **output voltage rises.**

VOLTAGE REGULATION

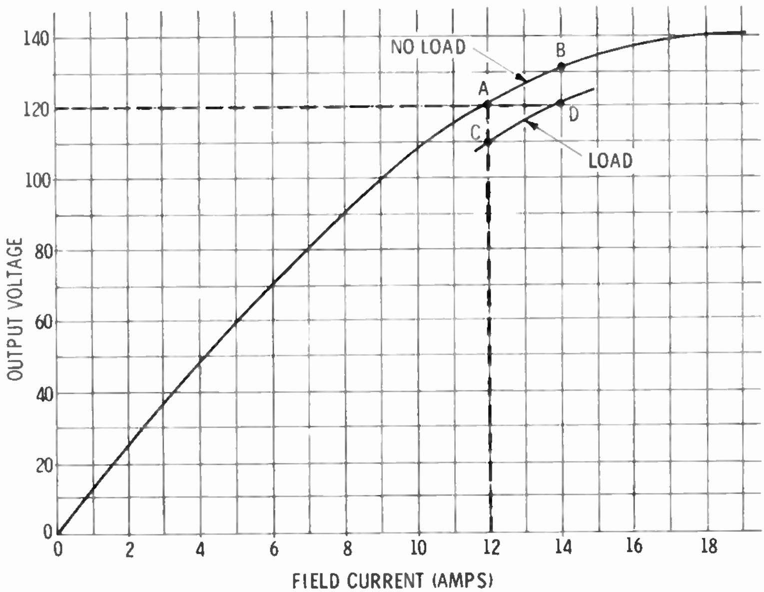
The best way to understand the need for regulating the output voltage of a generator is to determine what would happen if the voltage were not steady. One of the most disturbing things would be the constant flickering of electric lights. Certain motors would not maintain a constant speed. Radio and TV sets would not operate properly.

The voltage of an alternator depends on the speed of the machine, the number of turns in the winding, and the strength of the magnetic field. The speed of the shaft is maintained constant in order to maintain a constant frequency, so speed variation cannot be used to regulate voltage. The number of turns on the armature is fixed by the machine design and cannot be varied to regulate voltage.

The field strength is the only other factor that can be varied, but even it can be varied only a limited amount. The graph at the top of the next page shows how the no-load voltage of a typical alternator depends on the DC field current. An alternator operating at no load requires a minimum amount of field current—say 12 amps DC (point A). If the field current is increased to 14 amps, the voltage will be increased to 135V (point B).

Suppose the alternator is operating at 120V with no load. A load is now applied to the generator. The voltage output will change if the field current remains the same. In this case it drops to 110 volts (point C). Now if the field current is increased to approximately 14 amps, the voltage will go up again to 120V (point D).

RELATIONSHIP OF OUTPUT VOLTAGE AND FIELD CURRENT IN A TYPICAL ALTERNATOR



You can see that whenever a load is applied to an alternator, an increased field current should be applied in order to make up for the drop in output voltage. During the course of one day the load varies considerably. Such field-current changes must therefore be made automatically. A device for regulating the output voltage of a generator is called a **voltage regulator.**

Q16. Is the speed of an AC generator varied to control the output voltage? Why?

Q17. When a load is connected to an alternator, the output voltage of the alternator _______ if the field current is not changed.

Q18. Changes in the output voltage of an alternator can be corrected by changing the _____ _______.

Q19. A device that automatically maintains a constant generator output voltage is called a _______ _________.

Your Answers Should Be:

A16. The speed of an AC generator **cannot** be varied to control the output voltage because the speed also **determines the output frequency.**

A17. When a load is connected to an alternator, the output voltage of the alternator **changes** if the field current is not changed.

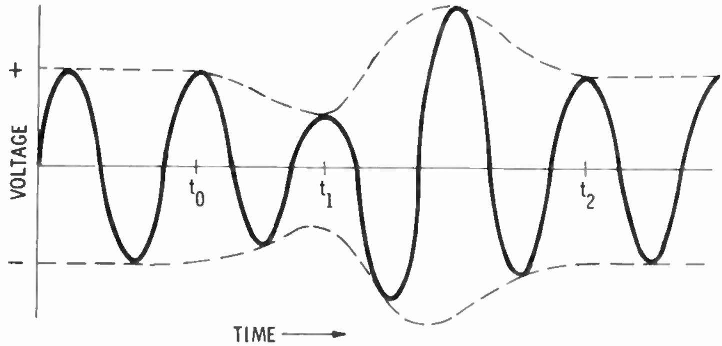
A18. Changes in the output voltage of an alternator can be corrected by changing the **field current.**

A19. A device that automatically maintains a constant generator output voltage is called a **voltage regulator.**

VOLTAGE REGULATORS

A voltage regulator must sense any change in output voltage and vary the DC field current so as to correct the change. There are many voltage regulators on the market, but they can be divided into two basic groups—those with moving parts and those without moving parts. An example of the first type will be given on the next page. For simplicity, only the basic parts will be shown.

The figure below shows the voltage sine wave during a voltage-regulating operation. The voltage begins to drop at t_0. The voltage regulator senses the drop and at t_1 begins to operate. The voltage first goes up and then gradually

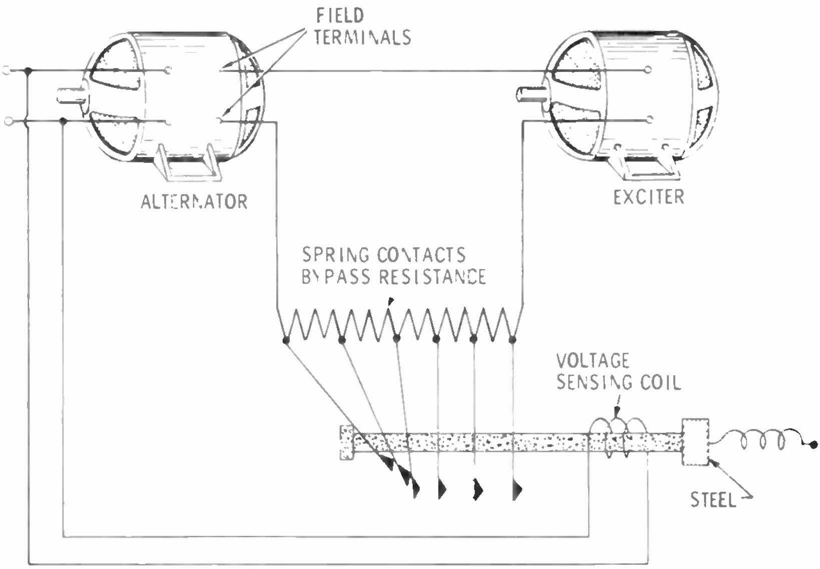


AUTOMATIC VOLTAGE REGULATION

returns to normal. The time required to return to normal varies from a few cycles, as shown in the figure, to a few seconds.

An example of a mechanical voltage regulator is shown in the figure below. If the voltage rises, the magnetic field of the coil increases, and the steel piece moves toward the coil. This causes some of the spring contacts to open, and

A MECHANICAL VOLTAGE REGULATOR



the resistance between the exciter and the alternator increases. This causes less field current to flow to the alternator, and the output voltage decreases to normal. If the voltage falls, the spring is able to pull the steel piece away from the coil. This closes more of the contacts. The resistance then decreases and the field current and output voltage increase. The resistance could also be placed in the exciter shunt-field circuit.

Q20. In the voltage regulator shown above, why is the resistance decreased when more of the contacts are closed?

Q21. Why does decreasing the resistance increase the output voltage?

Your Answers Should Be:

A20. Each pair of contacts **short-circuits part of the resistance.** Therefore, the total resistance decreases when more of the contacts are closed.

A21. Decreasing the resistance **increases** the field current. This causes the output voltage to increase.

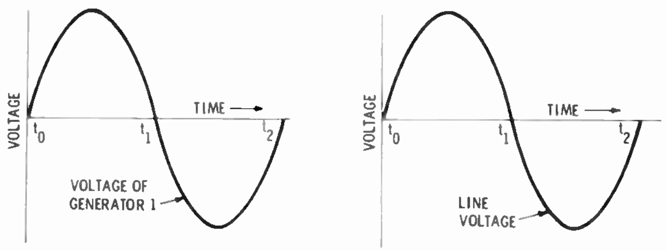
PARALLEL OPERATION

Most power plants have several generators operated in parallel. The advantage of this method is that it provides more reliable operation.

In a large power distribution system it is possible that power used in one area may come from generators operating several states away. This is because many power companies have their networks interconnected. In any large network, the line voltage is kept constant by the individual voltage regulation of each generator.

In order for generators to operate in parallel their frequencies must be equal, their voltages must be equal, and they must be in phase with each other (**synchronized**). While most power plants are strictly three-phase systems, the following paragraphs deal with a single-phase system for better understanding.

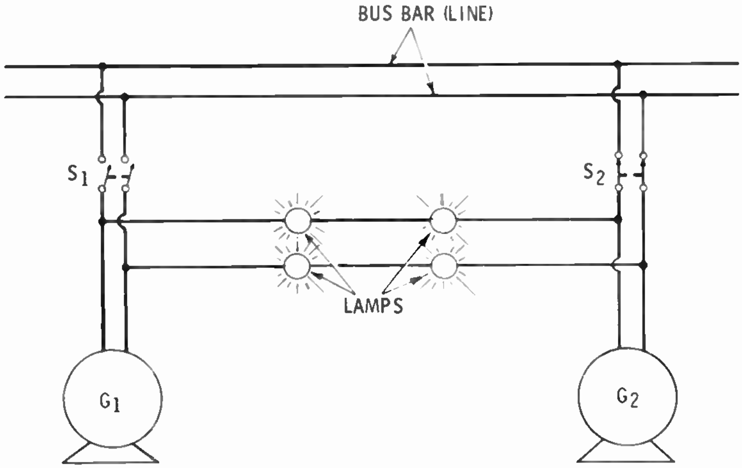
When a generator is being paralleled with others it is said to be brought "on the line." It must first be brought to line voltage and proper frequency, and then it must be synchronized. This means that its voltage and the line voltage must go through the same parts of their cycles at the same time.



OUTPUTS OF TWO SYNCHRONIZED GENERATORS

There are many methods of synchronizing generators, but the most common is by the **lamps method.** The circuit is shown below. Generator G_2 is supplying the load, and G_1 is to be brought on the line.

METHOD OF SYNCHRONIZING GENERATORS



The voltage of G_1 is brought up to line voltage. If the bulbs are lighted, there is a voltage difference between the generators, and therefore they are **not** in phase. In actual practice, the lights flash rapidly at first, as the operator adjusts the speed of G_1, then more and more slowly until they become dark. At this point the operator closes S_1, and the machine is on the line. The lights flash because the voltages are going in and out of phase with each other when the generators do not have exactly the same frequency. Considerable damage may result if the switch is closed when the lights are flashing, so this operation must be done only by qualified operators.

Q22. Why do the lights flash instead of remaining constantly lighted?

Q23. What three conditions must be met before two AC generators can be paralleled?

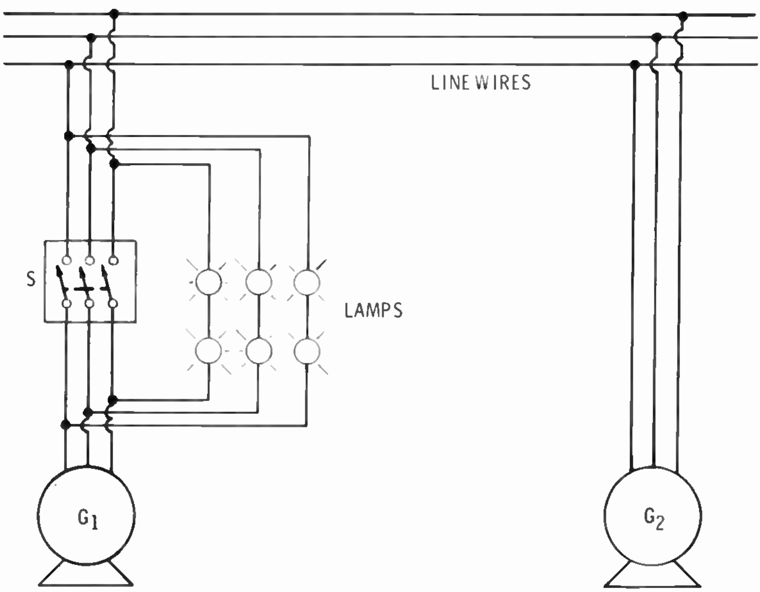
Q24. When synchronizing generators by the method above, what indicates that it is not safe to close the switch?

> **Your Answers Should Be:**
>
> A22. The lights flash because the voltages come **in and out of phase** with each other when the generators **do not have exactly** the same frequency.
>
> A23. Before two generators are paralleled their **frequencies must be equal**, their **voltages must be equal**, and they must be **in phase with each other.**
>
> A24. The switch must **not** be closed **when the bulbs are lighted.**

Paralleling Three-Phase Generators

The same general principles apply when paralleling three-phase generators as when paralleling single-phase generators. The voltages must be the same, the frequencies must be equal, and the generators must be synchronized.

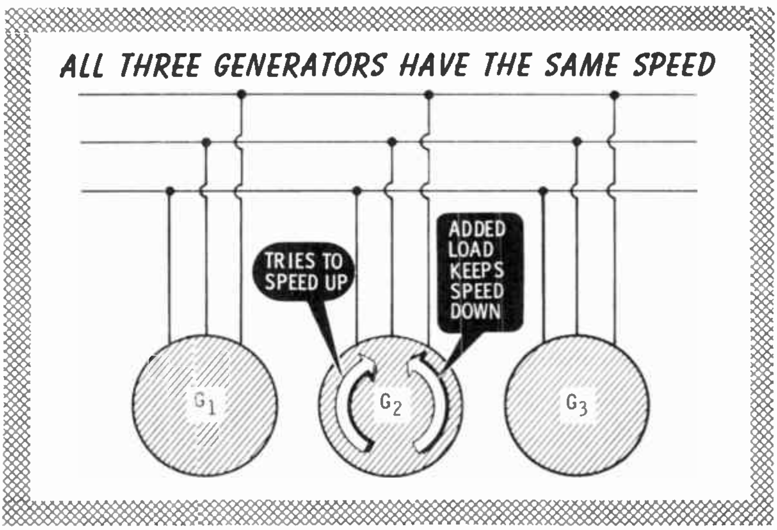
PHASING OUT A GENERATOR



Care must be taken that the three phases are in the right sequence. If the phases are reversed in the generator being placed on the line, it will be damaged. In order to avoid this situation, the following test is performed before paralleling the machine. This is called **phasing out** the generator.

Look at the figure at the bottom of the opposite page. With both G_1 and G_2 operating at the proper voltage and frequency, all lights must flash together and grow dark together. If they take turns in flashing, the connections to two of the phases of G_1 must be exchanged. When all the lights are dark, the machines are synchronized, and the switch (S) may be closed. This brings G_1 on the line.

When generators are operating in parallel, the frequency of all the generators remains the same. If one generator were to try to speed up or slow down, it would immediately be overloaded or underloaded and returned to the correct speed.



For instance, say that G_2 in the figure above tries to speed up. Additional load is immediately placed on this generator. This tends to hold the speed down. This action keeps all of the generators operating at the same speed.

Q25. Why is it necessary to phase out a three-phase generator before paralleling it with another three-phase generator?

Q26. What is indicated if all the bulbs do not flash at the same time when phasing out a generator?

Your Answers Should Be:

A25. Phasing out a three-phase generator before paralleling it with another generator is necessary to be sure the **phases of both generators are in the same sequence.**

A26. If all the bulbs do not flash at the same time, the connections to **two phases** of the oncoming machine have been exchanged.

WHAT YOU HAVE LEARNED

1. AC generators are called alternators and are composed of three basic parts—armature, field, and prime mover.
2. The armature of an alternator is the assembly of coils in which the output voltage and current are induced.
3. The armature is often the nonrotating part of an alternator because it is easier to take high voltages and currents from it in this arrangement.
4. The field of an alternator is produced by a DC current in the field windings.
5. The prime mover of an alternator can be any sort of device that turns the generator shaft.
6. The synchronous alternator is the basic AC generator.
7. A synchronous alternator is usually supplied with DC exciter current from a flat-compounded DC generator which is often coupled to the shaft of the alternator.
8. The inductor alternator is used to generate very high frequencies by means of a vibrating magnetic field.
9. The induction alternator is used to convert normal frequencies of AC to higher or lower frequencies for special purposes. It uses three-phase AC to set up a rotating magnetic field and a motor to vary the relative motion of the armature and the field.
10. A single-phase alternator delivers a single sine-wave output between two terminals.
11. Polyphase alternators have several independent windings and provide several sine-wave outputs.

12. The outputs of a two-phase alternator are normally 90 electrical degrees apart.
13. The two outputs of a two-phase alternator can be connected separately in a four-wire system, or one side of each output can be combined to provide a three-wire system.
14. In a three-wire, two-phase system, the two equal voltages of each phase combine to give a between-phase voltage 1.41 times the single-phase voltage.
15. A three-phase alternator has three phases 120° apart.
16. The between-phase voltage of a three-phase, wye-connected machine is 1.73 times the single-phase voltage.
17. Three-phase power is more efficiently and easily transmitted than single-phase power.
18. The type of load causes the voltage change due to armature reaction to vary. An inductive load causes the voltage to drop; a capacitive load causes the voltage to rise.
19. The frequency of an alternator depends on the number of field poles and the speed; it can be found by the formula $f = \frac{P \times S}{120}$. P is the number of poles and S is the speed in rpm.
20. Large power plants have devices for automatic frequency control because the speed of most motors, clocks, etc., depends on frequency.
21. Power plants also have automatic voltage regulation to provide a relatively constant voltage output.
22. The output voltage of an alternator is regulated by varying the DC exciter current with a mechanical or electronic voltage-sensitive device.
23. To be placed in parallel, alternators must be at the same voltage, at the same frequency, and synchronized.
24. Lamps can be used to synchronize alternators. When the lamps connected between the lines to be paralleled all flash at the same time and then go dark, the two machines are synchronized. There is no voltage difference between the lines when the lamps are dark.

5

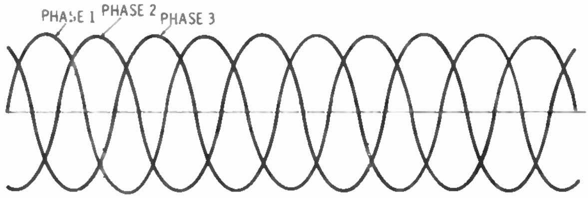
AC Motors

What You Will Learn

In this chapter you will learn how a three-phase AC power supply is used to create a rotating magnetic field. You will discover how this rotating field is used to turn synchronous and induction motors. You will find out how to recognize these motors, and you will learn their characteristics and applications. You will become familiar with the basic types of starting devices for AC motors, when they are needed, and their advantages and disadvantages.

THREE-PHASE FIELDS

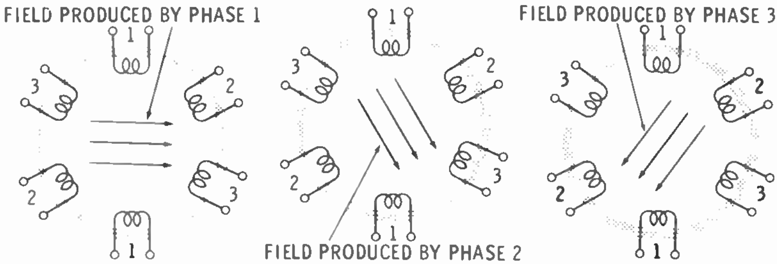
Remember that single-phase power is generated when a single constant magnetic field is rotated through a single winding (or vice versa). Three-phase power is generated in a similar manner when a magnetic field rotates in a three-phase winding. When single-phase power is fed into a single-phase winding, only a pulsating magnetic field is created. But a rotating magnetic field is created when three-phase power is fed into a three-phase winding.



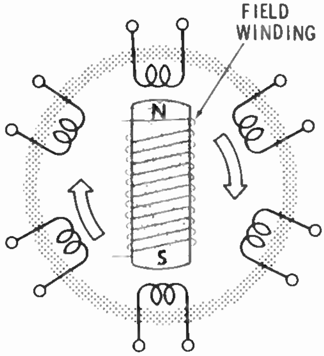
THREE-PHASE CURRENTS

The figure below shows the direction of the magnetic field produced by each phase winding. In the figure at the bottom of the opposite page, the current in phase 1 does not

PRODUCTION OF A ROTATING FIELD



stop suddenly, nor does the current start suddenly in phase 2. In other words, the phase-2 current is increasing at the same time that the phase-1 current is decreasing. In the same way, the phase-1 field does not suddenly disappear, and the phase-2 field does not suddenly appear. The phase-1 field decreases while the phase-2 field increases. The combined field does not jump suddenly from the position shown in part A of the figure above to the position shown in part B. Instead, it moves smoothly from one position to the other as the phase-1 current decreases and the phase-2 current increases. In a similar way, the field moves from the position shown in B to the position shown in C as the phase-2 current decreases and the phase-3 current increases. The magnetic field produced by the three-phase winding rotates just as the field winding in the alternator below rotates.

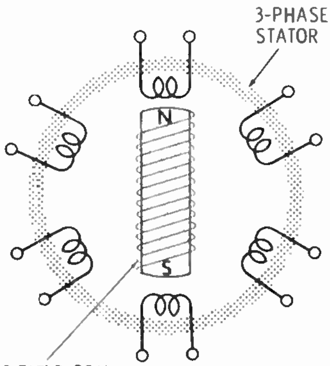


AN ALTERNATOR

SYNCHRONOUS MOTORS

Three-phase synchronous motors are similar in construction to three-phase synchronous generators. Both have a three-phase stator and a DC-powered field coil wound on the rotor. The electrical similarity can be seen from a comparison of the figure below with the figure at the bottom of the opposite page.

THREE-PHASE SYNCHRONOUS MOTOR



As the magnetic field in the stator rotates, the constant DC field rotates to keep aligned with it. As you can see, the speed of this motor depends on how fast the magnetic field rotates. The speed of the magnetic field depends on the frequency of the three-phase AC source. The synchronous motor cannot operate at any speed except that of the rotating field, which is called **synchronous speed.** Synchronous motors are used where it is important to maintain constant speed.

Q1. What sort of magnetic field is created in a single-phase winding fed with a single-phase AC current?

Q2. Three-phase power fed to a three-phase winding creates a _________ magnetic field.

Q3. The speed of the rotating field produced by a three-phase winding is called ____________ _____.

Q4. What type of three-phase motor is used when it is necessary to maintain a constant speed?

Your Answers Should Be:

A1. A single-phase current in a single-phase winding creates a **pulsating** magnetic field.

A2. Three-phase power fed to a three-phase winding creates a **rotating** magnetic field.

A3. The speed of the rotating field produced by a three-phase winding is called **synchronous speed.**

A4. A three-phase **synchronous** motor is used when constant speed is necessary.

POWER FACTOR

It was explained earlier that the power factor of the load determines how much DC field current an alternator requires to maintain a given output voltage. An inductive load (lagging power factor) causes a large voltage drop due to armature reaction, and a relatively high DC excitation is therefore required to maintain a given voltage. A capacitive load (leading power factor) requires relatively low excitation because the armature reaction strengthens the main field. A resistive load requires a normal amount of excitation.

Something similar to what happens in an alternator happens in a synchronous motor. The power factor of a synchronous motor can be controlled by varying the field current. The amount of DC current required to cause a motor (at a given load) to operate at unity power factor is known as a normal excitation.

If the DC current to the machine is less than the normal value, the motor will operate with a lagging power factor (like an inductor). If the DC current to the machine is higher than the normal value, the motor will operate with a leading power factor (like a capacitor).

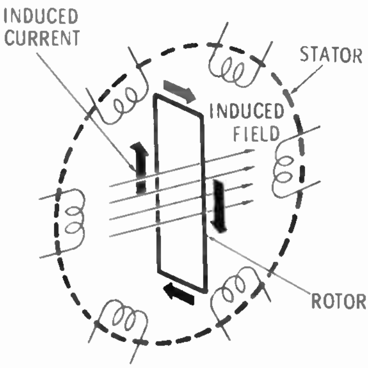
Synchronous motors are often operated at less than rated load but with overexcitation so that they help correct the power factor of a system. When a synchronous motor operates at no load and strictly for the purpose of correcting a system power factor, it is called a **synchronous capacitor.**

POLYPHASE INDUCTION MOTORS

The most important type of polyphase induction motor is the 3-phase motor. Induction motors have two types of rotors, the **wound rotor** and the **squirrel-cage rotor.** The principle of operation is the same for both types.

A basic induction motor has neither slip rings nor a commutator. The rotating three-phase field of the stator induces a voltage in the rotor windings (hence the name induction

BASIC THREE-PHASE INDUCTION MOTOR



motor). This voltage, in turn, creates a large current in the rotor circuit. The current is large because the only resistance opposing it is the resistance of the wires. This high current in the rotor loop creates a magnetic field of its own. The rotor field and the stator field tend to attract each other. This situation creates a torque which spins the rotor in the same direction as the rotation of the magnetic field produced by the stator.

Q5. The power factor of a synchronous motor can be varied by varying the _____ ________.

Q6. A synchronous motor operated without load and used only to provide power-factor correction is called a ____________ __________.

Q7. Current is induced in the rotor of an induction motor by the rotating _________ _____ of the stator.

Q8. Two types of rotors used in induction motors are the _____ rotor and the _________ ____ rotor.

Your Answers Should Be:

A5. The power factor of a synchronous motor can be varied by varying the **field current.**

A6. A synchronous motor operated without load and used only to provide power-factor correction is called a **synchronous capacitor.**

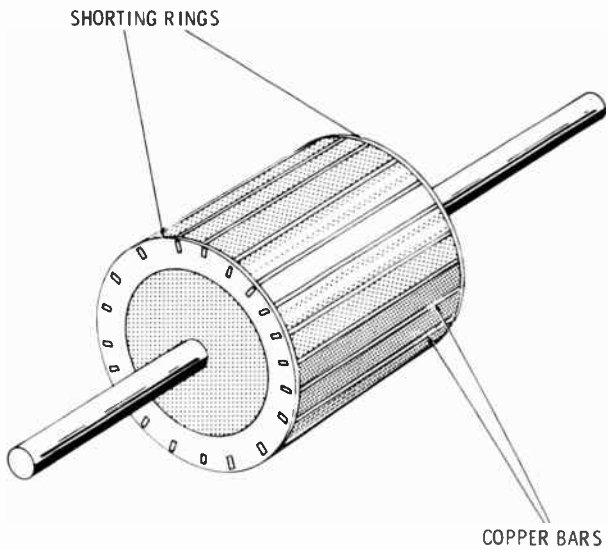
A7. Current is induced in the rotor of an induction motor by the rotating **magnetic field** of the stator.

A8. Two types of rotor used in induction motors are the **wound** rotor and the **squirrel-cage** rotor.

Squirrel-Cage Motors

Squirrel-cage induction motors are extremely rugged and trouble-free machines. They have heavy copper bars around

A SQUIRREL-CAGE ROTOR

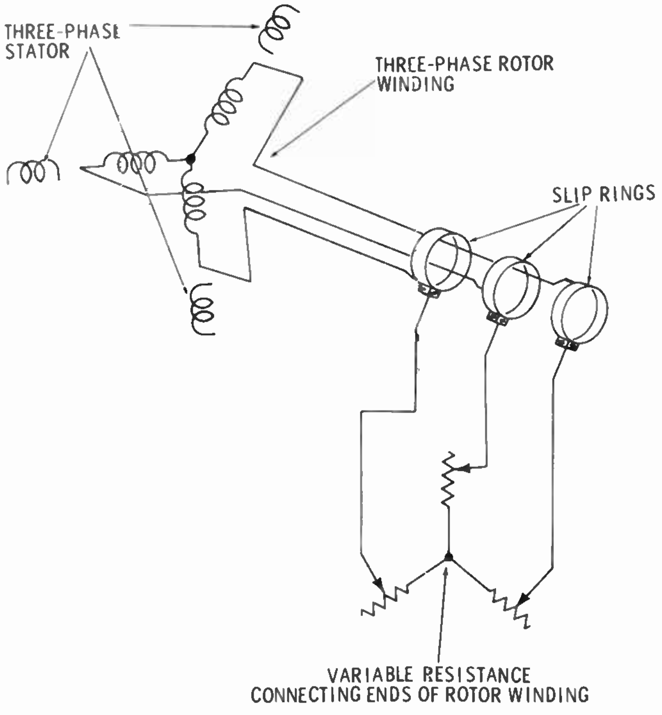


the rotor instead of a wire winding. The winding resembles a squirrel cage, from which it derives its name. The squirrel-cage motor has the advantages of requiring practically no maintenance and of costing much less than a wound-rotor motor.

Wound-Rotor Motors

In the wound-rotor motor, the rotor is not connected to any outside source of power. In order for this type of motor to operate, the terminals of all the rotor windings must be connected together either directly or through a resistor bank. This is accomplished by means of brushes and by slip rings connected to the ends of each winding. In effect, this allows the operator to control the resistance of the rotor windings.

WOUND-ROTOR INDUCTION MOTOR



Q9. In a squirrel-cage rotor, ______ ____ serve as the conductors.

Q10. Name two advantages of squirrel-cage motors.

Q11. Do the brushes feed external power into the rotor of a wound-rotor motor?

Your Answers Should Be:

A9. In a squirrel-cage rotor, **copper bars** serve as the conductors.

A10. Squirrel-cage motors are very rugged and require **almost no maintenance.** They are **relatively inexpensive.**

A11. The brushes **do not feed external power into the rotor** of a wound-rotor motor; they simply connect the ends of the windings.

SLIP

The speed of an induction motor can never be quite equal to synchronous speed. Synchronous speed is the speed of the rotating field (3,600 rpm for 2-pole machines and 1,800 rpm for 4-pole machines if the frequency is 60 cps). If the rotor moved at this speed, no magnetic lines of force would move across its conductors and no voltage would be induced in the rotor. An induction motor cannot be operated at synchronous speed; it can only approach it.

The difference between the synchronous speed of the magnetic field and the actual speed of the motor is called **slip.**

$$\text{Slip} = \text{Synchronous speed} - \text{Actual speed}$$

Percentage of slip in an induction motor is given by the formula:

$$\%\ \text{Slip} = \frac{S_S - S_A}{S_S} \times 100$$

where,

S_S is the synchronous speed in rpm,
S_A is the actual speed in rpm.

For example, what is the slip and the percent of slip in a two-pole, 60-cps induction motor whose speed at full load is 3,450 rpm?

$$\begin{aligned}\text{Slip} &= \text{Synchronous speed} - \text{Actual speed}\\ &= 3{,}600 - 3{,}450 = 150 \text{ rpm}\end{aligned}$$

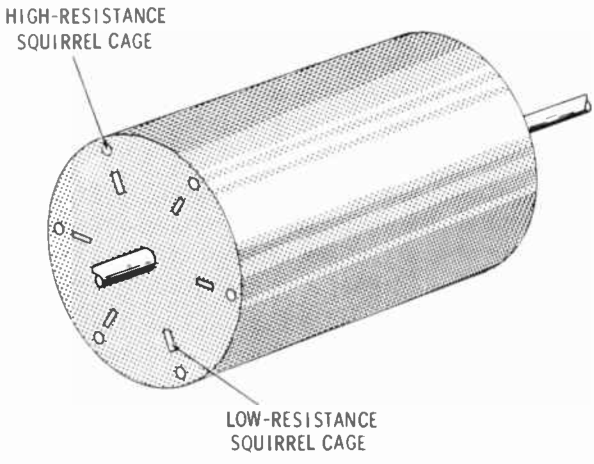
$$\%\ \text{Slip} = \frac{3{,}600 - 3{,}450}{3{,}600} \times 100 = \frac{150}{3{,}600} = 4.16\%$$

In most induction machines the full-load slip varies from 4 to 6%. The number of phases, whether one, two, or three, does not matter when calculating slip values.

The resistance of the rotor circuit can be varied in a wound-rotor motor. The slip depends on this resistance (a greater resistance causes a greater slip). Therefore, it is possible to control the speed of a wound-rotor motor by choosing the proper resistance bank in the rotor circuit. When starting induction motors which have a load attached at all times (such as a flywheel), maximum starting torque can be provided by varying the resistance of the wound rotor to the correct value.

A **double-squirrel–cage** motor takes advantage of the same effect to obtain improved starting torque. This type of motor has two separate squirrel-cage windings. One has a high resistance to provide good starting torque. The other has a

BASIC CONSTRUCTION OF A DOUBLE-SQUIRREL-CAGE ROTOR



Q12. What is synchronous speed?

Q13. What is slip?

Q14. If a four-pole motor is supplied from a 60-cycle source and operates at 1,750 rpm, what is the percentage of slip?

Q15. The speed and torque of an induction motor can be controlled by varying the ---------- of the rotor circuit.

Your Answers Should Be:

A12. Synchronous speed is the **speed of the rotating magnetic field.**

A13. Slip is the **difference** between the **synchronous speed** and the **actual speed** of the motor.

A14. Synchronous speed for a four-pole, 60-cycle motor is 1,800 rpm.

$$\% \text{ Slip} = \frac{1{,}800 - 1{,}750}{1{,}800} \times 100 = 2.8\%$$

A15. The speed and torque of an induction motor can be controlled by varying the **resistance** of the rotor circuit.

SINGLE-PHASE AC MOTORS

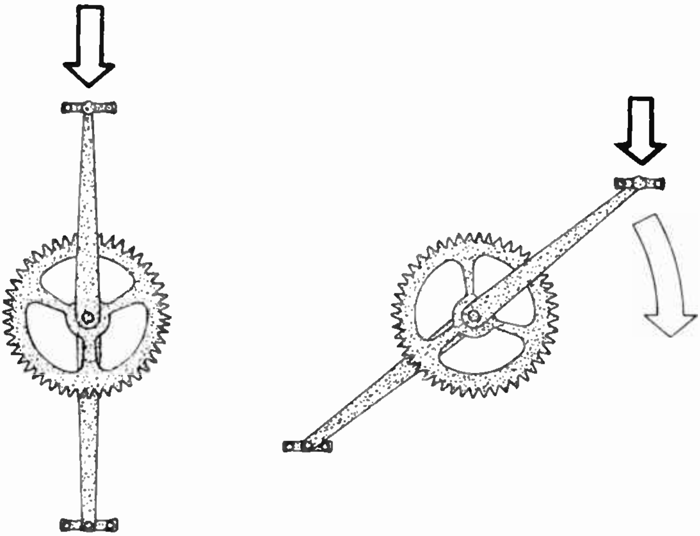
Single-phase AC motors are usually limited in size to about two or three horsepower. There are many different types found in almost every household and industrial building. In the home there are single-phase motors in air conditioners, air heaters, refrigerators, sewing machines, fans, ventilating units, and many other household appliances.

Since they have so many uses, there are many different types of single-phase motors. Some of the more common types are repulsion, universal, and single-phase induction motors. Single-phase induction motors include shaded-pole, split-phase, capacitor, and repulsion-induction motors.

Single-Phase Induction Motors

Single-phase induction motors have no means of starting by themselves. In a single-phase motor the field of the stator windings does not rotate as it does in a three-phase induction motor. The magnetic field set up in the stator by the AC power supply stays lined up in one direction. This magnetic field, though stationary, pulsates as the voltage sine wave does. The pulsating field induces a voltage in the rotor windings, but the rotor field can only line itself up with the stator field. Therefore, since the stator field is stationary, the rotor field is also stationary. Before it can start, the rotor must be turning so that there is, in effect, some slip and the two fields are not exactly lined up.

The single-phase induction motor acts much like the pedals of a bicycle. When the pedals are exactly lined up with the direction of the up-and-down motion of the rider's feet, the pedals will not turn. Once a slight turn has started them, inertia carries the pedals past the center point, and the pulsating up-and-down motion keeps the rotating motion going.



It is necessary then to find some means of giving the single-phase AC motor a means of starting the rotor into motion. Once the rotor is spinning at a reasonable rpm, its inertia will carry it through the dead-center position so that it will be kept rotating by the stationary field. An auxiliary starting system is required. The starting methods make up the primary differences between induction-motor types.

Q16. What is the largest size in which single-phase motors are usually made?

Q17. Name the three types of single-phase motors.

Q18. What are four types of single-phase induction motors?

Q19. The magnetic field of a single-phase motor (does, does not) rotate.

Your Answers Should Be:

A16. The largest size in which single-phase motors are usually made is **two** to **three horsepower.**

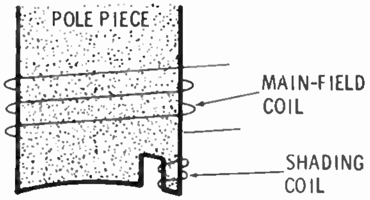
A16. Three types of single-phase motor are the **repulsion, universal,** and **single-phase induction** motor.

A18. Single-phase induction motors include **shaded-pole, split-phase, capacitor,** and **repulsion-induction** motors.

A19. The magnetic field of a single-phase motor **does not** rotate.

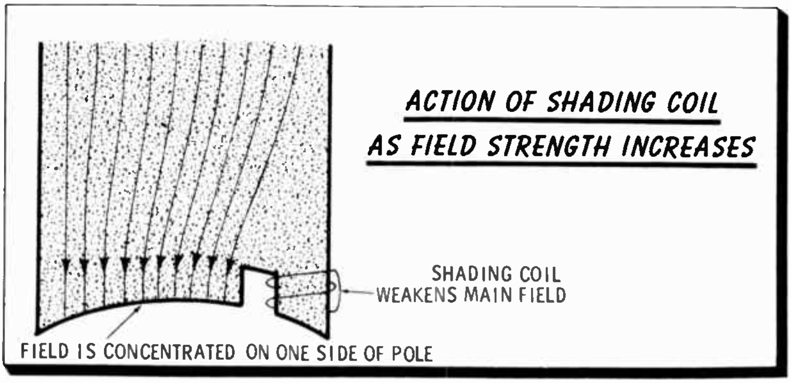
Shaded-Pole Motors

Shaded-pole motors are usually very small. They have a constant speed, and are usually in a size range of about 1/50 HP. The stator windings are arranged as shown below.



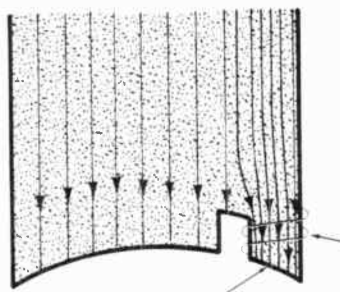
STATOR WINDINGS IN A SHADED-POLE MOTOR

The shading coil is short-circuited. As the field in the pole piece builds up, a current is induced in the shading coil. This current causes a magnetic field that opposes the main field. The main field will therefore concentrate on the oppo-



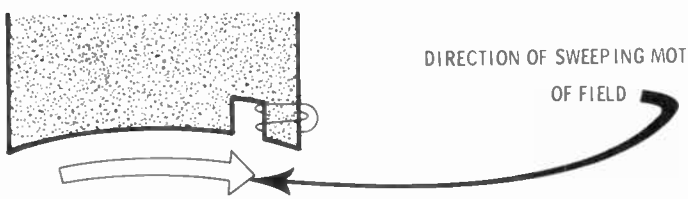
site side of the pole piece. The result is that the field in the part of the pole piece inside the shading coil reaches a maximum intensity later than the rest of the field. As the field in the part of the pole opposite the shading coil begins to decrease, the shading-coil field will start aiding the main field, and the concentration of flux moves to the other edge of the pole piece. The resulting field in the part of the pole piece inside the shading coil reaches zero after the main field.

ACTION OF SHADING COIL AS FIELD STRENGTH DECREASES



The effect of the shading coil is to produce a small sweeping motion of the main field from one side of the pole piece to the other as the field pulsates. This slight rotating motion is enough to start the motor.

APPARENT MOTION OF FIELD PRODUCED BY SHADING COIL



Q20. Shaded-pole motors usually have ----- horsepower ratings.

Q21. The field in the part of the pole piece inside the shading coil reaches maximum ----- the rest of the field.

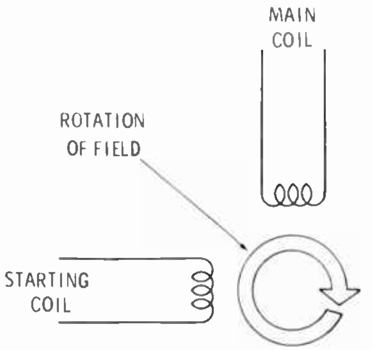
Your Answers Should Be:

A20. Shaded-pole motors usually have **small** horsepower ratings.

A21. The field in the part of the pole piece inside the shading coil reaches maximum **after** the rest of the field.

Split-Phase Motors

Split-phase motors usually have ratings of ¾ HP or less. They have two separate coils—a main coil of large wire and a starting coil of small wire. Both coils are placed in the motor in the same positions they would have if the machine were a two-phase motor. If the coils have the same number of turns, they have the same inductance. However, the starting coil has a higher resistance because it is wound with smaller wire. When the same voltage is applied to both windings, the current in the main coil lags behind the current in the starting coil. The two windings produce a rotating field in much the same way that a rotating field is produced in a two-phase motor. This rotating field causes the motor to start.



PRINCIPLE OF THE SPLIT-PHASE MOTOR

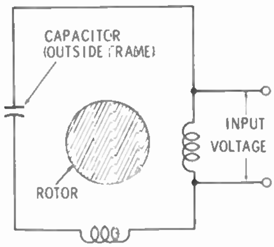
If used to run the motor, the starting winding is likely to burn out because of the small wire from which it is made. For this reason, a centrifugally operated switch is used to disconnect the starting winding when the motor reaches about 60% of operating speed.

Capacitor Motors

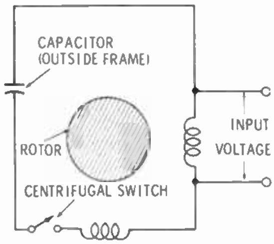
Capacitor motors have two stator windings. A large capacitor is connected in series with one of the windings. The single-phase input voltage produces two currents (one in each winding). One current is shifted out of phase with the applied voltage by the capacitor. This creates a starting torque similar to that of a two-phase motor.

Capacitor-Start, Capacitor-Run Motor—In this type of motor the starting capacitor stays in the system at all times. This type of machine is made in sizes from ⅛ to 10 HP. It has a relatively high power factor.

CAPACITOR MOTORS



Capacitor-Start, Capacitor-Run



Capacitor-Start With Centrifugal Switch

Capacitor-Start Motor—This motor starts with a capacitor in series with one of the windings. At about 75% of full speed a centrifugal switch opens the capacitor-winding circuit, and the motor operates as a single-phase inductor motor. This type is made in sizes from ⅛ to ¾ HP.

Two-Value, Capacitor-Start, Capacitor-Run Motor—This type combines the features of both capacitor-start and capacitor-start, capacitor-run motors. It has two capacitors in series with one winding and a centrifugal switch which cuts out one capacitor at about 75% of full speed. This type of machine has ratings from ⅛ to 10 HP. It has many industrial applications.

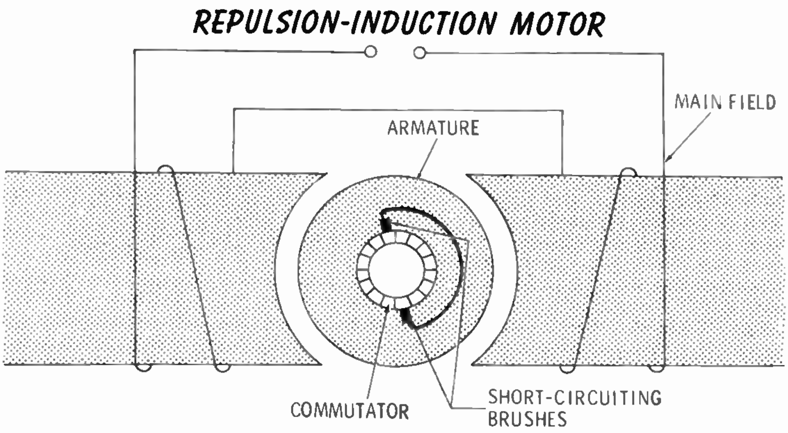
Q22. The various starting methods for single-phase induction motors all create a -------- magnetic field.

Q23. Why is a centrifugal switch used in a split-phase motor?

> **Your Answers Should Be:**
>
> A22. The various starting methods for single-phase induction motors all create a **rotating** magnetic field.
>
> A23. The **starting winding** of a split-phase motor would **overheat** if left connected. The centrifugal switch **disconnects the starting winding** when the motor reaches about 60% of full speed.

Repulsion Motors

The **repulsion motor** has an armature and commutator similar to that of a DC machine. The two brushes are connected by a low-resistance wire.



The stator windings (actually two windings in series) produce a current in the rotor windings by induction. This current produces magnetic poles in the rotor, their location depending on the position of the brushes. When the field of the rotor is at an angle with the main field, a torque is created by the interacting fields. The rotor moves in a direction to turn its field away from the main field, but as it moves, the brushes come into contact with a different pair of commutator segments and shift the field back.

There is no starting problem in a repulsion motor. They have good starting torque and are used where heavy starting loads are expected.

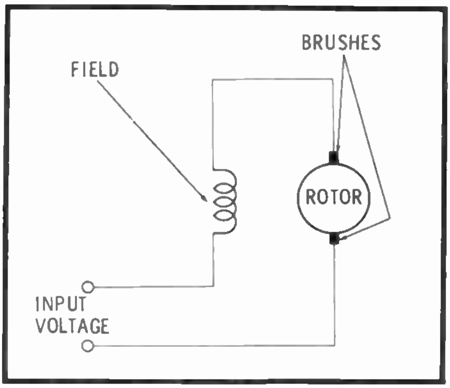
Repulsion-Induction Motors

The **repulsion-induction motor** has a wound rotor with a commutator. Shorting brushes make contact with the commutator, and the motor starts as a repulsion motor. As the motor nears full speed, a device short-circuits all the commutator bars. The motor then runs as an induction motor and operates at nearly constant speed. Its speed cannot be adjusted. This type of motor is made in sizes ranging from ½ HP to 10 HP.

Universal Motors

One of the most versatile motors is the **universal motor** which operates on either DC or single-phase AC. These machines have high starting torque and high slip. They are usually in the fractional-horsepower range and are used in small appliances, electric drills, etc.

UNIVERSAL MOTOR



As you recall, a DC series motor will continue to turn in the same direction if the line connections are reversed. A series DC motor will therefore work on AC. In fact, a universal motor is simply a DC series motor whose windings and pole pieces are designed to operate efficiently with AC power.

Q24. A repulsion motor (does, does not) have a commutator.

Q25. Repulsion motors have a ____ starting torque.

Q26. A universal motor can be operated on both __ and __.

Your Answers Should Be:

A24. A repulsion motor **does** have a commutator.

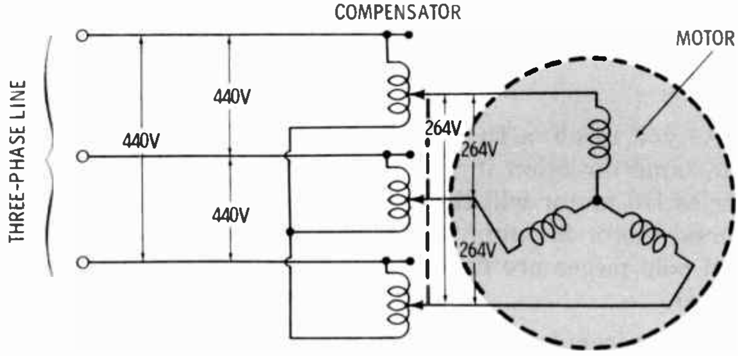
A25. Repulsion motors have a **high** starting torque.

A26. A universal motor can be operated on both **AC** and **DC.**

INDUCTION-MOTOR STARTING

When voltage is first applied to a three-phase induction motor, the current drawn is sometimes six or seven times higher than the normal running current. However, this current decreases rapidly as the machine gathers speed. In the case of a squirrel-cage induction motor, the starting current will not usually damage the motor itself, but it may create an undesirable voltage fluctuation in the power system. It is therefore customary when starting to apply full rated voltage only to the smaller squirrel-cage induction motors. Reduced starting voltage is applied to the larger-sized machines. The reduced voltage can be applied by means of an autotransformer, a series resistor, or a series reactor.

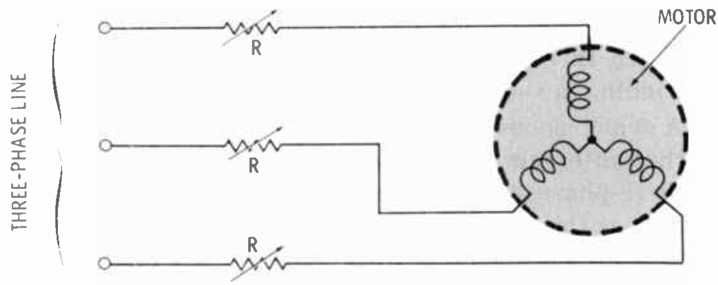
STARTING A SQUIRREL-CAGE MOTOR WITH A COMPENSATOR



The autotransformer method is shown above. The group of autotransformers used to limit starting current is called a **compensator.** When the motor reaches running speed, the compensator is bypassed and the full voltage is applied. The autotransformer will dissipate almost no power. (Only a negligible amount will be dissipated by the resistance of its windings.)

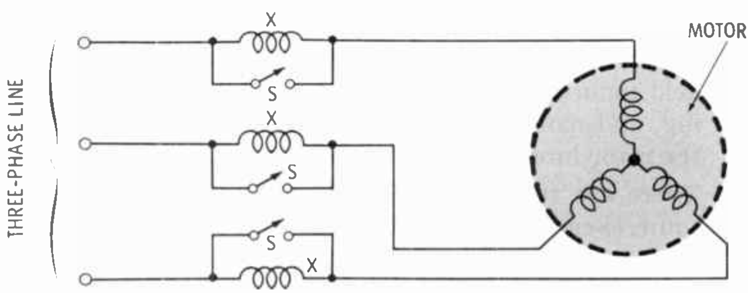
Another method of starting is to insert a resistor in series with each of the three motor windings, as shown below. The resistors will dissipate power.

STARTING A SQUIRREL-CAGE MOTOR WITH RESISTORS



A third method of starting a squirrel-cage motor is to use series coils (reactors). A coil with relatively high inductive reactance is inserted in series with each of the motor coils as shown below. When the motor has picked up speed, the switches are closed to bypass the reactors.

STARTING A SQUIRREL-CAGE MOTOR WITH INDUCTORS



Q27. Name three methods of limiting the starting current in an induction motor.

Q28. Would a ¼-horsepower, single-phase, squirrel-cage induction motor normally require a starter?

Your Answers Should Be:

A27. The starting current in an induction motor can be limited by using **compensators** (autotransformers), **series resistors,** or **series reactors** (coils).

A28. A ¼-horsepower, single-phase, squirrel-cage induction motor **normally requires no starter.**

WHAT YOU HAVE LEARNED

1. When three-phase power is supplied to a three-phase winding, a rotating magnetic field is created.
2. A synchronous three-phase motor has a DC-excited field that interacts with the rotating field created by the three-phase AC power supply and causes the rotor to turn at the same speed as the magnetic field.
3. Synchronous motors are used to provide constant speeds.
4. The power factor of a synchronous motor varies according to the amount of DC excitation. When the DC field current is below normal, the motor has a lagging power factor and behaves as an inductor. When the DC field current is at the normal excitation value, the machine presents a purely resistive load and has a power factor of one (unity). When the DC field current is above the normal excitation value, the motor has a leading power factor and acts as a capacitor.
5. In a polyphase induction motor, the rotating magnetic field induces a current in a short-circuited rotor winding, and motor action occurs when the field created in the rotor interacts with the main field.
6. There are two types of polyphase induction motors—squirrel-cage and wound-rotor.
7. A squirrel-cage motor has a rotor winding composed of copper bars embedded in the iron rotor core. A wound rotor has conventional wire windings.
8. Squirrel-cage motors are rugged and require very little maintenance. Therefore, they are relatively inexpensive.
9. An induction motor cannot operate at synchronous

speed. The difference between the speed of the rotating magnetic field and the motor speed is called slip.

10. The greater the resistance of the rotor winding of an induction motor, the greater is the slip.
11. Wound-rotor induction motors have a variable rotor resistance that is controlled by the operator and connected to the rotor through slip rings and brushes.
12. Single-phase induction motors must have some arrangement to create a rotating magnetic field for starting the machine. Single-phase induction motors are classified according to the starting method used.
13. Shaded-pole motors create a rotating-field effect by means of a short-circuited shading coil on one edge of the pole piece. This coil produces a field that first weakens and then aids the main field.
14. Split-phase motors have a high-resistance starting winding whose current and field are more nearly in phase with the applied voltage than those of the main winding. The combined field of the two windings creates a rotating-field effect.
15. A centrifugal switch is used to disconnect the high-resistance starting winding after a split-phase motor has picked up speed. This is done so that the starting winding will not burn out.
16. Capacitor motors use capacitors in series with one of the windings to produce a phase shift similar to that of a split-phase motor.
17. Capacitor-start, capacitor-run motors keep the capacitive winding in the circuit at all times. Capacitor-start motors have a centrifugal switch to disconnect the capacitive winding after the motor has started.
18. Repulsion motors have a wound rotor and a commutator that is short-circuited by brushes. This motor has a high starting torque.
19. A universal motor is similar to a series DC motor.
20. Starting current for large induction motors is limited in one of three ways—with a compensator (autotransformers), with series resistors, or with series reactors.

6

Three-Phase Systems

What You Will Learn

In this chapter you will learn how three-phase power is generated and distributed. You will become acquainted with the various ways in which three-phase alternators, motors, and transformers can be connected. You will be able to tell the difference between line voltage and current and phase voltage and current, and you will learn how to find one if the other is known. You will also learn how to calculate and measure power in three-phase systems.

THREE-PHASE GENERATION AND DISTRIBUTION

Throughout the world, power plants produce huge quantities of electrical power in order to supply the ever increasing requirements for light, electric heating, and heavy industry. Nearly all of this power originates from three-phase generators. The voltage is stepped up by transformers for transmission and further transformed to lower and higher voltages according to need. The power is eventually used in either three-phase or single-phase devices.

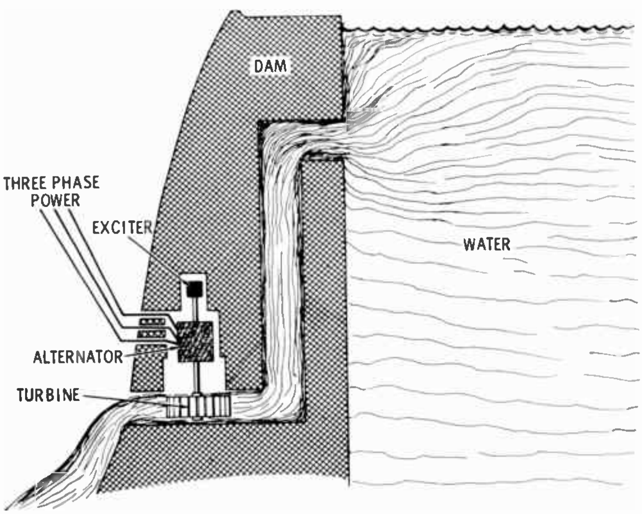
Voltages and frequencies are usually standardized. In the United States, for example, the frequency is 60 cycles per second for the major portion of the country. A frequency of 25 cps was quite common at the beginning of this century, and a few 25-cps units are still in operation. In Europe, both 50 cps and 60 cps frequencies are used, but the trend is toward adopting a uniform 60-cps frequency.

The great majority of the generators producing three-phase power are synchronous generators. This type is chosen because of its very high efficiency—as high as 99% for very large units—and for its ability to maintain a very steady voltage and frequency output.

All large power-generating systems have three basic components—a prime mover, a three-phase alternator, and a DC field exciter. The prime mover provides the mechanical power necessary to turn the rotor of the alternator and the exciter. Hydraulic turbines (driven by falling water), steam turbines, and Diesel engines are all possible prime movers. Steam and hydraulic turbines are the most common.

The three-phase alternator produces three-phase electricity at a given voltage and frequency. The voltage output may be varied to some extent by changing the DC excitation value, and the frequency may be varied by changing the speed of the rotor. Voltage and frequency regulating equipment is used to keep these quantities constant.

The DC field excitation provides control of the output voltage. The DC is monitored and controlled by a voltage regulator. The DC generator is usually mounted directly on the same shaft as the alternator or coupled to the alternator shaft by a belt drive.

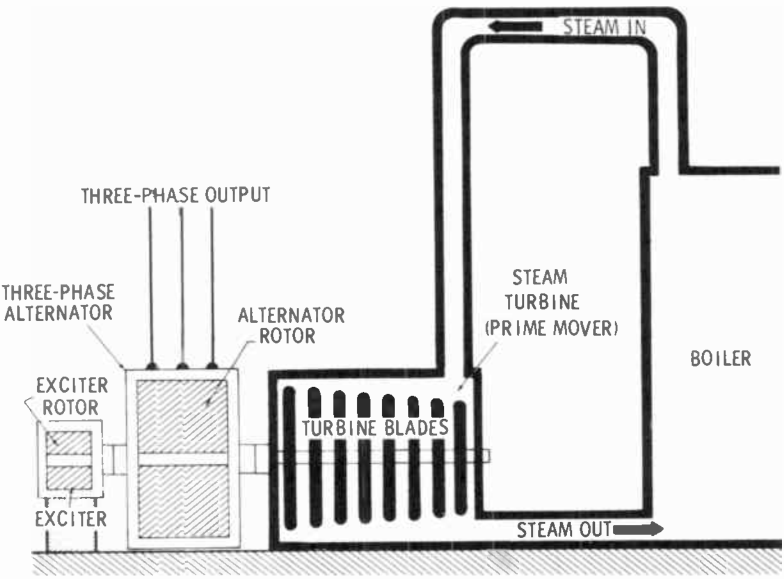


HYDROELECTRIC GENERATING PLANT

Water-driven generators are operated at low speeds. A typical speed is 200 rpm. Falling water enters the turbine case and spins the turbine which is connected to a shaft. This shaft rotates the alternator and exciter rotors. All units are usually mounted vertically. Such a generating system is called a **hydroelectric** plant.

The speed of a steam-driven generator is normally 3,600 rpm (for 60 cps). Some generators operate at 1,800 rpm, although these are less common. In a steam-generator plant, the components are arranged horizontally. Steam from an oil- or coal-fired boiler system, or from a system heated by an atomic reactor, is piped to the turbine. The steam expands and pushes against the blades, causing the turbine shaft to rotate. The shaft turns the rotors of the alternator and exciter.

STEAM GENERATOR PLANT



Q1. The standard frequency for AC in most of the world is — – – –.

Q2. Three essential parts of a generating system are the – – – – – – – – – –, – – – – – – – – – – –, and – – – – – – – –.

Your Answers Should Be:

A1. The standard frequency for AC in most of the world is **60 cps.**

A2. Three essential parts of a generating system are the **prime mover, alternator,** and **exciter.**

Transmission of Power

After power is generated at the power plant, the voltage is usually stepped up for transmission. Voltages such as 69,000V are common. By stepping the voltages up to these high values, it is possible to transmit large amounts of power with relatively low currents. The low currents can be carried by smaller wires in the transmission lines. Less copper is needed and less power is lost. (Power loss in a line is equal to I^2R.) As you will see, three-phase power lines use less copper than lines designed to carry the same amount of single-phase power at the same voltage.

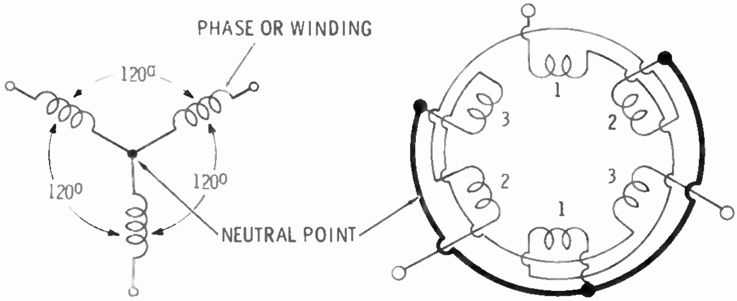
For most household uses the three-phase power is finally split up into single-phase, 120-volt AC. For many industrial applications, it is used as three-phase power. For example, three-phase power is used to drive three-phase induction and synchronous motors. The winding connections used in three-phase alternators, transformers, and motors make it possible to transmit power with four or even three conductors. Since these systems of winding connections appear wherever three-phase power is used, it is important for you to understand them.

WYE CONNECTION

The **wye-connected** system is probably the most common type of three-phase connection. The wye connection is also called a **star connection.** It is usually diagrammed as shown on the next page. Generators, motors, transformer windings, capacitors, resistors, etc., can all be connected in the same arrangement. Each phase is 120 electrical degrees away from the other two phases. The diagram resembles the letter Y, from which the name "wye" was taken.

The three windings in a wye connection are not only 120 electrical degrees apart, but they are also connected to a single common point. The ends of the three arms of the Y represent the three external ends of the windings. The center of the Y represents the three ends that are connected together and is called the **neutral point** or **common point.**

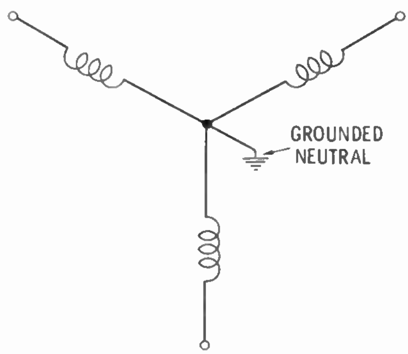
WYE CONNECTION



Connection Diagram **Winding Arrangement**

The neutral point is normally grounded (connected to the earth or a large mass of metal), in which case the wye connection is as shown below. This system is called a three-phase, four-wire wye connection.

WYE CONNECTION WITH GROUNDED NEUTRAL



Q3. Why is the generator voltage stepped up before power is transmitted?

Q4. In a wye connection, one end of each phase or wind- is connected to the ________ point.

Q5. The neutral point is usually _________.

Your Answers Should Be:

A3. High transmission voltages are used so that power can be transmitted with **lower currents.**

A4. In a wye connection, one end of each phase or winding is connected to the **neutral** point.

A5. The neutral point is usually **grounded.**

Voltage in a Wye-Connected System

In the case of a wye-connected generator with grounded neutral, there are several voltages that can be measured at its outputs. These voltages are shown in the diagram below and are as follows:

E_{AB}—The voltage between A & B

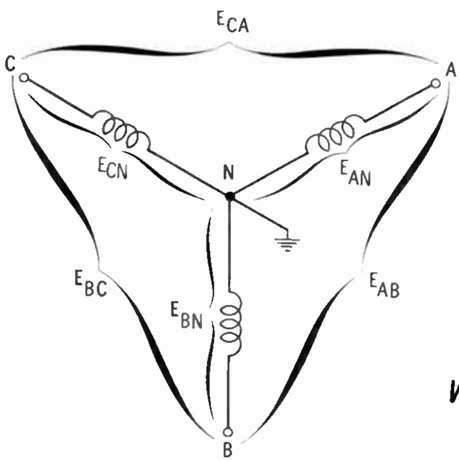
E_{CA}—The voltage between C & A

E_{BC}—The voltage between B & C

E_{AN}—The voltage between A & neutral (N)

E_{BN}—The voltage between B & neutral

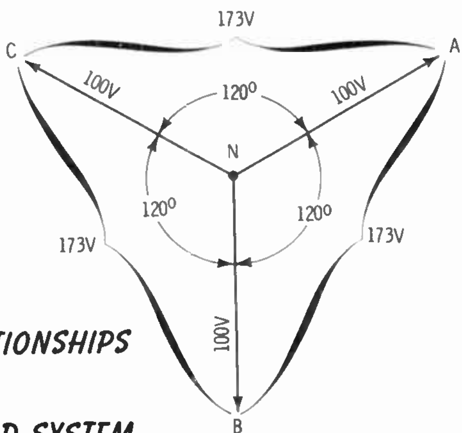
E_{CN}—The voltage between C & neutral



VOLTAGES IN A WYE-CONNECTED SYSTEM

In most cases, the voltages between each phase terminal and the neutral are equal. Thus, $E_{AN} = E_{BN} = E_{CN}$. The voltages between any two phases will then also be equal. Thus, $E_{AB} = E_{BC} = E_{CA}$.

The diagram below indicates how the voltages add. Just as the distance from A to B is greater than the distance from A to N, the voltage between A and B is greater than that between A and N, and so on. The voltage between any one phase terminal and the neutral (say E_{AN}) is considerably lower than any phase-to-phase voltage (say E_{AB}).



VOLTAGE RELATIONSHIPS IN A WYE-CONNECTED SYSTEM

The phase-to-phase voltage is the between-the-lines voltage, or simply the **line voltage.** The voltage between a line and the neutral is the **phase voltage.** Because of the phase relationships, the line voltage is 1.73 times the phase voltage in a wye-connected system if the phase voltages are equal.

Q6. The voltage between any two lines of a wye-connected, three-phase transmissions system is called the ____ ________.

Q7. The voltage between one line and ground is called the _____ ________.

Q8. How are these voltages related?

Your Answers Should Be:

A6. The voltage between any two lines of a wye-connected, three-phase transmission system is called the **line voltage.**

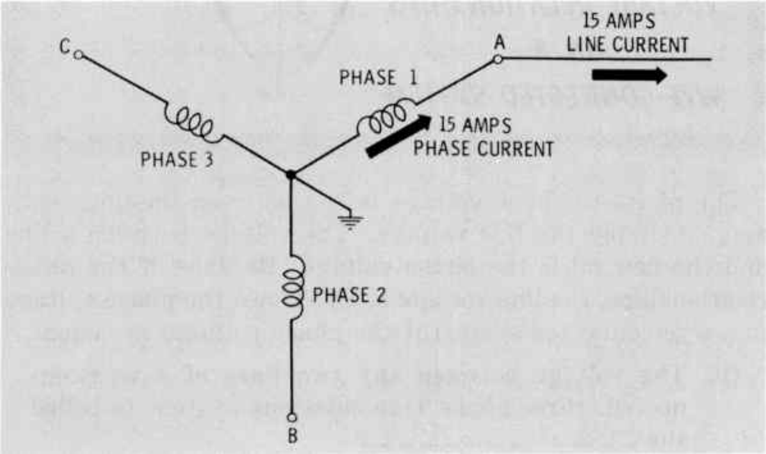
A7. The voltage between one line and ground is called the **phase voltage.**

A8. The line voltage **in a wye-connected system** is **1.73 times the phase voltage** if the phase voltages are **all equal.**

Current in a Wye-Connected System

The current flowing in a given line is called the **line current.** The current flowing through any one winding is the current in a single phase and is called the **phase current.**

The same current that flows through a line also flows through the windings to which it is connected in the wye system. Thus, the line current is equal to the phase current in a wye system. Note that this relationship applies to each phase individually. The current in one line does not necessarily equal the current in another phase.



CURRENT RELATIONSHIPS IN A WYE-CONNECTED SYSTEM

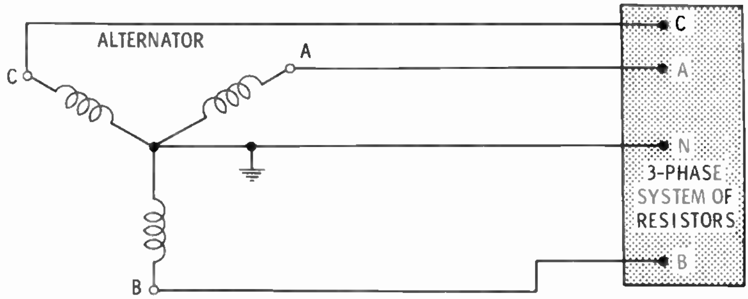
Summary of Wye-Connected Systems

If a three-phase, wye-connected system is operating in the normal way, and if the phase voltage from A to N is 100V rms, the voltages from B to N and C to N will also be 100V rms. The line voltage from A to B will be 1.73 times the phase voltage, or 173V rms. Line voltages from A to C and from B to C will also be 173V rms. If the current through line A is 15 amps, the phase current through winding A will also be 15 amps.

Note that the **effective** values of voltage and current are usually used. These are the rms values (also called the root-mean-square values). The rms values determine how much power is dissipated. The same relationships between line and phase voltage and between line and phase current are also true if you wish to consider peak values. Remember that when comparing voltages or currents they must all be in the same units (peak, rms, etc).

Here is a typical problem. Suppose a resistive load, as shown below, is supplied power from a three-phase, wye-connected alternator. The voltage between A and C is 208V and the current in each line is 10 amperes.

WYE-CONNECTED GENERATOR AND LOAD



Q9. What is the line voltage in this system?

Q10. What is the phase voltage?

Q11. What is the line current?

Q12. What current flows through the alternator windings?

Q13. What is the power used in each single-phase circuit in this system?

Q14. What is the total power in all three phases?

Your Answers Should Be:

A9. The line voltage is 208V.

A10. The phase voltage is the **line voltage divided by 1.73.**

$$\frac{208V}{1.73} = 120V$$

A11. The line current is **10 amps.**

A12. The line current of **10 amps** flows through the alternator windings.

A13. The power in each single-phase circuit is E × I × power factor.

$$120 \times 10 \times 1 = 1{,}200 \text{ watts}$$

A14. Since there are three single-phase circuits, the total three-phase power is 3 × 1,200 = **3,600 watts.**

Balanced Loads

In the preceding example, all three line currents (and all phase currents) were equal. When all **3 currents** in the lines **are equal** and are 120 electrical degrees apart, the load is said to be **balanced.**

When a load is balanced, the three currents meet at the neutral point of the load and at the neutral point of the generator and cancel. This cancelling effect is due to the phase relationships of the currents to each other. As long as all three are equal, there is no current in the neutral wire.

If the load is not balanced, current will flow in the neutral wire. The amount depends on the amount of current in each line and the phase relationships of the line currents to each other. It is always good practice to balance the load in any three-phase system when it is possible.

Power

You have found the power in a three-phase, wye-connected system with a balanced resistive load. This was done by multiplying phase current times phase voltage for each phase and then adding to find the total power.

Of course, if the load is inductive or capacitive, you must also multiply by the power factor. The formula for finding the power in **any kind of balanced load** in a wye-connected, three-phase system is:

$$P_T = I_p \times E_p \times 3 \times \cos\theta$$

where,

P_T is the total power,
I_p is the phase current,
E_p is the phase voltage,
$\cos\theta$ is the power factor.

There is also another way of finding power in a three-phase, wye-connected system with a balanced load. Since the phase voltage is always equal to the line voltage divided by 1.73, then:

$$P_T = \frac{\text{line voltage} \times \text{line current} \times 3 \times \text{power factor}}{1.73}$$

Note that line current is the same as phase current and also that 1.73 is the square root of 3. Therefore, $\frac{3}{1.73} = 1.73$. When the formula is simplified, it becomes:

$$P_T = I_L \times E_L \times 1.73 \times \cos\theta$$

where,

P_T is the total power,
I_L is the line current,
E_L is the line voltage,
$\cos\theta$ is the power factor.

Q15. Is the load balanced in a three-phase, wye-connected system whose line currents are 10 amps, 10 amps, and 15 amps?

Q16. In the system in Question 15, will there be any current in the neutral wire?

Q17. A balanced, wye-connected, three-phase system has a line voltage of 208V and a line current of 5 amps. The power factor of the load is 0.8. What is the total power supplied to the load? What is the current in the neutral?

Your Answers Should Be:

A15. If the currents are not equal, **the load is not balanced.**

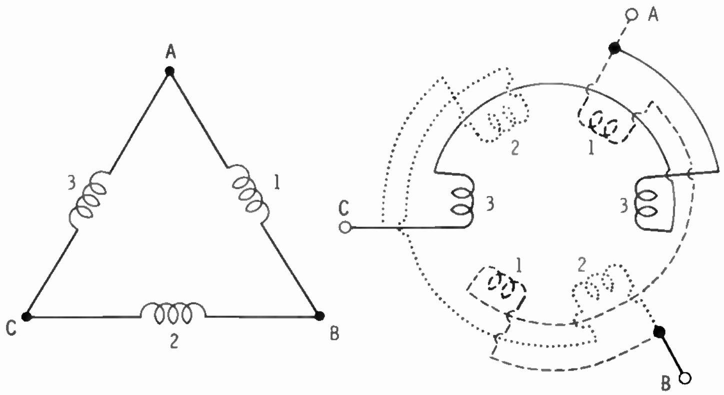
A16. There will **be current** in the neutral wire.

A17. $P_T = I_L \times E_L \times 1.73 \times \cos\theta$
$P_T = 5 \times 208 \times 1.73 \times 0.8 =$ **1439 watts**
The load is balanced, so the **current in the neutral is zero.**

DELTA CONNECTION

The three-phase, **delta-connected** system gets its name from the appearance of the diagram of its connections. Delta is the name of the Greek letter Δ.

DELTA CONNECTION



The windings are connected end to end in a sort of loop. When the system is properly balanced, almost no current flows around the loop because of the phase differences of the voltages. The delta-connected system has no neutral point. Delta-connected systems are not usually grounded.

The wye connection is essentially a series connection. The phase voltages combine to produce a higher line voltage because the line voltage is developed across two windings in series. The phase current and line current are the same. The delta connection, however, is essentially a parallel connection. The line voltage is simply the voltage developed across an individual winding, so the line voltage is equal to the phase voltage. The currents from two windings combine to give the line current. The amount of the line current depends on both the amount of the phase currents and the phase difference between them. If the load is balanced and the voltages are equal, the line current is 1.73 times the phase current.

In a balanced delta-connected system, the power can be found by multiplying phase voltage times phase current times the number of phases times the power factor:

$$P_T = I_P \times E_P \times 3 \times \cos\theta$$

The line voltage is equal to the phase voltage. The phase current is equal to the line current divided by 1.73. This leads to the following formula:

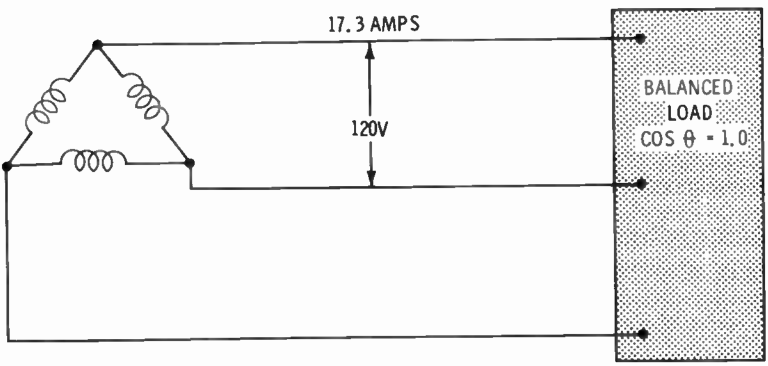
$$P_T = I_L \times E_L \times 1.73 \times \cos\theta$$

where,

P_T is the total power,
I_L is the line current,
E_L is the line voltage,
$\cos\theta$ is the power factor.

Note that the two power formulas for delta-connected systems are the same as the two for wye-connected systems.

Q18. For the circuit below, what is the line voltage, line current, phase voltage, phase current, and total power?



> **Your Answers Should Be:**
>
> A18. Line current, **17.3 amps**; line voltage, **120V**
> Phase current, **10 amps**; phase voltage, **120V**
> Power $= I_L \times E_L \times 1.73 \times 1 =$ **3,600 watts**
> or $I_p \times E_p \times 3 \times 1 =$ **3,600 watts**

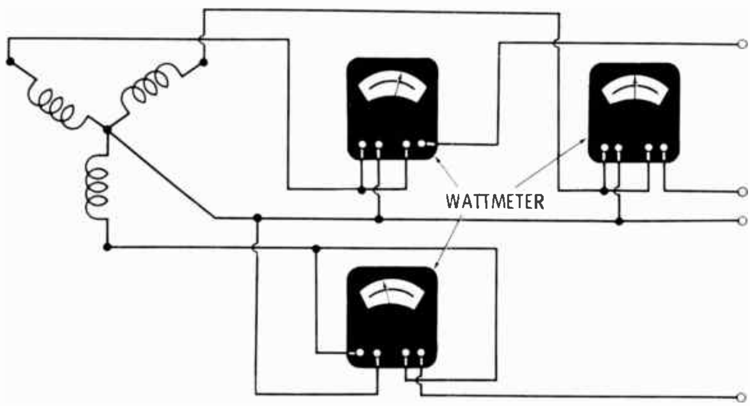
POWER MEASUREMENT

So far, you have learned how power is calculated but not how it is measured. In practical cases, all the information needed to calculate power may not always be available. The power factor of the load may be unknown, the load may not be balanced, or the voltage may fluctuate. In many cases, therefore, it may be necessary to measure power with a wattmeter.

Wattmeters have as inputs the factors one needs to know in order to calculate power—voltage and current. In effect, a wattmeter measures I and E and then calculates P mechanically. A wattmeter has a series connection to the line to measure current and a shunt connection to measure voltage. On power circuits, the wattmeter is connected to the main lines by a set of special instrument transformers which step down the voltage and current to safe values.

The Three-Wattmeter Method

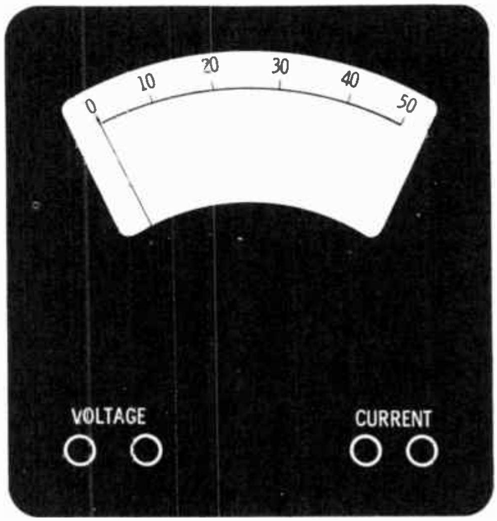
The three-wattmeter method is used primarily with three-phase, four-wire circuits. It can measure power in both bal-



anced and unbalanced systems. Three wattmeters are simply used to measure the power in all three phases. A typical connection is shown at the bottom of the opposite page.

In the three-wattmeter method, each wattmeter measures a separate phase. The meter receives as inputs the phase

A SIMPLE WATTMETER



voltage and phase current and gives a reading indicating phase power. In order to find the total power, add all three readings directly.

Q19. The power in a three-phase, four-wire, wye-connected system is measured by the three-wattmeter method. The individual meter readings are as follows for different loads. Find the three-phase power values. Which load is balanced?

	W_1	W_2	W_3
A	30W	40W	20W
B	20W	20W	20W
C	60W	60W	20W

Your Answers Should Be:

A19. (A) $P_T = 30 + 40 + 20 = 90W$

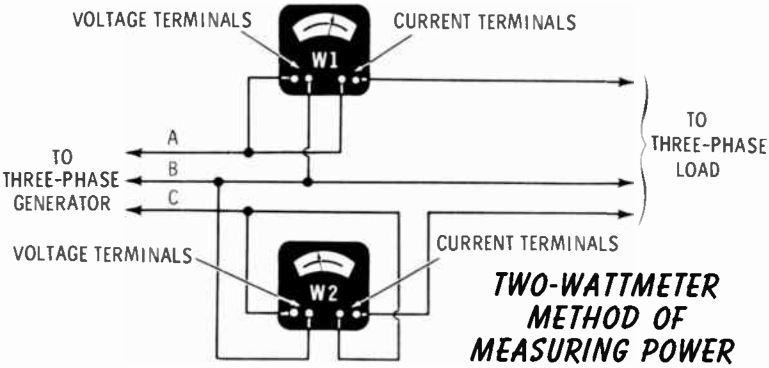
(B) $P_T = 20 + 20 + 20 = 60W$

(C) $P_T = 60 + 60 + 20 = 140W$

Only B is balanced since all its readings are equal.

The Two-Wattmeter Method

The two-wattmeter method employs line voltages and line currents and is suitable for either wye or delta connections. The two-wattmeter method can be used to measure power in both balanced and unbalanced circuits.



TWO-WATTMETER METHOD OF MEASURING POWER

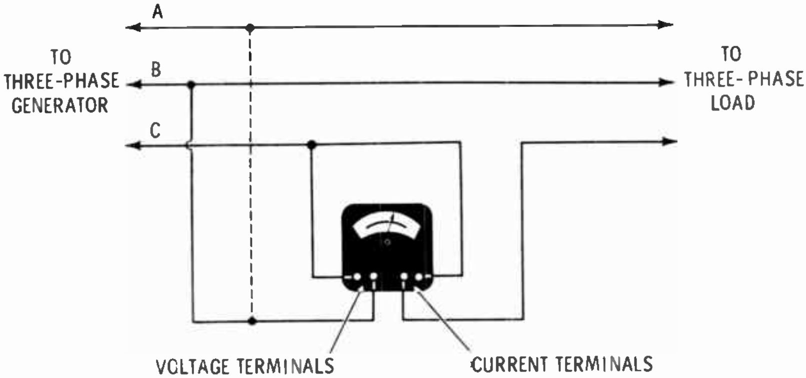
Total power is found by adding the two readings shown on the wattmeters. If the power factor of the load is less than 0.5, the wattmeter readings must be subtracted to obtain the total power. The sum (or difference) of the meter readings gives the total power because of the phase relationships of the voltages and currents in the three-phase system.

You can make a test to determine whether the power factor is less than 0.5. Connect the wattmeters as shown and so that both give an up-scale reading. (If the pointer of one of the wattmeters moves in the wrong direction, the voltage leads of this wattmeter must be reversed to obtain a reading.) Then temporarily move the voltage lead of W1 from line B to line C. (Or move the lead of W2 from line B to line A.) If the wattmeter then moves down-scale, the power factor is less than 0.5, and the smaller reading must be subtracted from the larger reading.

The One-Wattmeter Method

If the three-phase load is **balanced**, one wattmeter can be used to measure the total power as shown below. A reading

ONE-WATTMETER METHOD OF MEASURING POWER



is taken with one voltage lead connected to line B. The lead is then moved to line A, and another reading is taken. The sum of the readings gives the total power. A power factor less than 0.5 produces the same result in the one-wattmeter system as in the two-wattmeter system.

Of course, switches can be used to change the voltage leads in either the one- or two-wattmeter method. Wattmeters that have negative-zero-positive scales may also be used in both methods.

Q20. The two readings recorded from measuring the power by the two-wattmeter method are +20W and +40W. Find the total three-phase power.

Q21. The two readings recorded from measuring the power in a circuit by the two-wattmeter method are +40W and —15W respectively. Find the total three-phase power.

Q22. Four sets of readings found by the one-wattmeter method are:

A. +40, —20
B. +40, +40
C. +15, +20
D. —15, +30

Find the total power for each set of values.

Your Answers Should Be:

A20. $P_T = P_1 + P_2 = 20 + 40 = 60W$

A21. $P_T = P_1 - P_2 = 40 - 15 = 25W$

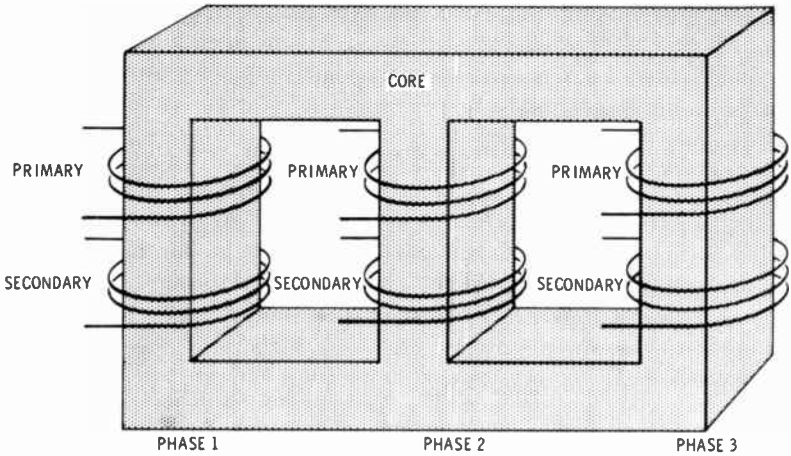
A22. (A.) 20W, (B.) 80W, (C.) 35W, (D.) 15W

TRANSFORMER CONNECTIONS

Wye and delta connections are used in many types of equipment. Three-phase motors are wye- or delta-connected, as are alternators. Another important type of a three-phase device is the three-phase transformer. Since power is often transmitted three-phase and since its voltage is transformed up and down at several points according to the needs of the distribution system, three-phase transformers are quite important.

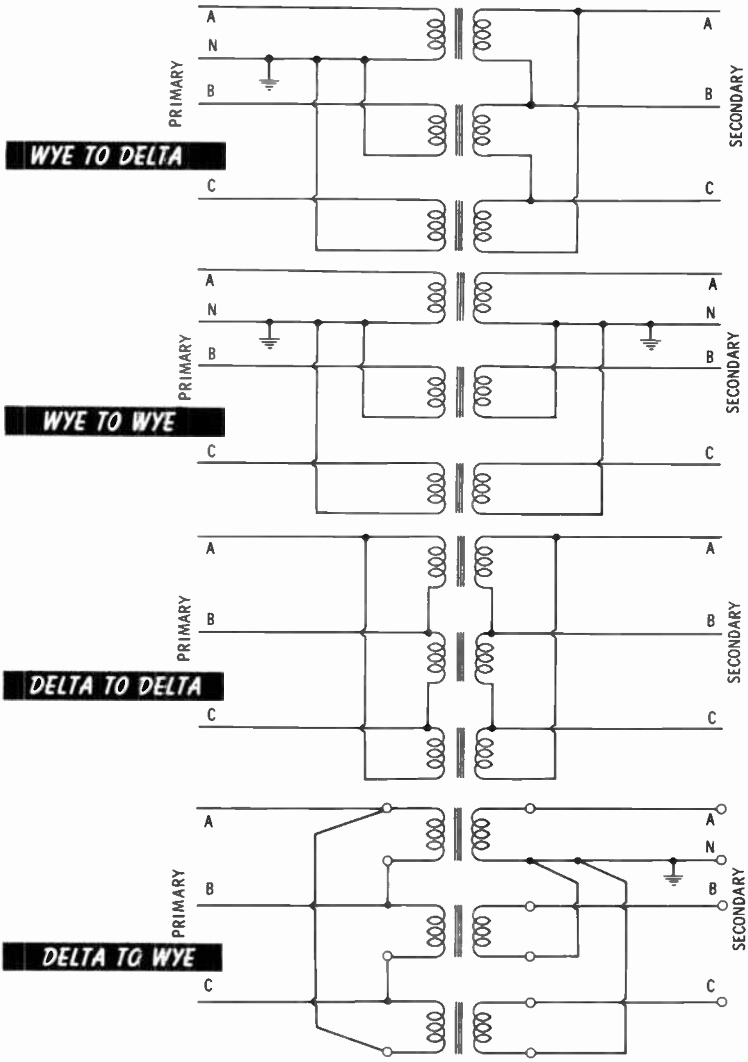
Three-phase transformers consist of either three single-phase transformers connected together or a single-core, three-phase winding, as shown below.

THREE-PHASE, SINGLE-CORE TRANSFORMER



The primaries and the secondaries can be connected in any combination of delta and wye. For example, the primaries can be wye-connected and the secondaries delta-connected, or vice versa. Or both the primaries and the secondaries can be wye- or delta-connected.

THREE-PHASE TRANSFORMER CONNECTIONS



Q23. Name the four ways in which transformers can be connected in a three-phase system.

Q24. What are the two kinds of three-phase transformers?

Your Answers Should Be:

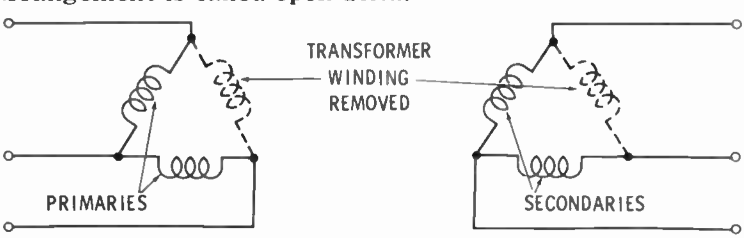
A23. Three-phase transformers can be connected in **wye-to-delta, wye-to-wye, delta-to-delta,** and **delta-to-wye** arrangements.

A24. A three-phase transformer can be made up of **three single-phase** transformers or a **single-core, three-phase** winding.

Both three-phase transformers and three single-phase transformers have their advantages. These are listed in the table below.

ADVANTAGES	
Three-Phase Transformer	Three Single-Phase Transformers
Lower initial cost Higher efficiency Less total weight Less total floor space Lower installation and transportation cost	Cheaper spare parts A single unit can be replaced in case of trouble Lower repair cost More voltage flexibility

Overall, the three-phase transformer is considered a better unit in most situations. One minor advantage of using three single-phase transformers in a delta connection is that it is possible to remove one of the transformers altogether and still have the system operate at reduced capacity. This arrangement is called **open delta.**

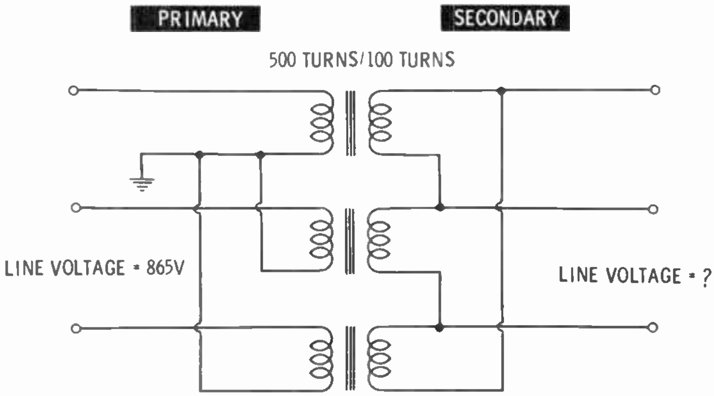


OPEN-DELTA CONNECTIONS

When using wye-to-delta or delta-to-wye connections, there is one important fact to remember. Line voltage and phase voltage are equal in the delta connection and line voltage is 1.73 times phase voltage in the wye connection. These facts can be used to get an additional step up or step down of voltage without adding extra turns to the transformers.

For example, suppose you are using a group of single-phase transformers with turns ratios of one to five to step up a three-phase voltage of 100 volts (line voltage). If the primaries of the transformers are delta-connected, the primary phase voltage is 100 volts. The **phase voltage** at the secondary will be 500 volts, but if the secondary is **wye-connected,** the **line voltage** will be $1.73 \times 500 = 865V$. If both sets of windings had been connected in the same way (both wye or both delta), the secondary line voltage would have been only 500 volts.

Q25. What is the secondary line voltage in the circuit below?



Q26. Draw a diagram showing three single-phase transformers connected in a wye-to-delta arrangement.

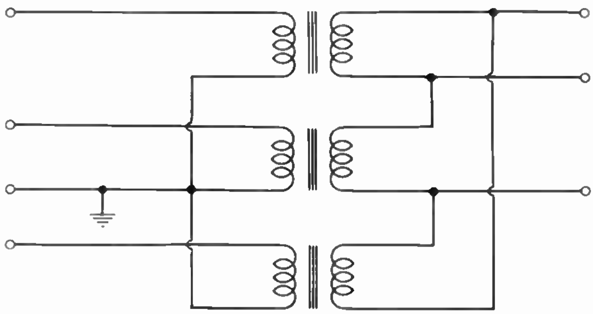
Q27. A delta-to-wye, three-phase transformer has a turns ratio of 10 to 1 and is used as a step-down transformer. If the input line voltage is 1,000V, what is the output line voltage?

Q28. What is one disadvantage of using the open-delta connection?

Your Answers Should Be:

A25. The phase voltage of the wye-connected primary is 865/1.73 = 500V. The phase voltage in the secondary is 100V. Since the secondary is delta-connected, the **line voltage** is also **100V.**

A26.



A27. The primary phase voltage is 1,000V. The secondary phase voltage is 1,000/10 = 100V. Since the secondary is wye-connected, the **secondary line voltage is 173V.**

A28. In the open-delta connection the transformers must be operated at **reduced capacity.**

WHAT YOU HAVE LEARNED

1. The power for most household and industrial use is generated and distributed as three-phase.
2. Three-phase power is usually generated in hydraulic or steam power plants.
3. In hydroelectric plants, falling water drives a generator at low speed.
4. In steam plants steam drives a turbine at high speed. In steam plants the turbine, alternator, and DC exciter are arranged horizontally.
5. Wye and delta connections make it possible to transmit three-phase power with four or even three conductors.
6. In the wye connection, one end of each winding is connected to a common point which is often grounded.

7. In the wye connection the voltage between the lines is called line voltage and is 1.73 times the voltage generated in any phase winding.
8. The voltage in a phase winding is called phase voltage, and appears between a line and neutral in the wye connection.
9. In the delta connection the windings are connected to form a closed loop. No current flows around this loop.
10. In the delta connection, line voltage and phase voltage are equal.
11. In the delta connection, line current is 1.73 times phase current.
12. In any three-phase system the total power is equal to the sum of the powers in all three phases.
13. The power in a three-phase system can also be found from line voltages and currents by the formula:

$$P_T = 1.73\ I_L\ E_L \cos \theta$$

14. Power in three-phase systems can be measured using one, two, or three wattmeters.
15. In the three-wattmeter method, power is simply measured in each phase. It is used primarily with three-phase, four-wire, wye-connected systems.
16. In the one-wattmeter and two-wattmeter methods, two readings must be either added or subtracted (depending on the power factor) to find the power in the system.
17. Transformers can be connected in wye or delta patterns.
18. The primary and secondary of a three-phase transformer need not be connected in the same pattern.
19. By connecting the primary of a transformer in wye and the secondary in delta, or vice versa, it is possible to have a greater change in voltage than is produced by the turns ratio of the transformer alone.
20. Three-phase transformers can either be three-phase units or combinations of three single-phase transformers.
21. Three single-phase transformers can be connected in open delta.

7

Power Converters

What You Will Learn

There are a number of devices that convert one type of power to another. You will now find out how DC can be converted to AC and AC to DC. You will learn how AC frequency can be changed and DC voltages stepped up or down. You will also learn how to draw schematics for some of these changes and how to choose the correct device for a particular application.

THE NEED FOR CONVERTERS

Electrical energy is generated and transmitted primarily as three-phase AC, usually at 60 cps and very high voltages. The voltages are transformed to lower values before being used. Sometimes only one phase is used for a particular piece of equipment. The most common type of power supplied to homes is single-phase AC.

Occasionally, DC is required at a remote location in rather large quantities. **Converters** provide a means of changing available AC currents to DC currents. Sometimes the supply source is DC, but AC currents are needed. A different kind of converter meets this need. Sometimes special frequencies of AC are required or high DC voltages are needed. Converters can provide these also.

The word **converter** actually includes any of the following changes in electrical form: AC to DC, AC to AC of a different frequency, DC to AC, DC to higher-voltage DC, DC to lower-voltage DC, etc.

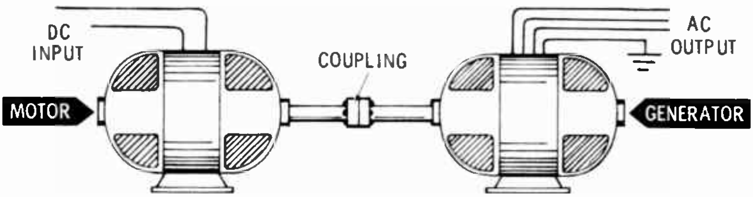
DC-TO-AC CONVERTERS

The conversion of DC to AC usually takes place when a DC source is available and a rather specialized AC frequency is required. The two basic methods of converting DC to AC are by means of a motor-generator (M-G) set and by vibrator action.

Motor-Generators

In the simplest form of M-G set, a DC **motor** drives an AC **generator.** Depending on the type of AC generator chosen, a DC-to-AC converter may deliver single-phase, two-phase, or three-phase AC power. Most generators in this type of converter are three-phase synchronous units.

DC-TO-AC MOTOR-GENERATOR SET



A DC motor chosen as the prime mover in an M-G set must have speed characteristics that are very constant. If the speed of the motor varies considerably as the load increases, the frequency of the AC generator will vary accordingly. (Frequency is directly proportional to the speed of the prime mover.) One suitable type of DC motor is the shunt motor, although compound motors are also used to a great extent. A series motor could not normally be used because of its poor speed control.

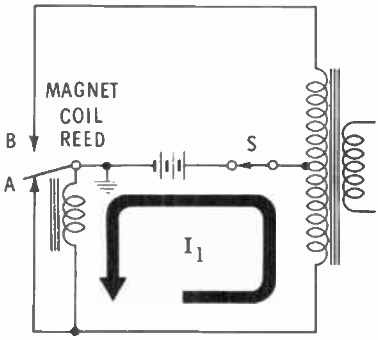
Vibrators

Vibrators are used in DC-to-DC converters and DC-to-AC converters but usually are able to deliver only very small amounts of power. The figure at the top of the opposite page shows a simple vibrator circuit. (The filtering components have been deliberately omitted so that the reader may better understand how it works.)

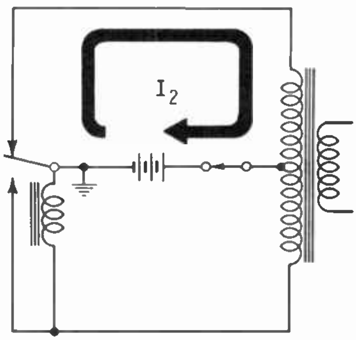
When switch S is closed, the current will flow through the magnet coil. This action causes the coil to attract the reed and thus closes contact A. When the reed touches contact

A, it short-circuits the magnet coil, thus releasing the reed from its position. The reed is released, it springs back, and its inertia sends it into contact with point B. By this time, the magnet coil again has current flowing through it, so it pulls the reed back to point A, and the cycle repeats itself.

A VIBRATOR CIRCUIT



CURRENT THROUGH LOWER WINDING



CURRENT THROUGH UPPER WINDING

The vibrating reed causes the current to flow through first the lower section of the transformer primary and then the upper section. This is very much like having an alternating current flowing in the primary. This action causes an AC voltage to be induced in the secondary of the transformer. The voltage is not a sine wave, however, but has a generally rectangular shape. Filtering action can smooth out the waveform.

The magnitude of the induced voltage depends on the turns ratio of the transformer. The frequency of the voltage depends on the speed with which the reed changes from A to B. The speed, in turn, varies with the weight of the reed and the strength of the magnetic field.

Q1. Do you think a special converter would be used to convert low-voltage AC to high-voltage AC? How would this be done?

Q2. Why it is necessary to use a constant-speed motor in a DC-to-AC motor-generator set?

Q3. The moving part of a vibrator is a _____________.

Your Answers Should Be:

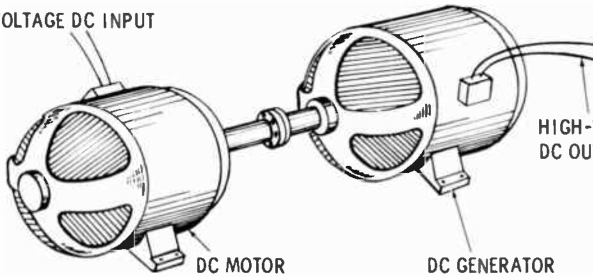
A1. No, a **transformer** changes the voltage of AC simply and efficiently.

A2. **If the speed** of the M-G set varies, the **frequency of its output also varies.**

A3. The moving part of a vibrator is a **vibrating reed.**

DC-TO-DC CONVERTERS

A simple means of obtaining a higher DC voltage from an existing DC source is to use an M-G set in which both the motor and the generator are DC machines.



DC-TO-DC MOTOR-GENERATOR SET

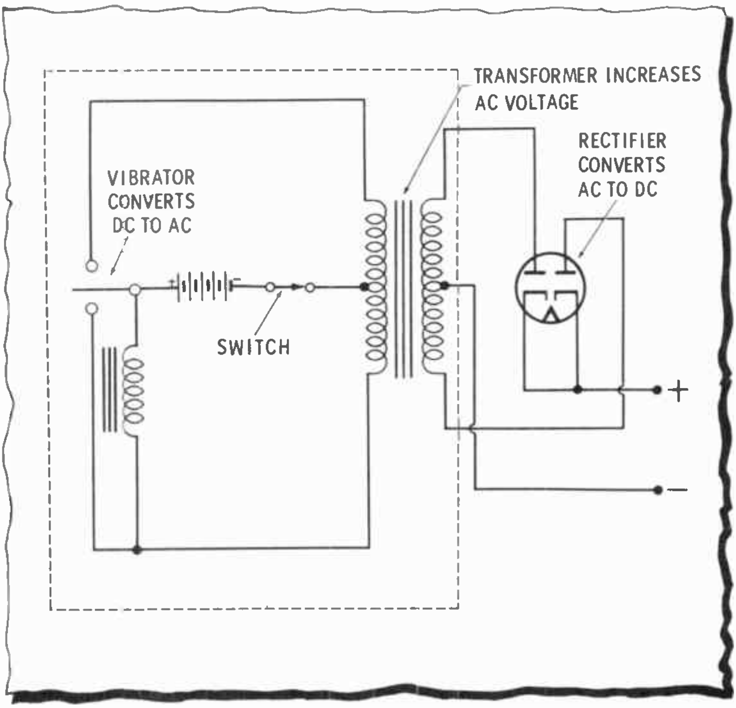
A shunt or compound DC motor is best because it has relatively constant speed for varying loads. The output voltage of the generator depends on the speed. A shunt or compound DC generator is best suited for use in M-G converters because it has good voltage regulation for varying loads.

When only a small DC output is required, a vibrator can be successfully employed. The vibrator converts the DC to higher-voltage AC. Then the AC is converted back to DC at this higher voltage. A typical circuit is shown on the opposite page.

The advantage of the DC-to-DC vibrator converter is that the AC output produced by the parts enclosed in the dashed line in the illustration can be converted to a DC voltage which is higher than that of the battery. The means by which AC can be converted back to DC will be discussed in the following section. The device shown is a **full-wave rectifier,** a type of electronic converter.

The DC-to-AC devices discussed so far are often called **inverters.** This distinguishes them from the more common AC-to-DC devices that are called **converters.**

DC-TO-DC VIBRATOR CONVERTER



Q4. What sort of DC motor would be best suited for use in a motor-generator set used as a DC-to-DC converter? Why?

Q5. What sort of DC generator would be best suited for this application? Why?

Q6. In one device for raising the voltage of small amounts of DC power, the DC is converted to __, and then the voltage is raised by a ____________. The AC is then converted to __.

Q7. An inverter is a device for converting __ to __.

Your Answers Should Be:

A4. **Shunt or compound** DC motors are best for this purpose because of their relatively **constant speed.**

A5. **Shunt or compound** DC generators are best for this purpose because their **output voltage does not change greatly with varying loads.**

A6. In one device for raising the voltage of small amounts of DC power, the DC is converted to **AC,** and then the voltage is raised by a **transformer.** The AC is then converted to **DC.**

A7. An inverter is a device for converting **DC** to **AC.**

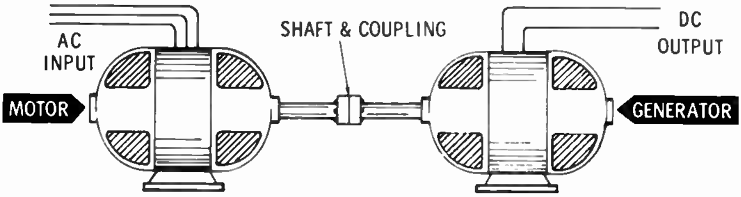
AC-TO-DC CONVERTERS

There are several ways of converting AC to DC. This can be done by any of the following: motor-generator set, synchronous converter, electronic rectifier, or contact rectifier.

Motor-Generator Sets

The use of M-G sets as AC-to-DC converters is quite similar to the method used in inverters. An AC motor drives a DC generator.

AC-TO-DC MOTOR-GENERATOR SET



It is customary to use three-phase motors of either the induction or synchronous type. The induction motor has the advantage of being lower priced and more rugged in construction than the synchronous motor. The induction motor can be wound for voltages as high as 13,500 volts, thus eliminating the need for step-down transformers in many cases.

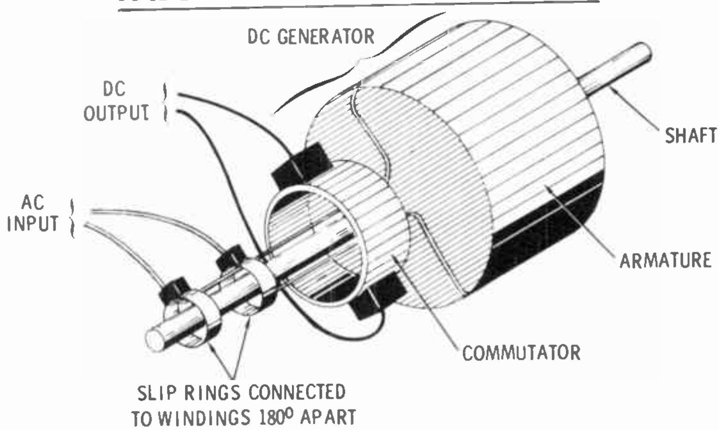
Synchronous motors have the advantage of constant speed and higher power factor. In large converter installations, the synchronous motor is usually preferred. By overexciting a synchronous motor, the overall power factor of the system can be improved. The overexcited synchronous motor becomes a synchronous capacitor. (That is, it does the job of a huge capacitor.)

The Synchronous Converter

The synchronous converter is sometimes called a **rotary converter.** It changes AC to DC. The synchronous converter consists of a DC field and a DC armature equipped with slip rings in addition to a commutator. You can consider it as a synchronous motor whose armature is equipped with a commutator to provide a DC output.

ARMATURE OF A SYNCHRONOUS CONVERTER

DC GENERATOR + SLIP RINGS = ROTARY CONVERTER



Under ordinary conditions, an alternating voltage is connected to the motor portion of the converter through slip rings, causing the machine to rotate at synchronous speed like an AC synchronous motor. At the same time, the machine also acts like a DC generator. This DC output is taken from the commutator by brushes and can be used to provide current for the field winding. This DC output can, in addition to energizing the field winding, furnish DC to an external load.

Q8. A synchronous converter has an armature equipped with ---- ----- and a ----------.

Q9. The DC output is taken from a synchronous converter through the ---------- brushes.

Your Answers Should Be:

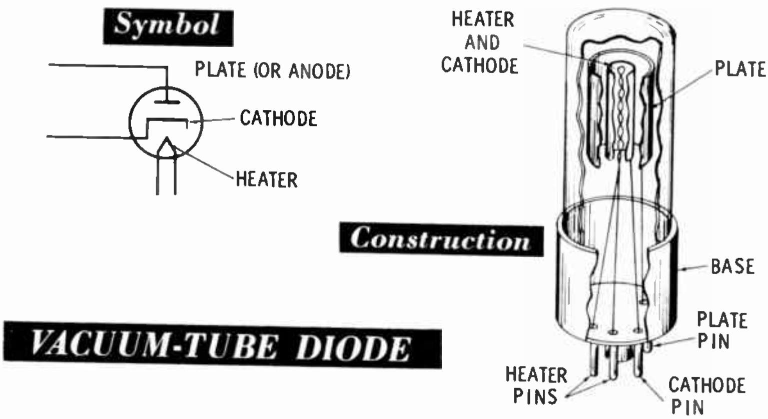
A8. A synchronous converter has an armature equipped with **slip rings** and a **commutator.**

A9. The DC output is taken from a synchronous converter through the **commutator** brushes.

Electronic Rectifiers

The simplest and most common type of electronic rectifiers are diode vacuum tubes (electron tubes). The principles of operation of electron tubes are covered more thoroughly in Volume 3 of this series.

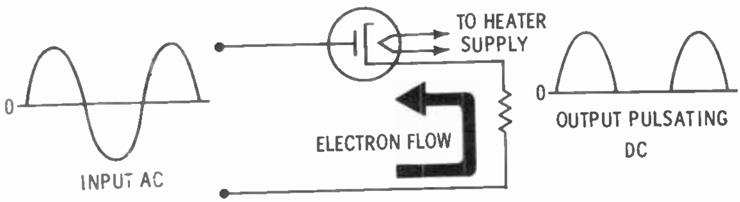
A vacuum-tube diode usually consists of three parts enclosed in a glass bulb from which the air has been removed to create a vacuum. The parts are the plate, cathode, and heater. In some tubes, the filament also serves as the cathode; this is called a directly heated cathode.



In a vacuum-tube diode, heating the cathode drives electrons off the cathode. If a positive voltage (with respect to the cathode) is applied to the plate, the plate will attract the electrons emitted from the cathode. The movement of electrons is, in effect, a current flow. If the plate is more negative than the cathode, no current flows since there is no positive charge to attract the electrons. The vacuum-tube diode thus acts as a valve. It conducts in one direction but not in the other.

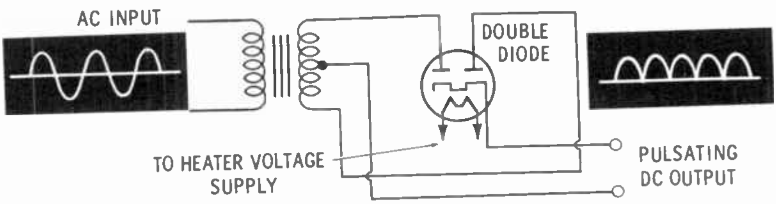
Look at the circuit diagram below. During the positive half cycle of the AC input, the plate is positive with respect to the cathode, and current flows. (A voltage drop appears across the load resistor, but it is a little less than the input voltage.) During the negative half cycle, the plate is negative with respect to the cathode, and no current flows.

HALF-WAVE RECTIFIER



The device just described is called a **half-wave rectifier** because only half of the AC sine wave appears in the output. Although this current never reverses direction, it is a very rough, pulsating DC which is not satisfactory for must purposes. A smoother DC can be obtained from a **full-wave rectifier.**

FULL-WAVE RECTIFIER



Both halves of the AC sine wave appear in the output of the full-wave rectifier. The output is still a pulsating DC, but it is smoother than the half-wave output. With proper filtering, the output of a full-wave rectifier can be smoothed further into a steady DC current.

Q10. A vacuum-tube diode conducts only when the plate is _________ with respect to the cathode.

Q11. The output from a ____ ____ rectifier is easier to smooth than the output from a ____ ____ rectifier.

Your Answers Should Be:

A10. A vacuum-tube diode conducts only when the plate is **positive** with respect to the cathode.

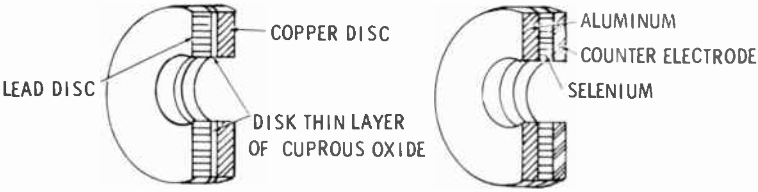
A11. The output from a **full-wave** rectifier is easier to smooth than the output from a **half-wave** rectifier.

Contact Rectifiers

Contact, or **barrier-layer,** rectifiers are devices which permit current flow in one direction only. (Actually, they present a very high resistance in the reverse direction.) They produce very much the same result as a vacuum-tube diode. Two very common types of metallic barrier-layer rectifiers are copper-oxide and selenium rectifiers.

The **copper-oxide** rectifier is produced by heating a copper disc to a high temperature and then quenching it in water. This produces a thin layer of red cuprous oxide sandwiched between the copper disc and a thick outer layer of green cupric oxide. The cupric oxide is then removed and a lead disc is pressed against the cuprous oxide. Electrons flow more easily from lead to copper than from copper to lead.

CONTACT RECTIFIERS



Copper Oxide — *Selenium*

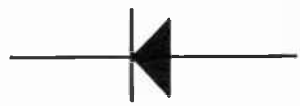
The **selenium** rectifier is made by depositing a layer of selenium on an aluminum plate. An alloy with a low melting point is then sprayed onto the selenium surface. This alloy is called the **counterelectrode.** The current-blocking layer is the surface between the selenium and the alloy. Electrons flow through this surface easily in one direction but not in the other.

Another type of rectifier is the **semiconductor** rectifier. The rectifying action is produced by the junction of P-type and N-type materials. Electrons flow easily from the N-type to the P-type material, but not in the reverse direction. You can learn more about the theory of semiconductor materials in Volume 3 of this series.

Small rectifier cells are often called **rectifier diodes** since they perform the same rectifying action as the diode vacuum tube. If large quantities of electricity need to be rectified, **rectifier stacks** are used. These are composed of a number of rectifier elements assembled and connected together.

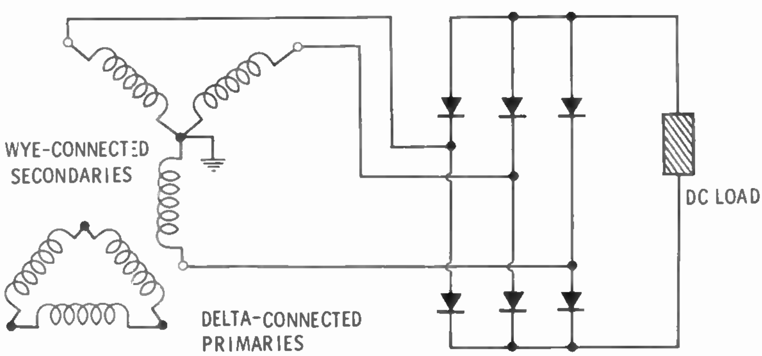
The symbol for a rectifier is shown in the figure below. The arrowhead points **against** the direction in which electrons move through the rectifier.

Contact-Rectifier Symbol



The rectifiers shown so far have had single-phase inputs. Three-phase current can also be rectified, as shown in the following illustration.

THREE-PHASE RECTIFIER CIRCUIT



Q12. Name three types of rectifier cells.

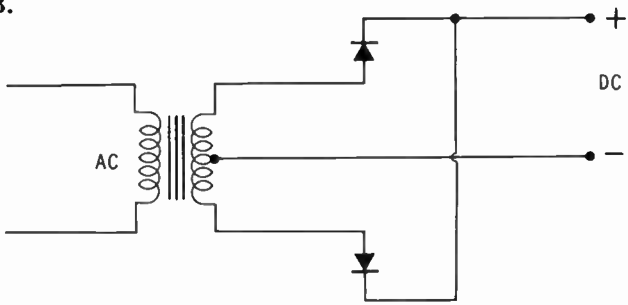
Q13. Draw a schematic of a full-wave rectifier using two rectifier cells.

Q14. What property of rectifiers makes them useful in converting AC to DC?

Your Answers Should Be:

A12. Three types of rectifier cells are: **copper oxide, selenium,** and **semiconductor.**

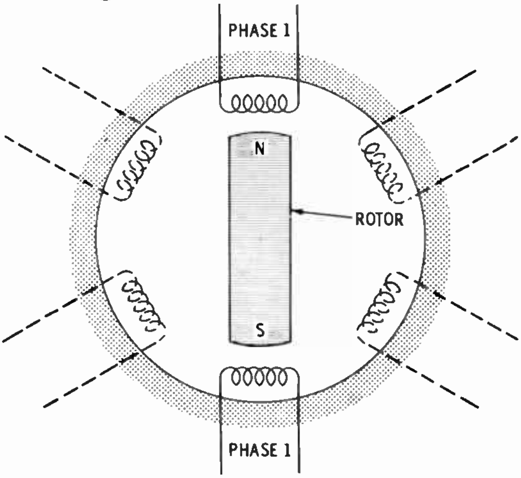
A13.



A14. Rectifiers have a **high resistance** to current flow **in one direction** and a **low resistance in the other direction.**

FREQUENCY CONVERTERS

The last type of converter to be discussed is the frequency converter. The simplest way of changing frequency is to provide a motor-generator set in which the motor is AC

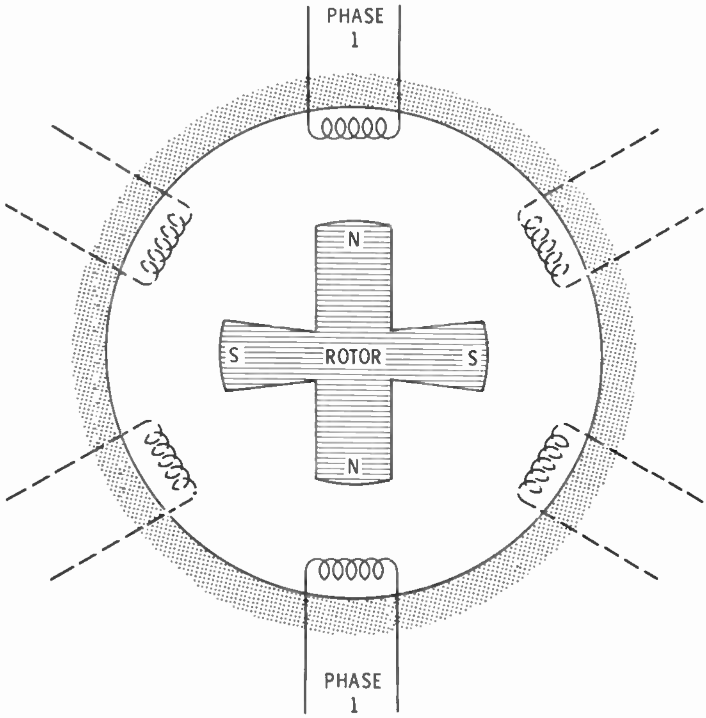


TWO-POLE MACHINE

(preferably synchronous) and the generator is an AC synchronous unit, but with different number of poles.

Look at the figure on the opposite page. If the machine is a generator, the emf induced in each winding goes through a complete cycle every time two unlike poles pass the winding. In the illustration, this happens once for every revolution of the rotor. If the machine is a synchronous motor, the rotor will make a complete revolution for each cycle of current in the windings.

FOUR-POLE MACHINE



Now look at the figure above. This machine has four poles on the rotor. **Four** poles pass each winding during each revolution. Therefore there are **two** complete cycles of current in each winding for each revolution of the rotor. A machine with **eight** poles will have **four** complete cycles of current in each winding for each revolution of the rotor, etc.

The formula relating the frequency to the speed and to the number of poles in a synchronous generator or motor is as follows:

$$S = \frac{120 \times f}{p}$$

or,

$$f = \frac{S \times p}{120}$$

where,

S is the speed (rpm),
f is the frequency (cps),
p is the number of poles.

Thus, if the motor in an M-G set is a two-pole machine operating at 60 cps, the speed of the shaft will be:

$$S = \frac{120 \times f}{p}$$

$$S = \frac{120 \times 60}{2} = 3{,}600 \text{ rpm}$$

If this motor is used to drive a generator having **six** poles, the output frequency will be:

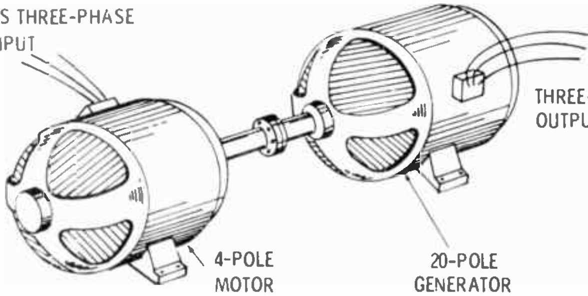
$$f = \frac{S \times p}{120} = \frac{3{,}600 \times 6}{120} = 180 \text{ cps}$$

The AC-to-AC motor-generator set is probably the simplest frequency-converting device. However, a number of other devices can be used for this purpose.

The **induction generator** discussed in Chapter 4 is basically a frequency-converting device. As you remember, it can be used to decrease the frequency if the rotor is driven in the same direction as the rotating magnetic field. If the rotor is driven in the opposite direction, the frequency is increased.

Higher frequencies for small amounts of current can be obtained with **vibrators** operated by AC instead of DC. Very small quanties of power at almost any frequency can be developed by an electronic **oscillator.** Since this type of device is used mainly in electronic work, it is discussed in Volumes 3 and 4 of this series. The oscillator is basically a DC-to-AC converting device.

Q15. Find the output frequency of the M-G set below.



Q16. Does a four-pole generator have to turn faster or slower than a two-pole machine to generate the same frequency?

Q17. A four-pole synchronous motor turns (faster, slower) than a two-pole synchronous motor receiving the same frequency.

Q18. Find the output frequencies when the motor input frequency is 60 cps and the poles are as shown.

	Motor Poles	Generator Poles
A	2	8
B	4	10
C	16	4
D	10	70

Q19. What device with no moving parts would you use to convert a moderate amount of AC to DC?

Q20. What type of device would you use to convert 60-cycle AC to 120-cycle AC?

Q21. What type of device would you use to obtain heavy DC currents from AC?

Q22. What type of device would you use to obtain a small AC current from DC?

Q23. How could you step up the voltage of a small amount of DC power?

Q24. The word inverter is often used to refer to a device that converts __ to ___.

Your Answers Should Be:

A15. The speed of the motor is:

$$S = \frac{120 \times f}{p} = \frac{120 \times 60}{4} = 1{,}800 \text{ rpm}$$

The frequency of the generator is:

$$f = \frac{S \times p}{120} = \frac{1{,}800 \times 20}{120} = 300 \text{ cps}$$

A16. A four-pole generator turns at **half the speed** of a two-pole machine to generate the same frequency.

A17. A four-pole synchronous motor turns **slower** than a two-pole motor receiving the same frequency.

A18. **(A) 240 cps, (B) 150 cps, (C) 15 cps, (D) 420 cps**

A19. **A rectifier** has no moving parts and can be used to convert a moderate amount of AC to DC.

A20. **An M-G set with twice as many poles on the generator as on the motor** will convert 60 cps to 120 cps.

A21. **An M-G set with a synchronous motor and a shunt or compound DC generator** will convert heavy AC currents to DC.

A22. **A vibrator** will provide a small AC current from a DC input.

A23. **A vibrator combined with a transformer and a rectifier** can step up DC voltages.

A24. The word inverter is ofen used to refer to a device that converts DC to AC.

WHAT YOU HAVE LEARNED

1. Power converters are used to change one type of power to another. For example, they change AC to DC, DC to AC, AC to AC of a different frequency, or DC to higher-voltage DC.
2. DC can be converted to AC by use of a motor-generator set or by a vibrator.
3. An M-G set consisting of a DC motor and an AC gen-

erator can convert DC to AC. The best DC motor for this purpose is a shunt or compound type that has nearly constant-speed characteristics.

4. A vibrator can convert small amounts of DC to AC through the action of a vibrating reed.
5. Vibrators require filtering circuitry to convert the square-wave output into a smoother sine-wave AC.
6. Vibrators can also be used to convert low-voltage DC to high voltages. This is done by converting the low-voltage DC to a high-voltage AC output with a vibrator and transformer and using a rectifier to change it back to DC.
7. AC can be converted to DC by the use of M-G sets, synchronous converters, electronic rectifiers, or contact rectifiers.
8. AC-to-DC M-G sets usually use a synchronous or induction motor and a shunt or compound generator.
9. A synchronous converter is a machine whose armature is equipped with slip rings and a commutator. It converts AC to DC.
10. An electronic rectifier is a diode vacuum tube. An electronic rectifier allows current to pass in one direction but not in the other.
11. A contact rectifier operates similar to a vacuum-tube rectifier. Contact rectifiers have a high resistance in one direction and a low resistance in the other.
12. The most common types of contact rectifiers are: copper-oxide, selenium, and semiconductor.
13. Electronic and contact rectifiers can be connected in either half-wave or full-wave arrangements. A half-wave rectifier converts only half of the AC sine wave to DC; a full-wave rectifier converts both halves of the AC sine wave to DC and gives a smoother DC output.
14. AC frequencies can be converted by the use of an M-G set consisting of a synchronous motor and a synchronous generator with a different number of poles.
15. Vibrators and induction generators are also used to convert the frequency of AC currents.

8

Servo Control Systems

What You Will Learn

In this chapter you will learn how a servo control system can move and precisely position a heavy load through application of a small input signal. You will become acquainted with the basic principles of servo and synchromechanisms and how these devices can be used in controlling the direction and amount of rotation of an electric motor. You will discover how synchromechanisms can be used to transmit data from one location to another.

WHAT IS A SERVO CONTROL SYSTEM?

There are many load-positioning tasks which man has neither the muscle, mental ability, nor desire to perform. For the accomplishment of such tasks, he uses a servo control system. A servo system is used to move the heavy rudder of a ship, position the beam of large searchlights, or sight an observatory telescope, weighing several tons, on a distant star.

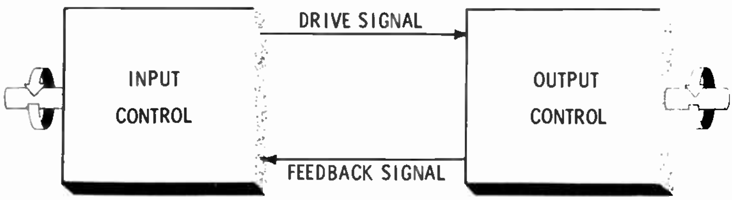
Servo systems can be designed for automatic operation. These systems can be used with radar for automatic tracking of targets, in weapons systems for automatic aiming of guns or missile launchers, in aircraft for automatic positioning of control surfaces, in missiles for automatic guidance through prescribed flight paths, and in many other installations where automatic and precise control is desired.

THE SERVO PRINCIPLE

The terms **servo system, servomechanism,** and **servo** are often used interchangeably to identify a complete system or one of its parts. To prevent confusion, an individual device will be identified by its noun name, servomotor for example, and a working combination of these devices will be called a servo (or control) system.

The Basic Servo System

All servo systems perform two functions. These functions are called **input control** and **output control.**



The figure above shows a shaft feeding a rotational signal to the input control which causes the output control to rotate its shaft in the same direction. The turning of the output shaft moves a load to a desired position. The output control continuously feeds a signal back to the input to reveal the precise position (in a rotational direction) of the output shaft. If there is a difference between input and output shaft positions, the latter will continue to turn until the desired amount of rotation is attained. All servo systems operate in accordance with this principle.

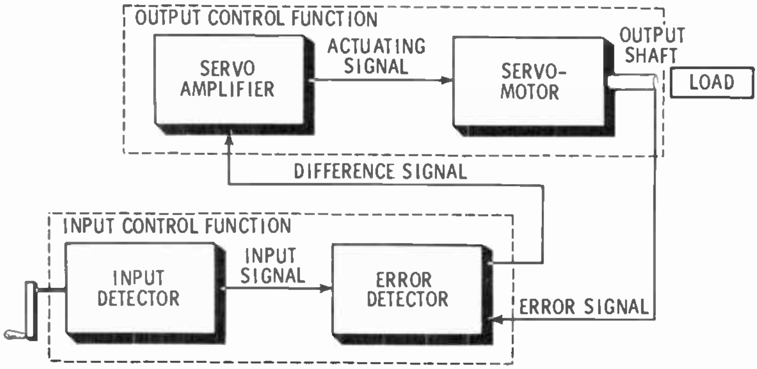
Electrical, mechanical, hydraulic, or air-pressure devices may be used for control mechanisms or transmission of signals between the two control functions. Because of their economy, reliability of operation, and ease of control, most servo systems employ electrical or electromechanical devices. Transmission of signals between control devices is nearly always done electrically. This is particularly true when the input control is located at some point remote from the output control.

Since it reveals position difference between input and output, the feedback signal is frequently called an **error signal.** Sometimes the drive signal is called an **actuating signal.**

Basic Parts of a Servo System

A servo system may have as few as two or three devices or as many as a hundred or more. The number and variety depend on the complexity of the system and the type of work it must perform. A modern radar, for example, must aim its antenna in elevation (up and down) and in bearing (left and right) as a result of manual or semiautomatic control. It must then automatically follow the target when it has been "locked-on." However, any servo system basically consists of four functional devices shown in the figure below.

BASIC PARTS OF A SERVO SYSTEM



The input detector senses any movement of the input shaft and sends a signal to the **error detector** where it is matched with an error signal which reveals the position of the output shaft. If the shafts are not in the same position, a difference signal is generated and then amplified by the **servo amplifier** to a value which will turn the **servomotor.** The motor will continue to turn until the difference between the input and the error signals is zero. When this occurs, the two shafts will be in the same angular position.

Q1. What are the two signals which reveal the positions of the input and output shafts?

Q2. When a difference signal is generated, input and output shafts (are, are not) in alignment.

Q3. What are the basic parts of the input and output control functions, respectively?

Your Answers Should Be:

A1. The **input signal** shows the position of the **input shaft.** The **error signal** reveals the position of the **output shaft.**

A2. When a difference signal is generated, input and output shafts **are not** in alignment.

A3. Input and error detectors are part of the **input control. Servo amplifiers and motors** are found in the **output control.**

OPEN AND CLOSED SERVO SYSTEMS

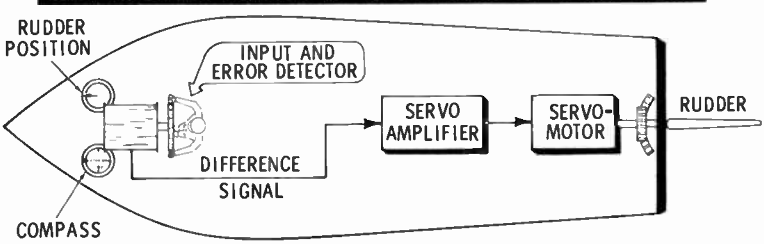
A servo system may be defined as either open or closed. In an **open system** the behavior or position of the output shaft is not automatically matched with the input position. Matching or correction is accomplished by manual or semi-automatic methods.

In a **closed system,** input and error signals are automatically compared to bring input and output conditions into automatic alignment.

An Open Servo System

The figure below shows an example of an open servo system. It is a steering system that could be used on a ship. The rudder turns in a direction and an amount determined by the rotation of a wheel in the pilot house. Since the rudder is large and heavy, it is pivoted by a servomotor.

AN OPEN SERVO CONTROL SYSTEM

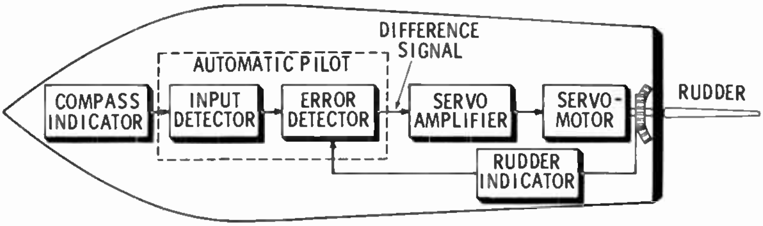


In this case, the man at the wheel is the input and error detector. He moves the wheel to maintain the ship on a specified course. He does this by watching the direction on a compass. When wind or ocean currents move the ship off course, he turns the wheel (and consequently the rudder) to bring the ship back on course. Because it is not automatic, the system is open.

A Closed Servo System

By replacing the man with an electric device, sometimes called an automatic pilot, the steering system can be made into a closed servo system as shown in the figure below.

A CLOSED SERVO CONTROL SYSTEM



When the ship drifts off course, the change in compass heading generates a voltage signal which is transmitted to the error detector. Since the rudder and heading (compass) positions no longer agree, a difference signal is sent to the servo amplifier and motor to turn the rudder an amount and in the direction required to bring the ship back on course. When the ship is back on course, the rudder will have been returned to its amidships (straight ahead) position.

If the ship is heading west (270° compass reading), for example, and the wind pushes it to a heading of 265°, there will be a 5° angular difference between the established positions of rudder and compass. A difference signal of an amount required to compensate for the deviation will be generated. The rudder will be turned to the right five degrees. Now the compass and rudder positions are the same, and the difference signal is zero. As the ship turns back to 270°, the rudder angle is decreased correspondingly and is returned to amidships when the ship heading becomes due west again. This system is a closed servo system.

Q4. A system which continuously self-compensates for differences between input and output is a(n) ______ servo system.

Q5. The difference signal will be zero when the _____ signal is equal to the _____ signal.

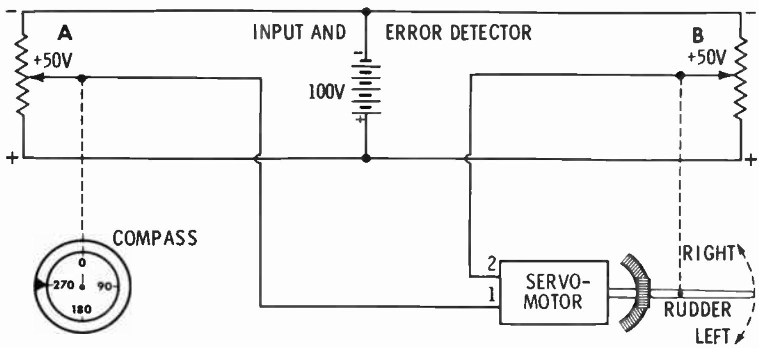
Your Answers Should Be:

A4. A system which continuously self-compensates for differences between input and output is a **closed** servo system.

A5. Difference signal will be zero when the **input** signal is equal to the **error** signal.

OPERATION PRINCIPLES

This is a simplified diagram of the steering servo system.



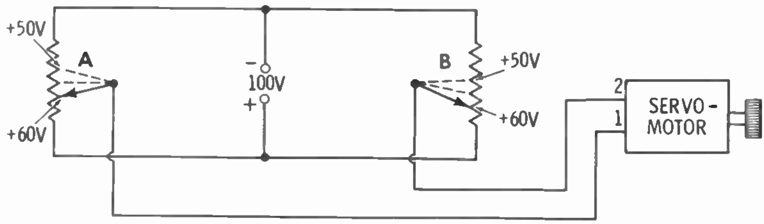
The input and error detectors contain a **balanced potentiometer**—the resistances of both potentiometer legs are identical. Potentiometer arm A responds to the turning of a compass. Arm B follows the movement of the rudder. Arms A and B are connected to the servomotor at terminals 1 and 2, respectively. A 100-volt battery is connected across the potentiometer.

When the ship is steering 270°, arm A is at the midpoint of the resistance. When the rudder is amidships, arm B is likewise at the midpoint of its resistance. Thus, both arms are selecting 50 volts. Since the voltage difference is zero, the motor will not turn.

If the ship swings 10° to the right, the compass will rotate to show a 280° heading. Arm A will be moved downward. Assume that it is now selecting +60V. The rudder is still amidships and arm B is still selecting +50V. Terminal 1 of the servomotor is now +10V with respect to terminal 2. The motor is so wired that it will turn the rudder 10° left.

When the rudder has reached the 10° position, arm B will have been moved to the +60V position. The potential difference at the motor terminals is zero and the motor is stopped. This situation is shown in the illustration below.

COMPASS AND RUDDER POSITIONS RETURNING TO ZERO



The angle of the rudder now turns the ship to the left. Since 0° on the compass always points north, the compass scale remains steady, and the ship, in effect, turns under it. The heading of the ship begins to move from 280° back to the desired 270°. As it does, arm A makes a corresponding movement back to its midpoint. If, for example, arm A is selecting +58V while arm B is still at +60V, terminal 2 is now two volts positive with respect to terminal 1. The servomotor turns in a direction to decrease the rudder angle. Arm B follows the rudder movement, decreasing its distance from the center resistance point.

As the ship continues to turn back to 270°, arm A is continuously leading arm B. Theoretically, arms A and B arrive at their midpoints simultaneously, and the difference signal becomes zero. This type of input control, however, is subject to overcompensation and will cause the ship heading to swing past the desired setting. Since the rudder will always follow, the ship will steer a winding course, weaving back and forth across the desired heading.

Q6. The resistances of a(n) ________ ______________ are equal.

Q7. If arms A and B (in the example given on these two pages) are selecting ⅔ and ⅗ of their resistances, respectively (measured from the negative ends), what is the voltage across the servomotor terminals?

Q8. Assuming the rudder is amidships at the beginning of Q7 conditions, which way will it be turned?

Your Answers Should Be:

A6. The resistances of a **balanced potentiometer** are equal.

A7. If arms A and B are selecting 2/5 and 3/5 of their resistances, respectively, **terminal 2 will be 20V positive with respect to terminal 1.**

A8. Under the conditions given, an amidships **rudder will be turned to the right.** The heading of the ship will be to the left of its desired course, and the polarity of the difference signal is such that it will rotate the servomotor in a direction which will turn the rudder to the right. This will bring the ship back to its desired course.

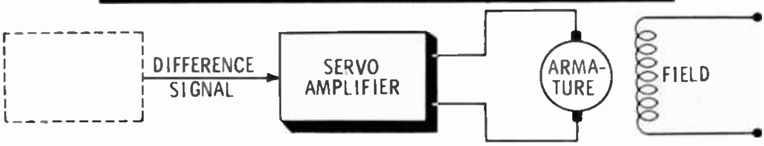
SERVOMOTORS

The preceding example used a DC servomotor to position a load. If the voltage source had been AC, an AC servomotor could have been substituted. Requirements of a motor used in a servo system include ability to drive a load in either direction and at varying speeds.

DC Servomotors

DC motors are selected for use in servo systems because of their high-stall torque characteristics and their ability to be operated at varying speeds. A **shunt-field motor,** the most predominant type of DC servomotor, is shown below.

SHUNT-FIELD DC SERVO MOTOR

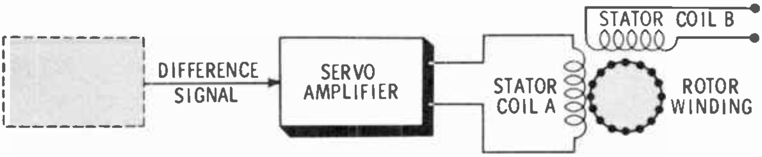


Voltage across the shunt field is obtained from a source separate from the servo system. This produces a uniform magnetic field. Voltage fed to the armature is controlled by the output of the servo amplifier (DC). Speed of the motor is determined by the magnitude of the voltage difference between terminals 1 and 2. Direction of armature rotation is determined by the polarity of these voltages.

AC Servomotors

Where low power and low speed ranges are permissible in a servo system, an AC servomotor is used. A distinct advantage is the ability to use a comparatively simple servo amplifier when an AC power source is available.

TWO-PHASE INDUCTION AC SERVO MOTOR



The diagram illustrates a **two-phase induction** motor, the type most frequently used in AC servomotor applications. Either a squirrel-cage or short-circuited rotor may be used.

The two stator coils are physically displaced 90°. Coil B, connected to a separate excitation source, develops a steady magnetic field in the top and bottom poles. Coil A magnetizes the left and right poles and its magnetic field depends on the magnitude and phasing of the AC voltage obtained from the servo amplifier. As you learned in a previous chapter, the rotor will turn when voltages applied to coils A and B are 90° out of phase.

The direction of rotor rotation is reversed when the servo amplifier reverses the direction of current through coil A. Speed of rotation is controlled by varying the strength of the magnetic field which, in this case, depends on the amount of current flowing through coil A.

In most installations, the value and direction of current flow is controlled by the characteristics of the difference signal fed to the servo amplifier. Since the difference signal will be AC, the servo amplifier can be a relatively simple electronic amplifier. In small servo systems, the difference signal may be fed directly to the servomotor.

Q9. (DC/AC) servomotors are used in servo systems requiring high torque to move a load.

Q10. (DC/AC) motors have the wider range of speeds.

Q11. DC servomotors are normally the ---------- type and AC servomotors are the ---------- type.

Your Answers Should Be:

A9. DC servomotors are used in servo systems requiring high torque to move a load.

A10. DC motors have the wider range of speeds.

A11. DC servomotors are normally the **shunt-field** type and AC servomotors are the **induction** type.

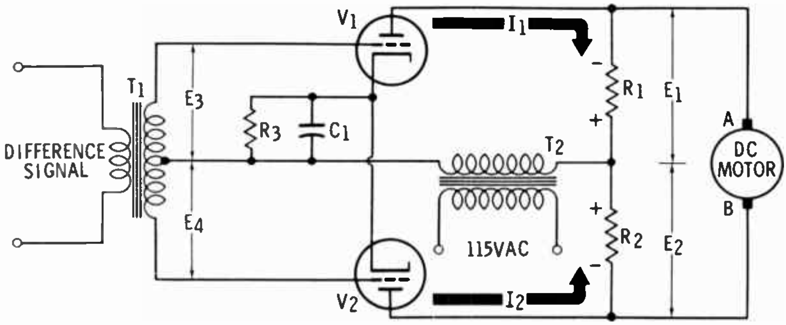
SERVO AMPLIFIERS

A **servo amplifier,** as you recall, converts the difference signal into a voltage or current to drive a servomotor at a desired speed and in the correct direction. DC servo amplifiers can be either electronic or electromechanical. AC servo amplifiers are usually electronic.

Vacuum-Tube DC Servo Amplifier

There are several varieties of electronic circuits used as DC servo amplifiers. Since nearly all difference signals are AC voltages, these circuits are designed to convert an AC signal into a DC output and to be sensitive to changes in phase. The circuit shown below is typical.

A SINGLE-STAGE DC SERVO AMPLIFIER



The servomotor used in such a circuit will probably be one with permanent-magnet poles. The secondary of T_2 applies an AC voltage to the plate of V_1 and V_2. As can be seen, the plate voltages are in phase. The difference signal enters through T_1 and is applied to the two grids 180° out of phase. C_1 and R_3 form the common-cathode bias for both tubes. With no signal applied across the primary of T_1, each grid is at the same potential and the plate currents are therefore equal. Voltage drops across the load resistors are equal and there is no difference of potential between points A and B of the motor armature. Therefore, the servomotor does not turn when there is no difference signal.

When a difference signal is applied across T_1, one of the grids will become positive with respect to the secondary center tap and the other grid negative with respect to the same point. Since the primaries of T_1 and T_2 receive power from the same line, one of the grids will be in phase with its plate voltage and the other 180° out of phase.

Assume that E_3 is causing the grid of V_1 to become more positive (the plates are going positive at the same time) while E_4 is causing the grid of V_2 to go negative by the same amount. Plate current I_1 through V_1 will increase and I_2 through V_2 will decrease. E_1 will increase (negative to positive from top to bottom) and E_2 will decrease (negative to positive from bottom to top). The voltage appearing across the DC servomotor armature will be the algebraic sum of E_1 and E_2. Since E_1 is greater than E_2, the armature voltage will be negative at A with respect to B. Current will flow through the armature from A to B, causing it to turn in a given direction.

When the difference signal reverses in phase, I_2 becomes greater than I_1. The difference between E_2 and E_1 causes an armature voltage which is negative at B with respect to A. The armature will now turn in the opposite direction.

Although the voltage across A and B is pulsating DC, its waveform is sufficiently smoothed out to cause armature rotation. The speed of armature rotation is determined by the magnitude of the difference signal.

Q12. The plates of V_1 and V_2 are always (in phase, 180° out of phase).

Q13. The grids of the two tubes are always (in phase, 180° out of phase).

Q14. The grid of which tube is always in phase with its plate?

Q15. _____ and __________ of the difference signal determine armature direction and speed, respectively.

Your Answers Should Be:

A12. The plates of V_1 and V_2 are always **in phase.**

A13. The grids of the two tubes are always **180° out of phase.**

A14. The grid of **either** tube can be in phase with its plate, depending on the difference-signal phase.

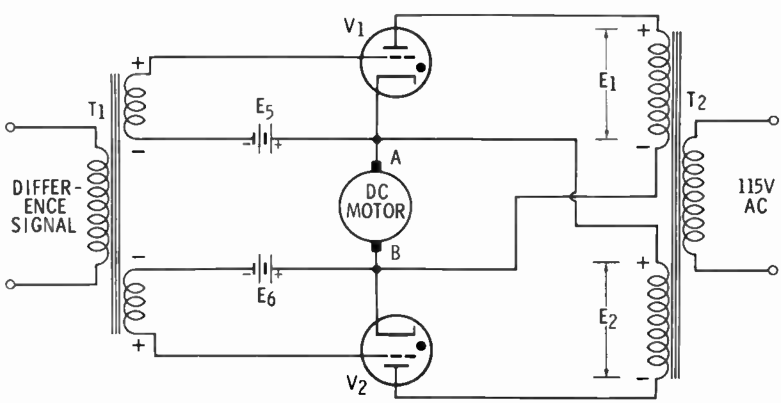
A15. **Phase** and **magnitude** of the difference signal determine armature direction and speed, respectively.

Thyratron DC Servo Amplifier

One way to obtain a greater amount of power from a DC servo amplifier is to use **thyratron** tubes. A thyratron is a gas-filled tube capable of passing eight or more amps as compared to the milliamps of a vacuum tube.

A thyratron has a **firing potential** determined by its plate and grid voltages. Assuming a given bias voltage on the grid, plate voltage can be gradually increased until it reaches a value which overcomes the repelling effect of the grid. At this point, plate current immediately rises from zero to a value determined solely by the plate voltage. The grid no longer has control over the current. The usual method of interrupting the plate current is to shut off the plate voltage.

A typical thyratron servo amplifier is shown below.



A BIDIRECTIONAL THYRATRON DC SERVO AMPLIFIER

T_2 is connected so that the plate voltages of V_1 and V_2 are 180° out of phase. E_5 and E_6 place a bias on each grid of sufficient value so that no plate current will flow when the difference signal is zero. T_1 is connected so grid voltages are in phase with each other as shown in the diagram.

Assume a difference signal on T_1 that causes the grids to swing positive while the plate voltage of V_1 is going positive. V_1 will conduct. Current will flow in the secondary of T_2, through the DC servomotor from B to A, and back to the cathode of V_1. During this half cycle the plate of V_2 is negative and the tube will not conduct. When the plate of V_2 becomes positive during the next half cycle, its grid signal is going negative and prevents the thyratron from conducting.

When the phase of the difference signal is reversed, the grid of V_2 is going positive at the same time as its plate. Current flows through the servomotor in the opposite direction, from A to B, causing it to rotate in the other direction.

As in the vacuum-tube amplifier, the direction of motor rotation is determined by the phase of the difference signal with respect to the voltage phase on the thyratron plates. Rotation speed is controlled by the magnitude of the signal.

Duration of plate current flow varies in accordance with the magnitude of the input difference signal. A low value signal allows the tube to remain at firing potential only a short period of time. To obtain a longer firing duration, some amplifiers use a means of phase-shifting control. A separate voltage, 120° out of phase with the plate transformer voltage, is added to the difference signal, allowing the grid to rise to firing potential sooner.

Q16. A thyratron conducts (more, less) current than a vacuum tube.

Q17. What is the difference between the schematic symbols for a thyratron and a vacuum tube?

Q18. Firing potential of a thyratron is determined by the ____ and _____ potentials.

Q19. When E_1 is negative to positive (top to bottom) and the grid of V_1 is going positive, which tube will conduct? (See illustration on opposite page.)

Your Answers Should Be:

A16. A thyratron conducts **more** current than a vacuum tube.

A17. The schematic symbol for a thyratron has a **large dot within its envelope**; a triode does not.

A18. Firing potential of a thyratron is determined by the difference of potential between **grid** and **plate.**

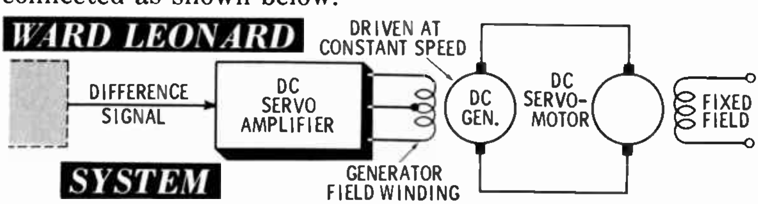
A19. With the conditions indicated, V_2 will **conduct.** When the plate of V_1 is negative, the plate of V_2 will be positive and the tube is capable of conducting. Since the input voltages to the grids are in phase, the grid of V_2 will also be going positive, allowing plate current to flow.

ELECTROMECHANICAL DC SERVO AMPLIFIERS

When large amounts of power are required to move a load, electromechanical DC servo amplifiers are used. Two of these are the Ward Leonard system and the amplidyne.

The Ward Leonard System as an Amplifier

The principles of a **Ward Leonard system** were explained in a previous chapter. When used in a servo system, it is connected as shown below.



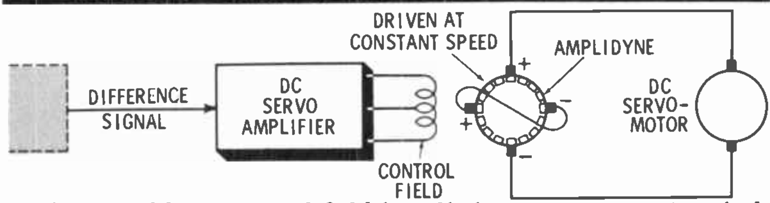
The field winding of the DC generator is in the output circuit of a vacuum-tube amplifier. The output of the generator is controlled by the strength of its magnetic field. The value of current through the field will be determined by the size of the amplified difference signal. A large difference signal will cause the servomotor to attain high speed; a smaller signal a lower speed.

When the phase of the difference signal reverses, the output polarity of the servo amplifier will also reverse, changing the direction of the magnetic field in the generator. The polarity of the generator output will reverse and the armature of the servomotor will change its direction.

An Amplidyne as an Amplifier

The **amplidyne** is a modified DC generator capable of power amplification of more than 10,000 times. A DC generator, described in an earlier chapter, uses about 100 watts of power in its field coils to generate 10 kilowatts of power. During its operation, the rotating armature develops a large reaction flux at right angles to the field. By short-circuiting the armature at this point, as shown in the diagram below, and reducing the power applied to the field to 1 watt, the same amount of power can be developed as before.

AMPLIDYNE IN A SERVO SYSTEM



The amplidyne control field is split into two separate windings and connected to the output of the servo amplifier. With no difference signal, the voltages across the two coils are equal and opposite, causing no generator output. With a difference signal fed to the servo amplifier, its output and the coil voltages become unbalanced. The coil with the higher voltage determines the direction of the magnetic field. The amplidyne amplifies the power of the field in exciting the armature of the servomotor.

Q20. Number the following DC servo amplifiers in descending order of power output level. The device having the largest output should be labeled #1.

Thyratron amplifier
Vacuum-tube amplifier
Amplidyne
Ward Leonard system

Q21. The Ward Leonard system consists of a(n) __ generator and a(n) __ servomotor.

Q22. An amplidyne has ___ pairs of brushes; one pair is _____ __________ to increase output.

Your Answers Should Be:

A20. In descending order of power output level, the DC servo amplifiers should be listed as: (1) Amplidyne, (2) Ward Leonard system, (3) Thyratron amplifier, and (4) Vacuum-tube amplifier.

A21. The Ward Leonard system consists of a DC generator and a DC servomotor.

A22. An amplidyne has two pairs of brushes; one pair is **short-circuited** to increase output.

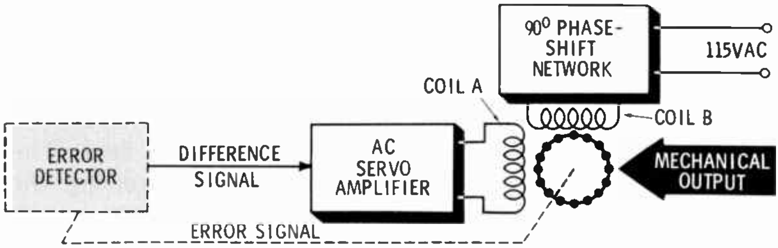
AC SERVO AMPLIFIERS

In most DC applications, the excitation voltages are applied to the servomotor armature; in AC servomotors, the voltages are applied to the stator.

A Basic AC Servo Amplifier

The illustration below shows an AC servo amplifier connected to an AC servomotor, a two-phase induction type.

BASIC AC SERVO AMPLIFIER AND MOTOR



Coil B, the reference winding, is excited from an AC line through a 90° phase-shifting network. Since the same line feeds the rest of the servo system, the difference signal, in phase or 180° out of phase with the line, will either lead or lag the voltage in coil B by 90°. The servo amplifier amplifies the difference signal before it is applied to coil A.

Since the magnetic fields in the coils are 90° out of phase, the motor will rotate in a direction to correct the error signal fed back to the error detector. If the phase of the difference signal changes, the magnetic field in coil A reverses, changing the direction of motor rotation.

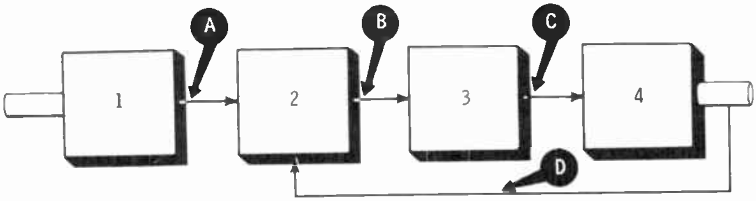
Types of AC Servo Amplifiers

AC servo amplifiers are always of the electronic type. The three most predominant types of circuits used include thyratron, multistage, and single-stage vacuum-tube amplifiers.

Thyratron Amplifier—Like its DC counterpart, the AC amplifier employs thyratrons in pairs. However, only one of the tubes will conduct during one phase of the difference signal.

Multistage Vacuum-Tube Amplifier—There are usually at least three stages in such an amplifier. The first stage adjusts the phase of the difference signal to insure that the two induction-motor fields will be 90° out of phase. The second is a stage of phase inversion to permit the final stage to operate as a push-pull amplifier for maximum output.

Single-Stage Vacuum-Tube Amplifier—In servo systems where power-output requirements are low, a cathode follower with one of the induction-motor coils in its cathode circuit will serve the purpose.



Q23. Provide the proper titles for the numbered blocks in the servo-system diagram above.

Q24. What is the signal that appears at A above?

Q25. What determines the magnitude of signal B?

Q26. The name of signal D is _____ ______.

Q27. In most applications, the output of block 3 is a(an) __ or pulsating __ voltage.

Q28. Block 4 can be an AC __________ motor or a DC _____ field motor.

Q29. Electronic servo amplifiers employ either ___________ or ______ _____; the ____ _______ system and the __________ are electromechanical servo amplifiers.

Your Answers Should Be:

A23. The titles for the blocks in the servo system diagram are: **(1) Input Detector, (2) Error Detector, (3) Servo Amplifier, (4) Servomotor.**

A24. A in the diagram is the **input signal; it identifies the rotational position of the input shaft.**

A25. The magnitude of B, the difference signal, is **determined by the amount of difference existing between the input (A) and error (D) signals.**

A26. The name of signal D is **error signal.**

A27. In most applications the output of the servo amplifier is an **AC** or pulsating **DC** voltage.

A28. Block 4 can be an AC **induction** motor or a DC **shunt**-field motor.

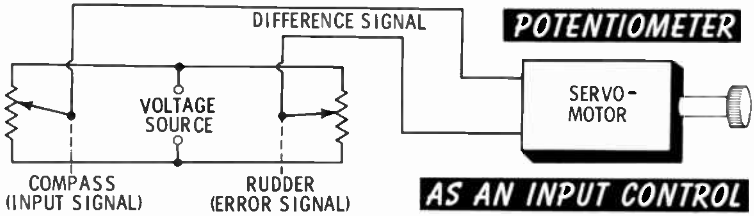
A29. Electronic servo amplifiers employ either **thyratrons** or **vacuum tubes**; the **Ward Leonard** system and the **amplidyne** are electromechanical servo amplifiers.

INPUT CONTROL FUNCTIONS

Thus far you have learned how the output control devices (servo amplifiers and motors) perform the function of positioning a load in response to a signal from the input control section. The question that remains to be answered is how the input control devices detect and match the input and error signals to generate a difference signal.

Input Control Devices

Earlier in this chapter you were introduced to a hypothetical ship steering system. A simplified version of the system is shown below.



Synchromechanisms as Input Control Devices

Although a potentiometer is used for input and error detection for many small servo systems, there are devices which accomplish these functions better. The most widely used is a device called a **synchro, or synchromechanism.**

A synchro is basically a transformer with one of its windings free to rotate. Using this principle, a combination of synchros can transmit positional data electrically from one location to another or detect and compute the difference existing between two or more shaft positions. There are five different types of synchro units.

Synchro Transmitter—This unit is sometimes called a **synchro generator.** When its **rotor** (rotating winding) is turned mechanically, the generator develops a set of voltage signals which identify the position of the rotor shaft.

Synchro Receiver—This receiver is sometimes called a **synchro motor, repeater,** or **follower.** It has the same electrical construction as the synchro transmitter and receives voltage signals to position its rotor at the same positional angle as the transmitter rotor.

Differential Synchro Transmitter—This transmitter develops and transmits the sum or difference (depending on connections) of an electrical and a mechanical input signal.

Differential Synchro Receiver—This receiver develops a mechanical (rotational) output representing the sum or difference of two electrical input signals.

Synchro Control Transformer—This transformer has both an electrical and a mechanical input. It computes, in the form of an electrical signal, the positional difference of the two inputs. The output can be used as the input to a servo amplifier.

Q30. In the diagram on the opposite page, the potentiometer arms are selecting the same amount of resistance. The servomotor (will, will not) turn.

Q31. A synchro unit acts like a(n) ___________ with a(n) ________ winding.

Q32. Which syncho unit can be used to transmit a compass direction to a remote location?

Q33. Which synchro unit can be used as an error detector in a servo system?

Your Answers Should Be:

A30. The servomotor **will not** turn. If the resistances at the arms are equal, the selected voltages will be equal. The voltage difference at the motor terminals will be zero.

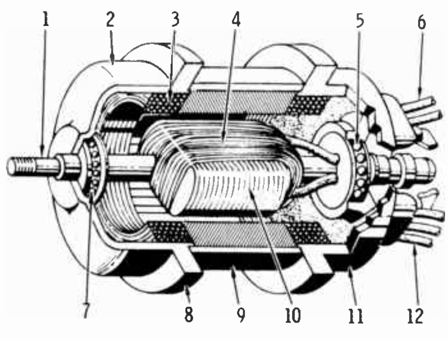
A31. A synchro unit acts like a **transformer** with a **rotating** winding.

A32. A **synchro transmitter** (develops voltages which identify the angular position of its rotor) can be used to transmit a compass direction.

A33. Since it computes the positional difference of an electrical and a mechanical input, a **synchro control transformer** can be used as an error detector in a servo system.

SYNCHRO FUNDAMENTALS

You have learned that a synchro unit is constructed physically as a generator (or motor) but operates electrically as a transformer. The figure below shows the construction details of a synchro transmitter. A synchro receiver is identical with the exception that it has a mechanical damper to prevent free-running or oscillation of its rotor. The differential units and the control transformer have three rotor windings instead of one.



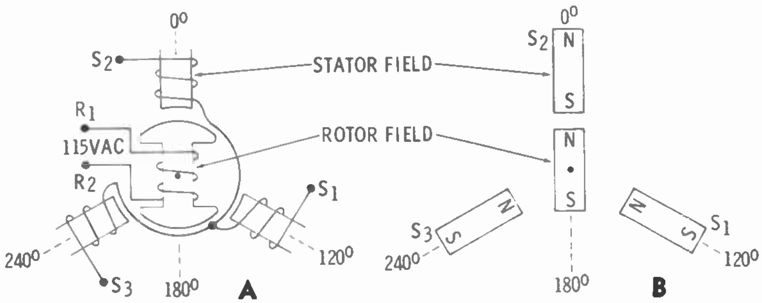
1 - ROTOR SHAFT
2 - UPPER END CAP
3 - STATOR COILS
4 - ROTOR COILS
5 - BEARING
6 - ROTOR LEADS
7 - BEARING
8 - MOUNTING FLANGE
9 - SHELL
10 - ROTOR
11 - LOWER END CAP
12 - STATOR LEADS

SYNCHRO-TRANSMITTER CONSTRUCTION

Magnetic Fields in a Synchro

In the illustration below, Part A shows the schematic symbol for a synchro transmitter or receiver. Figure B substitutes bar magnets for the rotor and stator fields.

REPRESENTATION OF A SYNCHRO UNIT



Schematic Symbol | **Magnetic Analogy**

S_1, S_2, and S_3 are the three stator windings of a synchro. They are physically displaced 120° apart, or at equal distances around a circle. The rotor is free to rotate and is said to be positioned at 0° when the axis of the rotor is in line with the axis of winding S_2, as shown in part A.

Assuming that the windings are energized, their magnetic fields can be represented by the bar magnets shown in part B. Regardless of its angular position at the time the fields are energized, the rotor will turn to the position shown. The north pole of the rotor will be attracted to the south pole of S_2. The north poles of S_1 and S_3 are at equal distances to the left and right of the rotor and will pull the south pole of the rotor to the 180° position. No matter how the rotor is manually rotated, it will return to the position shown.

If the polarities of all four magnets are reversed at the same time, as in the case of AC magnetic fields, the rotor will remain in the same position. If the three stator magnets are rotated together to the left or right, the rotor magnet will follow the rotational movement.

Q34. If magnet S_2 in part B above is removed, in which direction, if any, would the rotor turn?

Q35. If magnet S_1 is removed, in which direction, if any would the rotor turn?

Your Answers Should Be:

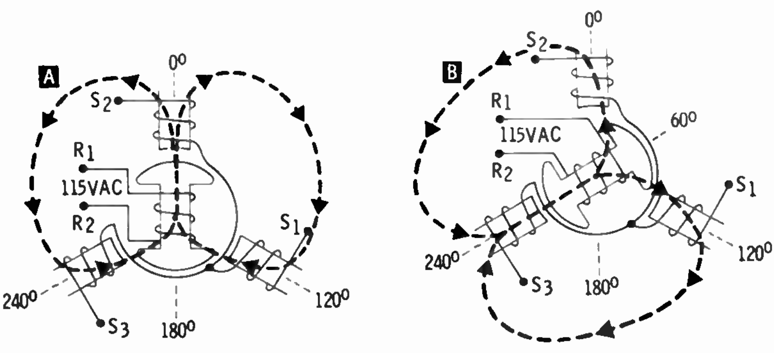
A34. The rotor will not turn if magnet S_2 is removed. The north poles of S_1 and S_2 will retain an equal attraction for the south pole of the rotor, keeping it in the same position.

A35. The rotor will turn clockwise if magnet S_1 is removed. It will turn until its N and S poles are at equal distances from S_2 and S_3, respectively.

Transformer Action in a Synchro Unit

It is apparent that the rotor will align itself with the resultant field of the three stator windings. In the diagram shown below, the rotor winding is the primary and the stator windings the secondary.

TRANSFORMER ACTION IN A SYNCHRO TRANSMITTER



In part A, the rotor is positioned at zero degrees. When 115V AC is applied to the rotor winding (the primary), a magnetic field is developed. As in any transformer, lines of flux cut the secondary windings inducing a voltage in them.

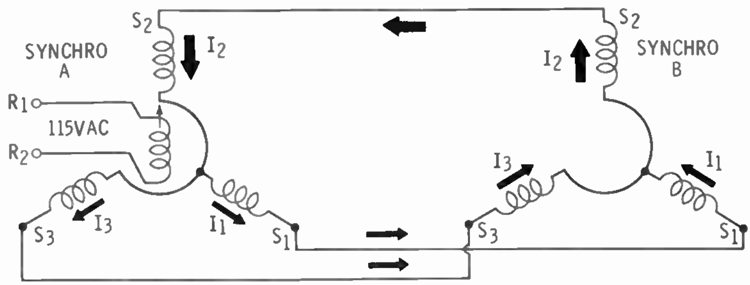
The amount of voltage induced depends on the relative position of the rotor and stator windings. In part A, maximum voltage is induced in the S_2 winding because the rotor winding is exactly parallel to it. (Lines of flux are cutting the coil turns at right angles.) Windings S_1 and S_3 have a smaller induced voltage since the rotor winding and its magnetic field are at a 60° angle to their axes. The resultant induced magnetic field is shown by broken lines.

In part B, the rotor is at the 60° position and aligned parallel to the S_3 winding. If the stator terminals are again short-circuited to permit current flow, maximum voltage will be developed across S_3. Since the rotor is now displaced 60° to either side of S_1 and S_2, lesser but equal voltages are developed in their windings. The resultant magnetic field is shown by broken lines.

Now imagine the rotor positioned at 30°. In this position it is 90° from (at right angles to) the S_1 winding. The lines of flux are parallel to the S_1 coil turns and not cutting across them. No current or voltage is induced. The rotor axis is 30° from S_2 and S_3, and lines of flux are cutting across these windings at an angle that is 30° less than maximum (right angles). The voltage induced is greater than that of the 60° rotor position in part B.

In the figure below, the stator windings of two synchro units are connected together. Because of the position of the

CURRENT FLOW IN TWO SYNCHRO UNITS



rotor in the left-hand synchro unit, maximum voltage is developed across S_2 and lesser voltages across S_1 and S_3. The voltages are such that induced current I_2 is equal to the sum of I_1 and I_3 induced in S_1 and S_3, respectively. Identical currents are flowing through the respective stators of synchro B. As a result, the voltages developed across the synchro-B stator windings are equal to those across the respective windings of synchro A.

Q36. Stator windings are placed ____ degrees apart.

Q37. The direction of the resultant magnetic fields in the two synchros above (will, will not) be the same.

Q38. Why is AC instead of DC used in a rotor winding?

Your Answers Should Be:

A36. Stator windings are placed 120 degrees apart.

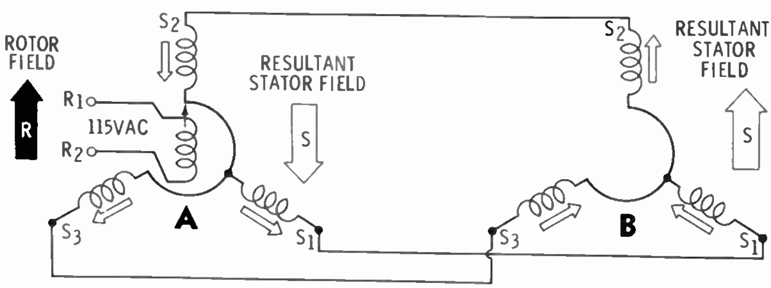
A37. The direction of the resultant magnetic fields in the two synchros **will not** be the same. Current flows through the stator coils of synchro B in a direction opposite to that in synchro A.

A38. AC is applied to a rotor winding because **its varying current will produce an increasing and decreasing magnetic field.**

A SYNCHRO TRANSMITTER-RECEIVER SYSTEM

The magnetic field produced by the primary of a transformer induces a current in the secondary. Current in the secondary winding develops a magnetic field that is opposite in polarity to the field in the primary. The diagram below shows a similar action occurring in a synchro. Direction of the rotor field is shown by a dark arrow. The induced fields in the individual stator winds are represented by small white arrows showing a direction in opposition to the rotor field. The large white arrow shows the direction of the resultant stator magnetic field.

COMPARISON OF RESULTANT MAGNETIC FIELDS

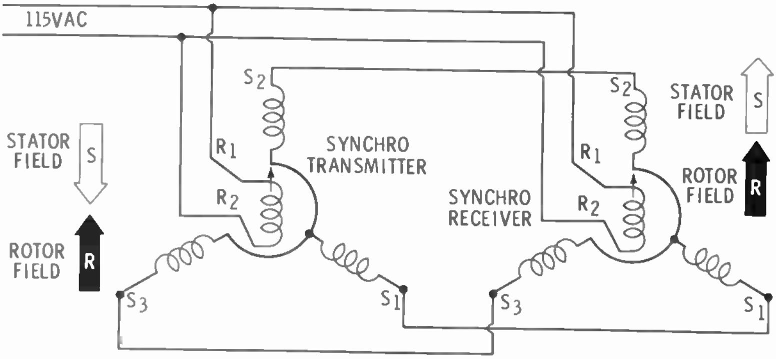


In synchro A, the direction of the developed rotor field is up, as shown. The induced magnetic fields in the individual stators are along their axis but in a downward direction. The combination of all the stator fields produces the resultant field shown by the large white arrow. It is an induced field and is directly opposite to the rotor field.

The induced stator currents flowing in synchro B take an opposite direction to those in A. Therefore, the individual stator fields produced are also in an opposite direction. And the resultant stator field is in an opposing direction to its counterpart in synchro A. Therefore, the synchro-B stator field takes the same direction as the synchro-A rotor field.

Following is a synchro transmitter and receiver. Note that the two rotors are connected to the same AC source.

MAGNETIC FIELDS IN A TRANSMITTER-RECEIVER SYSTEM



Since the rotor currents are in phase, the directions of their magnetic fields will be identical. The stator field in the transmitter is opposite to the rotor field. However, the stator field of the receiver will be in the same direction as the transmitter rotor field. The rotor field of the receiver will be attracted to align itself in the stator field direction.

If the transmitter rotor is turned, the stator fields in both synchros will rotate the same amount. The receiver stator field will maintain the same direction as the transmitter rotor field. Thus, the rotor of the receiver will follow the stator field.

Q39. If a synchro transmitter rotor is pointing toward 90°, the transmitter stator field is pointing toward _____, the receiver stator field is pointing toward _____, and the receiver rotor is pointing toward _____.

Q40. For proper operation, the ______ of the transmitter and receiver must be connected to the same voltage source.

Your Answers Should Be:

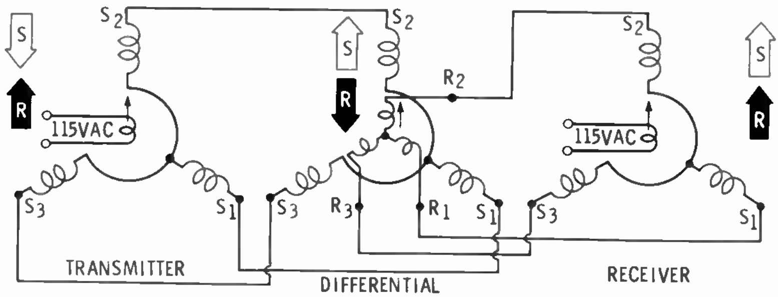
A39. If a synchro transmitter rotor is pointing toward 90°, the transmitter stator field is pointing toward 270°, the receiver stator and rotor fields are pointing toward 90°.

A40. For proper operation the **rotors** of the transmitter and receiver must be connected to the same voltage source.

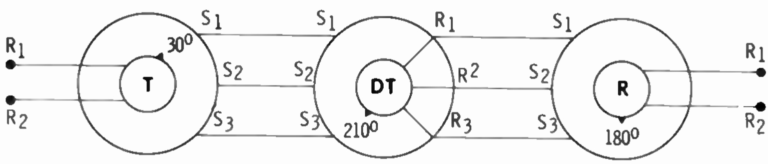
DIFFERENTIAL SYNCHROS

Differential synchro transmitters and **receivers** are similarly constructed and have a three-winding rotor.

TRANSMITTER-DIFFERENTIAL-RECEIVER SYNCHRO SYSTEM



Zero position for a synchro differential is where R_2 lines up with S_2. The stator windings of the transmitter develop a magnetic field in the differential stators as shown. This field induces an opposing differential rotor field which develops a receiver stator field in the opposite direction. The interaction of these fields when the transmitter and differential rotors are turned cause the receiver rotor to turn to the difference between the other two rotor positions.

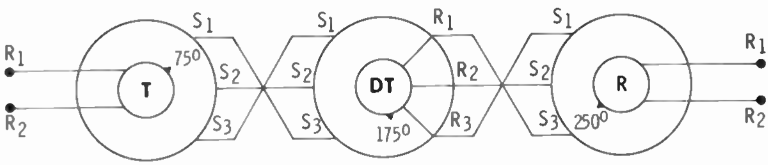


SUBTRACTION BY A T-DT-R SYNCHRO SYSTEM

With T and DT motors mechanically turned to 30° and 210°, the interacting magnetic fields will cause rotor R to electrically turn to the difference position, 180°.

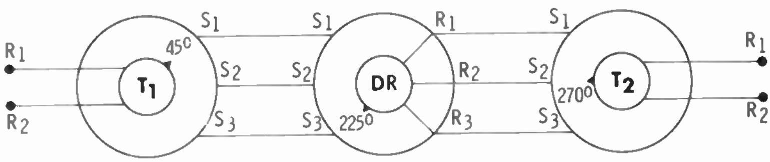
Differential transmitters will add if connected in the manner shown below. Here, S_1 and S_3 of T are crossed to S_3 and S_1 of DT. R_1 and R_3 of DT are crossed to S_3 and S_1 of R. The angular positions of 75° on T and 175° on DT are added to produce an R rotor position of 250°.

ADDITION BY A T-DT-R SYNCHRO SYSTEM



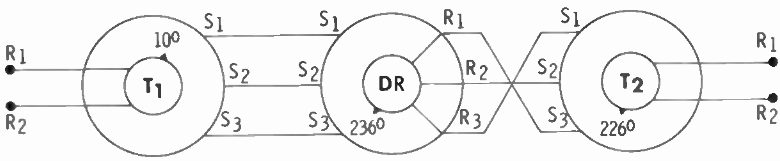
When connected to two synchro transmitters, the DR rotor position is the sum or difference of the rotor positions of the two generators. The synchros below are connected for subtraction.

SUBTRACTION BY A T-DR-T SYNCHRO SYSTEM



Addition with a differential receiver recording a sum of two angles is accomplished by the following connections.

ADDITION BY A T-DR-T SYNCHRO SYSTEM



Q41. In a T-DR-T system, the inputs to the DR are (electrical, mechanical) and its output is ___________.

Q42. In a T-DT-R system, one DT input is electrical and the other mechanical; the output is ___________.

Your Answers Should Be:

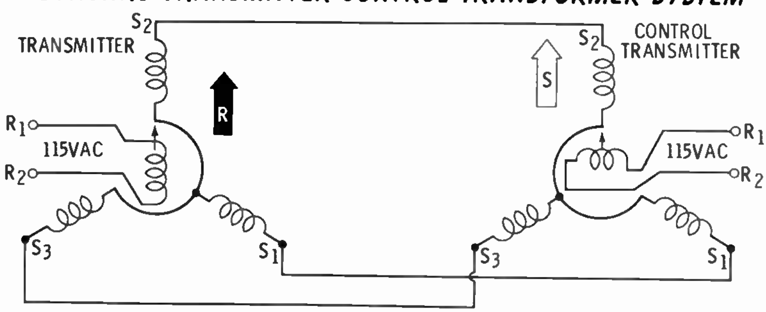
A41. In a T-DR-T system, the inputs to the DR are **electrical** and its output is **mechanical.**

A42. In a T-DT-R system, one DT input is electrical and the other mechanical; the output is **electrical.**

THE SYNCHRO CONTROL TRANSFORMER

A control transformer (CT) has three stator windings. Its rotor is designed to generate a voltage, the amplitude of which represents the difference between two angular positions and the phase of which shows the direction of difference.

A SYNCHRO TRANSMITTER-CONTROL TRANSFORMER SYSTEM



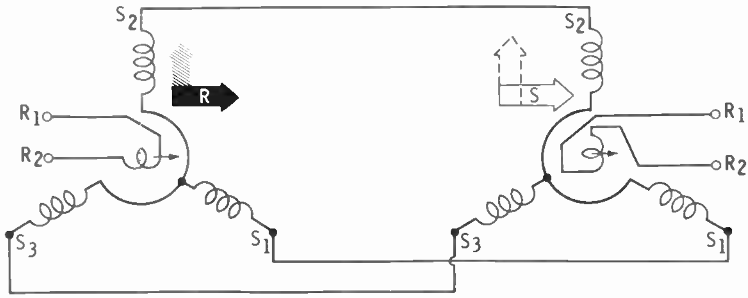
The rotor of a control transformer is at zero position when it is at right angles to S_2 as shown in the diagram above. The induced stator field in the CT will be in the same direction as the rotor field of T. In the positions shown, no voltage will be produced between R_1 and R_2 of the CT.

If the T rotor is moved in a clockwise direction, the CT stator field will follow. As the stator field of the CT rotates, its flux lines cut the rotor winding. Rotation in a clockwise direction will produce a voltage in the rotor in phase with the AC on the T rotor. When the CT stator field is 90°, the voltage between R_1 and R_2 is maximum. A 360° rotation of the stator field will produce an AC sine wave.

If the T rotor is turned in a counterclockwise direction, the flux lines of the CT stator field will cut its rotor winding in the opposite direction. This will produce a voltage across the CT rotor 180° out of phase with the T rotor voltage.

The rotor of the control transformer will not turn as the result of the moving stator field. It can be rotated by manually turning the rotor shaft. The following diagram demonstrates what occurs when the rotor is turned.

ROTATING CT ROTOR TO REDUCE VOLTAGE OUTPUT TO ZERO



Assume that the T rotor has been turned clockwise from 0° to 90°. The CT stator field will make the same rotation. If the CT rotor remains at 0°, maximum voltage in phase with the AC line voltage can be measured across R_1 and R_2. If the CT rotor is now turned to 90°, the voltage reading will reduce to zero. In this position the rotor winding is at right angles to the stator field.

It is evident that this type of synchro system can be used to develop the difference voltage for a servo system. The synchro transmitter rotor can reflect the desired angular position and the CT rotor the present position of a load. If there is a difference in positions, the magnitude of the voltage on the CT rotor will be proportional to the amount of difference, and the phase of the voltage will reveal the direction of difference.

If more than two position readings are required in a servo system, a differential transmitter can be substituted in place of the synchro transmitter. The output of the DT to the CT will be the sum or difference (depending on the stator and rotor connections) of two position conditions.

Q43. When the stator field of a CT rotates in a(n) ---------- direction, the developed voltage is in phase with transmitter rotor voltage.

Q44. Maximum voltage is developed if the stator field and rotor winding are (at right angles, parallel).

Your Answers Should Be:

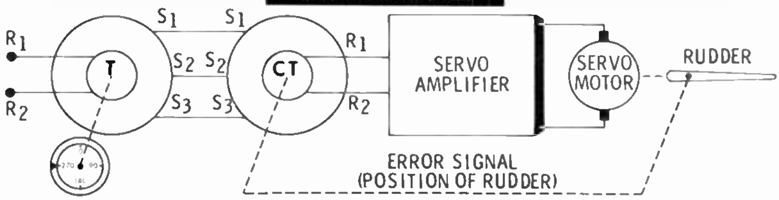
A43. When the stator field of a CT rotates in a **clockwise** direction, the developed voltage is in phase with transmitter rotor voltage.

A44. Maximum voltage is developed when the stator field and rotor winding are **parallel.**

THE COMPLETE SERVO SYSTEM

The diagram below illustrates a complete system.

SYNCHRO SYSTEM USED AS INPUT CONTROL



The rotor of the synchro transmitter is physically connected to a compass. As the ship swings right or left of the established course (set at rotor zero position), the stator field of the control transformer will follow the transmitter rotor. This will generate a voltage across the rotor of the control transformer. The amplitude of the voltage will be proportional to the difference between compass and rudder positions. The phase will show whether the compass has rotated clockwise or counterclockwise.

The voltage output of the CT rotor is fed to the servo amplifier as the difference signal. This unit amplifies the signal to the level of power required to operate the servo motor. The amplitude of the signal will determine how fast the motor will turn the rudder. The phase of the signal will control the direction in which it will be turned.

When the rudder angle has matched the off-course angle of the compass, the motor will stop. Since the rudder is connected to the rotor of the control transformer, an error signal is returned to this synchro unit. As the rudder is turned to its desired position, the CT rotor is approaching right angle (zero voltage) alignment with the stator field. This causes the difference signal to decrease in amplitude until zero voltage is reached when compass and rudder angles are the same.

The rudder angle causes the ship to swing back to its course. A new difference signal is generated in the opposite phase. The motor turns the rudder in the opposite direction and toward amidships again. When the ship is finally on course, transmitter and control transformer rotors are in alignment and the difference signal is zero.

SERVO SYSTEM APPLICATIONS

Commercial and military aircraft use servo systems to operate the control surfaces of airplanes and as an automatic pilot to keep the plane on a desired course and altitude. Servos are also used in analog computers to detect and compute rates of change of quantities. With an amplidyne, industry uses servo systems to move and position heavy loads.

Military applications include the positioning of radar and heavy directional radio antennas, pointing of guns and missile launchers, automatic control of missile steering mechanisms, and other uses requiring precise positioning of a load or rapid data computation.

Q45. In the diagram on the opposite page, the _______ ____________ is an input detector, and the _______ ____________ is an error detector.

Q46. Since the servo amplifier output is being applied to the armature of the servo motor, the motor is (DC, AC).

Q47. If the motor were (DC, AC), the output would be applied to one of two fields in the motor.

Q48. The following synchro units have three windings on their rotors: (a) _____________ ____________; (b) _____________ _________.

Q49. The following synchro units have a single winding on their rotors: (a) ____________; (b) _________; (c) _______ ____________.

Your Answers Should Be:

A45. In the diagram on the opposite page, the **synchro transmitter (T)**, is an input detector, and the **control transformer (CT)** is an error detector.

A46. Since the servo amplifier output is being applied to the armature of the servo motor, the motor is **DC.**

A47. If the motor were AC, the output would be applied to one of two fields in the motor.

A48. The following synchro units have three windings on their rotor: (a) **differential transmitter;** (b) **differential receiver.**

A49. The following synchro units have a single winding on their rotors: (a) **transmitter;** (b) **receiver;** (c) **control transformer.**

WHAT YOU HAVE LEARNED

1. A servo system is a combination of devices which permit automatic control and positioning of a load. Each system, large or small, includes two functions—input control and output control. The former detects a deviation between desired and existing position of a load and sends a correcting signal to the output control function which realigns the load.
2. The input control function contains an input detector and an error detector. The output control function has a servo amplifier and a servomotor. Two of these operations can be contained in a single device, or several mechanisms may be required to perform a single operation.
3. An open servo system has some of its operations performed by manual or semiautomatic means. A closed system is completely automatic.
4. An AC servomotor, normally an induction type, is used in a control system when low power and low speed are permissible. High torque and/or a wide speed range calls for a shunt or permanent magnet DC motor.

5. The purpose of a servo amplifier is to convert a difference signal into sufficient power and polarity to turn a servomotor in the correct direction at the desired speed.
6. Electronic servo amplifiers, vacuum-tube or thyratron, can be designed to drive either an AC or DC servomotor.
7. When large amounts of power are required to move a load in a servo system, electromechanical DC servo amplifiers are used. Examples are the Ward Leonard DC generator-motor and the amplidyne. Because it has a short-circuited generator armature, an amplidyne has a power amplification factor of up to 10,000 or greater.
8. The most widely used device to perform the input control function of input- and error-signal detection is the synchro. A synchro unit is basically a transformer with one of its windings free to rotate. Synchro units may also be used to transmit data between remote locations.
9. A synchro transmitter or receiver contains three stator windings (placed 120° apart) and a rotor with a single winding. If AC is applied to the rotor, the magnetic field induces current and a magnetic field in the stator windings. The rotor and stator fields lie along the same axis but take opposite directions. If the stator terminals of two synchro units are connected, the induced stator field of the second unit will take the same direction as the rotor field of the first unit.
10. A data-transmission system can be formed by connecting the stator windings of a synchro transmitter to those of a synchro receiver. Since the receiver stator field follows the rotation of the transmitter rotor field and since the receiver rotor field will line up with its stator field, the receiver will precisely duplicate the angular position of the transmitter.
11. Differential synchro transmitters and receivers have three stator windings and three rotor windings. A differential transmitter receives an electrical and a mechanical input and delivers an electrical output. A differential receiver accepts two electrical inputs and delivers a mechanical output. When connected to other synchro units, a differential will develop the sum or difference of two positions, depending on the connections.

12. A control transformer has three stator windings and a single-coil rotor which will develop a voltage of an amplitude proportional to the difference of its rotor and stator fields, and of a phase representative of the direction of difference. When a synchro transmitter is connected to a control transformer, the pair can perform the input control function of a servo system.

Index to the Series

Boldface numeral indicates volume number: lightface numeral indicates page in that volume. For example:

Ampere, 1-48, 3-18

means that ampere appears on page 48 of Volume 1 and on page 18 of Volume 3.

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Preface to the Series

We live in a world of electricity and electronics. Electrical power provides us with artificial light and heat and the energy for doing many kinds of work. Electricity is the basis of radio, television, computers—the entire area of science known as electronics.

Although our advances in technology have reached the point where we can successfully break the space barrier, we are still learning new things about electricity and electronics. One of the reasons for this is that electricity has certain intangible aspects. In other words, electricity cannot be observed by our human senses in the normal manner. However, we can observe the results of the existence of electricity, and we are continually finding new ways to use it, particularly in the field of electronics.

Electronics is a relatively new science. Even though we can trace electricity back to Franklin, Bell, and Edison, electronics goes back only a few decades to discoveries and developments by such people as Marconi and De Forest. In fact, electronics didn't really become a full-fledged science until radio came into being. World War II brought about the need for rapid technological developments, and long-range radio, radionavigation, radar, sonar, etc., became realities. In the years since World War II, developments in electronics have continued at a rapid pace; actually, the pace has been so rapid that educational and training facilities have had difficulty keeping up.

The science of electronics has expanded to such a breadth and depth that now it is really a combination of specialized technologies. Yet, these individual technologies are all based on the same fundamental principles, principles which heretofore were difficult to comprehend because of the teaching materials and methods available.

This 5-volume series represents a major step toward a unified and simplified approach to the principles of electricity and electronics. Utilizing all the modern techniques known to motivate and enhance learning, the content is designed to serve as a standard curriculum. Moreover, the programmed format has been specially prepared to provide a self-teaching tool; instructors using these volumes as classroom texts will therefore be able to teach the subject more objectively and with greater efficiency than ever before.

While each volume has been carefully written to "stand on its own," an understanding of the principles involved in each volume requires knowledge of the material presented in the previous volumes. The first volume in the series provides a general introduction to the overall subject of electricity and electronics. This volume is intended primarily to provide a foundation for the study of later volumes in the series. However, it can be used without the other volumes by the reader who requires only a relatively simple coverage of the subject.

The second volume covers basic AC and DC circuits. For the reader who has some knowledge of basic electricity, this volume can stand alone as a general text on circuit fundamentals.

The third volume is a complete text on the subject of tube and transistor circuits. It is written on the assumption that the reader is familiar with the principles covered in the first two volumes.

The first three volumes offer coverage of general electrical and electronic principles. They provide the basis for further study of a general or specialized nature.

The fourth and fifth volumes deal with specialized areas of study. If the reader already has a thorough understanding of the material presented in the earlier parts of the series, either of the last two volumes can be used alone as a text in its specialized field—test equipment and servicing in Volume 4, and motors and generators in Volume 5.

Many authors, editors, and consultants have contributed to the development of this series. It is their hope that it will serve the long-felt need for a standard text that can be used as self-teaching guide or used in any type of training course that requires an understanding of the principles of electricity and electronics.

TRAINING & RETRAINING, INC.

April, 1964

Acknowledgments

Grateful acknowledgment is made to all those who participated in the preparation, compilation, and editing of this series. Without their valuable contributions this series would not have been possible.

In this regard, prime consideration is due Bernard C. Monnes, Educational Specialist, Navy Electronics School, for his excellent contributions in the areas of writing, editorial organization, and final review of the entire series. The finalization of these volumes, both as to technical content and educational value, is due principally to his tireless and conscientious efforts.

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SEYMOUR D. USLAN, *Editor-in-Chief,*
Training & Retraining, Inc.

Introduction

This first volume in the series carefully explains the basic principles that are the foundation for understanding electricity and electronics. Following a unique method of presentation, these principles are related through simple analogies to devices with which you are familiar. You will learn that the principles are the same for both electricity and electronics and that they are not difficult to master. When you complete the volume, you will be able to understand what makes electrical and electronic devices work, and to discuss with confidence the applications of these principles.

The knowledge gained from this volume will serve as an excellent foundation for further studies in the vast fields of electricity and electronics. The conventional method of learning these subjects is through study of the many individual parts, leaving it to the student to tie them together when he has finished. Experience has shown that this approach is not always successful. Therefore, this text develops only the basic principles, applies them immediately to familiar devices, and summarizes their applications in electronic equipment. In other words, this volume presents a "big picture" of the electrical/electronic field in a manner that is easily understood. The reader can study the subject without fear of becoming lost in details; he will always be able to relate what he learns to appropriate applications in the "big picture." This approach has been tried and proved successful in training thousands of students.

WHAT YOU WILL LEARN

This volume clearly explains the principles of voltage, current, and resistance, as well as their relationships to each other. You will learn the basic requirements of DC and AC circuits, how to use meters as test instruments, how parts are connected, how to read schematic diagrams, and how proper soldering techniques are carried out. You will also learn about the construction and operation of coils, capacitors, transformers, diodes, transistors, and vacuum tubes. You will discover how basic electrical devices work, including telephone systems, radio and television transmitters and receivers, etc. In addition, the text describes experiments that you can perform to improve your understanding of some of the more important principles.

WHAT YOU SHOULD KNOW BEFORE YOU START

The only prerequisites for learning electricity and electronics from this text are an ability to read and a desire to learn. All terms are carefully defined. Enough math is used to give precise interpretation to important principles, but if you know how to add, subtract, multiply, and divide, the mathematical expressions will give you no trouble. You will be shown how to interpret the meanings of simple mathematical expressions—which, incidentally, is more important to your learning than actually solving the problems.

WHY THE TEXT FORMAT WAS CHOSEN

During the past few years, new concepts of learning have been developed under the common heading of programmed instruction. Although there are arguments for and against each of the several formats or styles of programmed textbooks, the value of programmed instruction itself has been proved to be sound. Most educators now seem to agree that the style of programming should be developed to fit the needs of teaching the particular subject. To help you progress successfully through this volume, a brief explanation of the programmed format follows.

Each chapter is divided into small bits of information presented in a sequence that has proved best for learning purposes. Some of the information bits are very short—a single sentence in some cases. Others may include several paragraphs. The length of each presentation is determined by the nature of the concept being explained and the knowledge the reader has gained up to that point.

The text is designed around two-page segments. Facing pages include information on one or more concepts, complete with illustrations designed to clarify the word descriptions used. Self-testing questions are included in most of these two-page segments. Many of these questions are in the form of statements requiring that you fill in one or more missing words; other questions are either multiple-choice or simple essay types. Answers are given on the succeeding page, so you will have the opportunity to check the accuracy of your response and verify what you have or have not learned before proceeding. When you find that your answer to a question does not agree with that given, you should restudy the information to determine why your answer was incorrect. As you can see, this method of question-answer programming insures that you will advance through the text as quickly as you are able to absorb what has been presented.

The beginning of each chapter features a preview of its contents, and a review of the important points is contained at the end of the chapter. The preview gives you an idea of the purpose of the chapter—what you can expect to learn. This helps to give practical meaning to the information as it is presented. The review at the completion of the chapter summarizes its content so that you can locate and restudy those areas which have escaped your full comprehension. And, just as important, the review is a definite aid to retention and recall of what you have learned.

HOW YOU SHOULD STUDY THIS TEXT

Naturally, good study habits are important. You should set aside a specific time each day to study in an area where you can concentrate without being disturbed. Select a time when you are at your mental peak, a period when you feel most alert.

Here are a few pointers you will find helpful in getting the most out of this volume.

1. Read each sentence carefully and deliberately. There are no unnecessary words or phrases; each sentence presents or supports a thought which is important to your understanding of electricity and electronics.

2. When you are referred to or come to an illustration, stop at the end of the sentence you are reading and study the illustration. Make sure you have a mental picture of its general content. Then continue reading, returning to the illustration each time a detailed examination is required. The drawings were especially planned to reinforce your understanding of the subject.

3. At the bottom of most right-hand pages you will find one or more questions to be answered. Some of these contain "fill-in" blanks. Since more than one word might logically fill a given blank, the number of dashes indicates the number of letters in the desired word. In answering the questions, it is important that you actually do so in writing, either in the book or on a separate sheet of paper. The physical act of writing the answers provides greater retention than merely thinking the answer. Writing will not become a chore since most of the required answers are short.

4. Answer all questions in a section before turning the page to check the accuracy of your responses. Refer to any of the material you have read if you need help. If you don't know the answer even after a quick review of the related text, finish answering any remaining questions. If the answers to any questions you skipped still haven't come to you, turn the page and check the answer section.

5. When you have answered a question incorrectly, return to the appropriate paragraph or page and restudy the material. Knowing the correct answer to a question is less important than understanding **why** it is correct. Each section of new material is based on previously presented information. If there is a weak link in this chain, the later material will be more difficult to understand.

6. In some instances, the text describes certain principles

in terms of the results of simple experiments. The information is presented so that you will gain knowledge whether you perform the experiments or not. However, you will gain a greater understanding of the subject if you do perform the suggested experiments.

7. Carefully study the review, "What You Have Learned," at the end of each chapter. This review will help you gauge your knowledge of the information in the chapter and actually reinforce your knowledge. When you run across statements you don't completely understand, reread the sections relating to these statements, and recheck the questions and answers before going to the next chapter.

This volume has been carefully planned to make the learning process as easy as possible. Naturally, a certain amount of effort on your part is required if you are to obtain the maximum benefit from the book. However, if you follow the pointers just given, your efforts will be well rewarded, and you will find that your study of electricity and electronics will be a pleasant and interesting experience.

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1

The World of Electricity and Electronics

What You Will Learn

You are about to become acquainted with the fascinating world of electricity and electronics. You are going to learn what electricity is, what it does, and how it does it. You will use this information to obtain a better understanding of what electrical and electronic devices are all about, how they work, and how to test and repair them.

WHAT IS ELECTRICITY?

Electricity is a combination of a force called voltage and the movement of invisible particles known as **current.**

Voltage

The force of voltage can be compared to the force of a water pump. The force of a pump moves water through a distribution system, generally an arrangement of pipes. Voltage is the force which causes electric current to flow through a system of wires.

Q1. Voltage is a _ _ _ _ _ .

Q2. The force in electricity is _ _ _ _ _ _ _ .

Q3. The force of voltage is something like the force of a _ _ _ _ _ _ _ _ _ .

Your Answers Should Be:

A1. Voltage is a **force.**

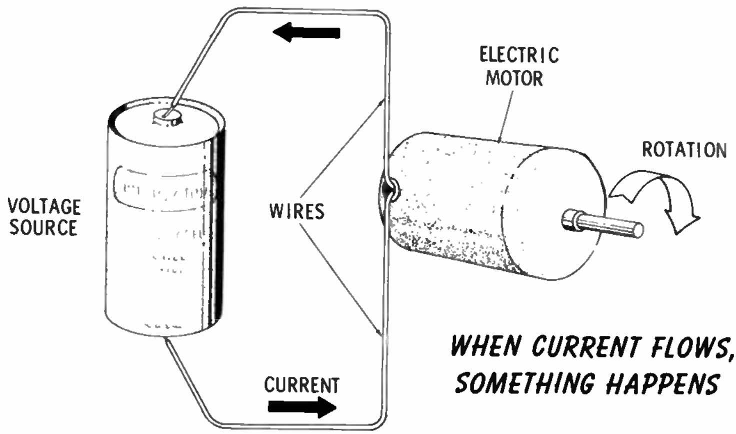
A2. The force in electricity is **voltage.**

A3. The force of voltage is something like the force of a **water pump.**

If your answers were not the same as those above, return to the preceding page and study the text again.

Current

Current, the movement of invisible particles, causes electrical and electronic devices to operate. We cannot see current, but we can determine its presence by the effects it produces.



WHEN CURRENT FLOWS, SOMETHING HAPPENS

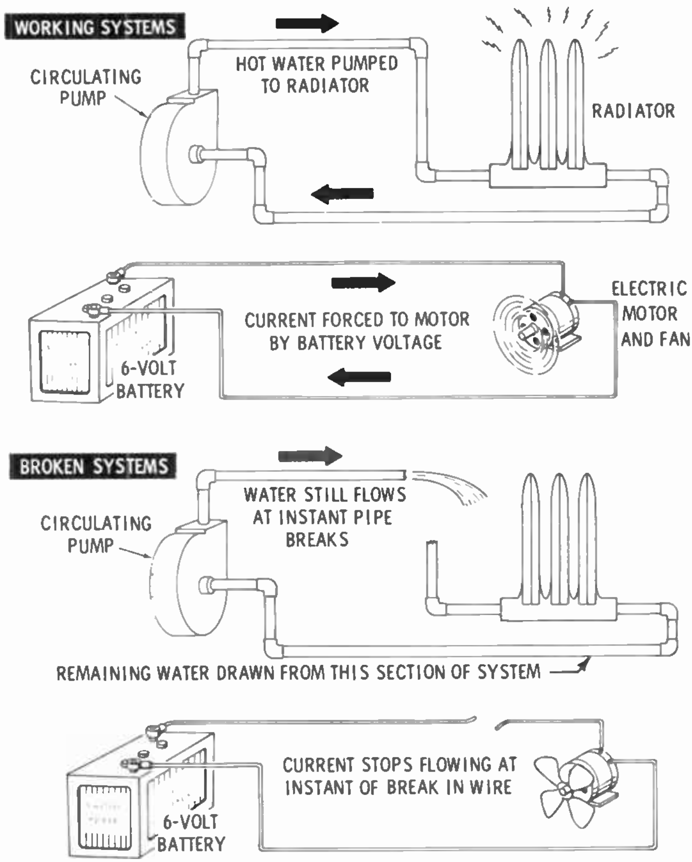
Current flows through the wires of an electrical or electronic device in much the same way water flows through pipes.

Voltage is the electrical force that causes current to flow.

Current consists of invisible atomic particles called **electrons.**

There is an important difference between current in wires and water in pipes, however. Water can flow out of a broken pipe, but current cannot flow out of a broken wire. In fact, current will not flow anywhere in the broken wire. When the wire is broken, the force of the voltage is removed.

The Flow of Water and Current Are Not Exactly the Same



Q4. Current is a movement of invisible particles called __________.

Q5. You cannot see ________, but you can detect its presence.

Q6. When electric lights are operating, you know that ________ is flowing.

Q7. When the wires of an electric toaster glow red, you know that ________ is ________.

Q8. Current is to ______ as water is to pipes.

Q9. Wires provide a path for ________ in much the same way that pipes provide a path for water.

Your Answers Should Be:

A4. Current is a movement of invisible particles called **electrons.**

A5. You cannot see **current,** but you can detect its presence.

A6. When electric lights are operating, you know that **current** is flowing.

A7. When the wires of an electric toaster glow red, you know that **current** is **flowing.**

A8. Current is to **wires** as water is to pipes.

A9. Wires provide a path for **current** in much the same way that pipes provide a path for water.

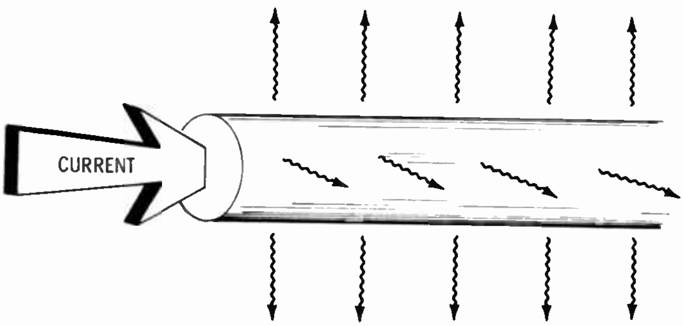
HOW ELECTRICAL/ELECTRONIC DEVICES WORK

Every electrical and electronic device makes use of one or more properties of electrical current, such as heat and electromagnetism.

Heat

Wires can be heated until they are red or white-hot by causing current to flow through them. The amount of heat

CURRENT FLOW HEATS WIRES



given off by a wire is determined by the type of metal in the wire and the quantity of current that is forced through it. A large current produces more heat in the same size and type of wire than a smaller current. If the current is the same, a smaller wire gives off more heat than one that is larger in diameter. Also, some metals produce more heat than others as the result of current flow.

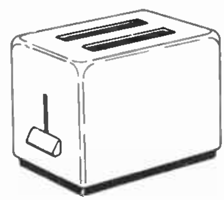
In fact, manufacturers select the size and type of wire that will produce a desired amount of heat. To do this, they must know the amount of current that will flow through it.

Electrical Appliances—Electrical appliances, such as toasters, irons, heaters, and broilers, make use of the heat produced by current flowing through a wire.

Devices That Use Heat Produced by Current Flow Through Wires

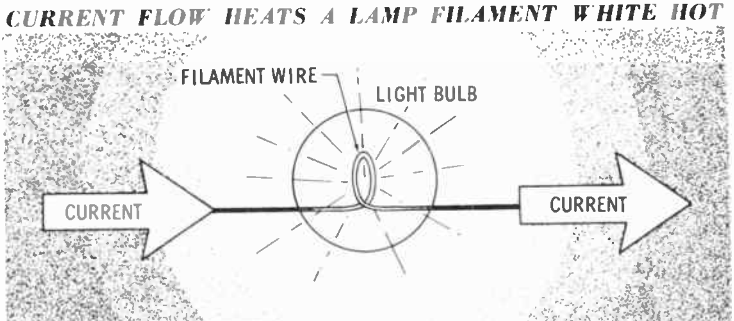
MOST ELECTRIC IRONS HAVE CONTROLS THAT REGULATE THE AMOUNT OF HEAT DEVELOPED BY THE HEATING ELEMENT (WIRE).

SIZE AND TYPE OF WIRE FOR TOASTERS ARE SELECTED FOR MOST EFFICIENT TOASTING HEAT.



Electric Lights—The filament wire in an electric light bulb is heated white-hot by the current flowing through it.

CURRENT FLOW HEATS A LAMP FILAMENT WHITE HOT



THE WHITE-HOT FILAMENT GIVES OFF LIGHT

Q10. Current flow _____ wires.

Q11. The heat caused by _______ ____ is used to toast, iron, heat, and broil.

Q12. Current flow _____ the filament of an electric light bulb white-hot.

Your Answers Should Be:

A10. Current flow **heats** wires.

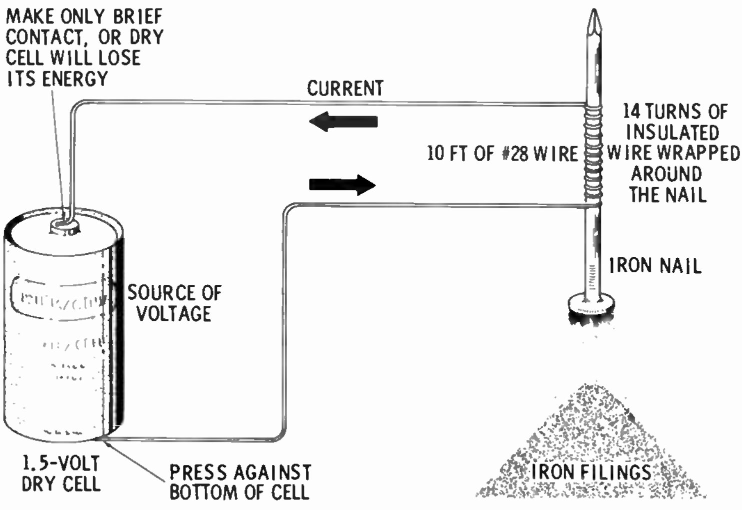
A11. The heat caused by **current** flow is used to toast, iron, heat, and broil.

A12. Current flow **heats** the filament of an electric light bulb white-hot.

Electromagnetism

When current flows through a coil of wire, the coil acts like a magnet. This can be proved by experimenting with an electromagnet like the one shown below.

CURRENT FLOW PRODUCES MAGNETISM

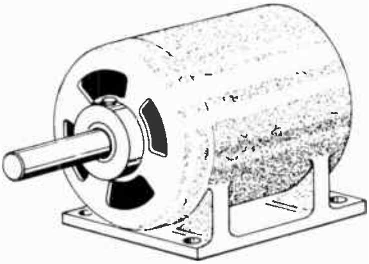


Current flowing through a wire develops a magnetic field. This field is called an **electromagnetic force** because it is the result of the flow of electric current. If, as shown in the illustration, the magnetic field passes through certain kinds of metal, such as soft iron, the metal will become **magnetized** and take on the properties of a magnet.

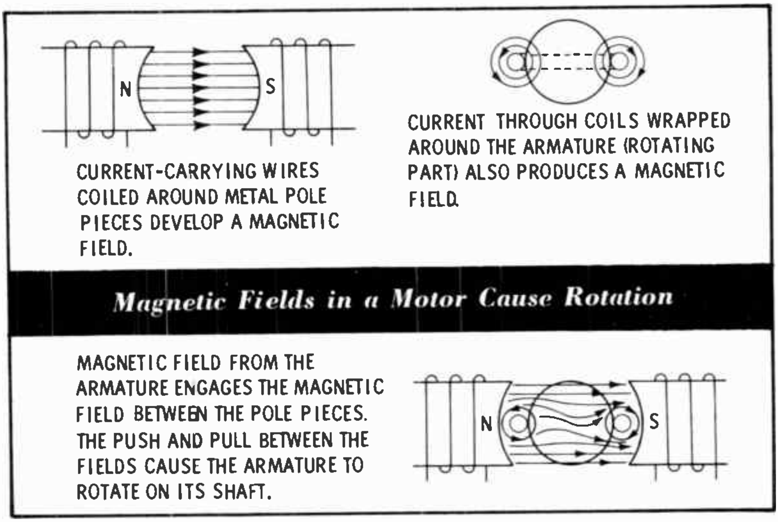
The electromagnet retains its magnetic capability—continues to attract iron filings—as long as current flows through the coil. When the current stops, the metal gradually loses its effectiveness as a magnet.

Electric Motors—Electric motors make use of the magnetic forces created by current flow in a coil of wire.

ELECTRIC MOTORS ARE TURNED BY MAGNETIC FORCES



The magnetic forces in a motor attract and repel each other. This causes the **armature** (rotating part of the motor) to turn.



Magnetic Fields in a Motor Cause Rotation

The magnetic forces in the motor are created by current flowing through the motor coils.

Q13. A(an) _________ _____ **forms around a wire through which current is flowing.**

Q14. _________ **forces are created by current flowing in motor coils.**

Q15. **The armature of an electric motor is turned by** _________ **forces created by** ________ **flowing through the motor coils.**

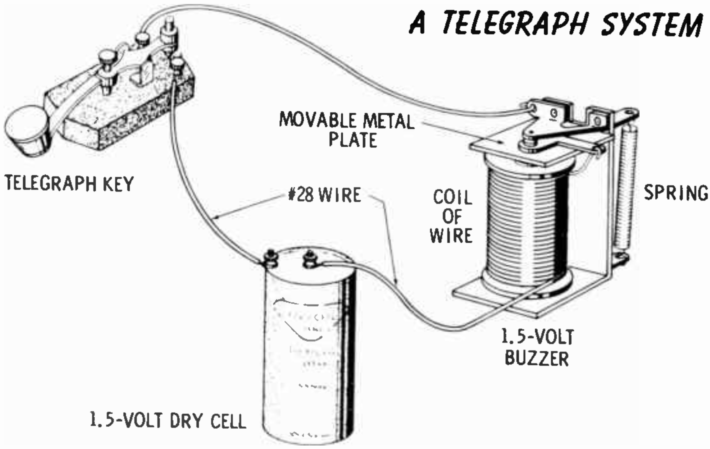
Your Answers Should Be:

A13. A **magnetic field** forms around a wire through which current is flowing.

A14. **Magnetic** forces are created by current flowing in motor coils.

A15. The armature of an electric motor is turned by **magnetic** forces created by **current** flowing through the motor coils.

The Telegraph—The telegraph system also makes use of magnetic forces. Current flowing through a coil of wire creates magnetic forces to operate a buzzer, or other noise producers. The sounds from the buzzer represent the dots and dashes sent by the operator.

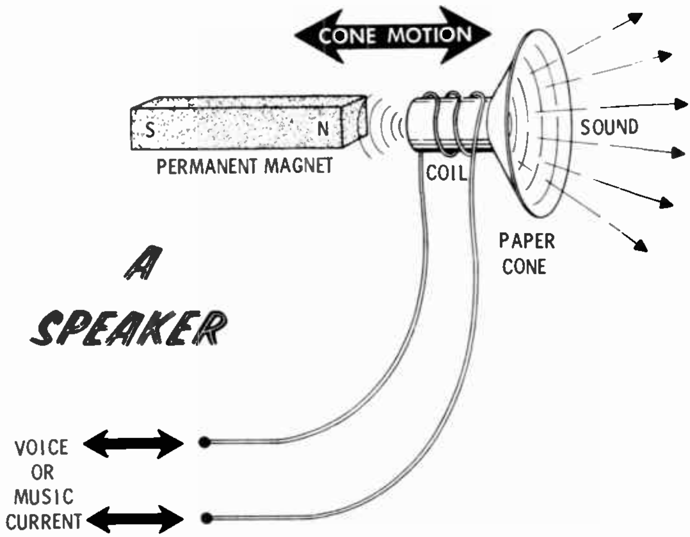


When the telegraph key is closed (pressed down), current flows from the battery through the coil of wire. The resulting magnetic force causes a movable metal plate to be attracted to the soft-iron core of the coil, producing a buzzing sound. In this manner dots and dashes (short and long buzzes) are transmitted.

The Speaker—The speaker in a radio, television, or telephone earpiece is an example of another familiar device operated by magnetic forces created by current flowing in a coil of wire.

The speaker consists of a permanent magnet and a coil of wire cemented to a paper cone. Electrical currents which represent voice, music, or other sound flow through the coil.

Magnetic forces created by these currents cause the coil and cone to be attracted and repelled by the permanent magnet. The movement of the paper cone creates corresponding changes in air pressure heard as sounds.



Later in this volume you will learn how sounds are converted into currents that operate speakers.

Q16. _________ ______ in the telegraph are created by current flowing in a coil of wire.

Q17. Closing the key allows ________ to ____ through a coil of wire.

Q18. The magnetic force created by this ________ ____ operates a buzzer.

Q19. Magnetic forces can be developed by current flowing through a wire or a(an) ____.

Q20. When currents are passed through the coil of a speaker, _________ ______ are created.

Q21. Magnetic force causes the coil and cone to be __________ or _________ by a permanent magnet, causing changes in air pressure.

Your Answers Should Be:

A16. **Magnetic forces** in the telegraph are created by current flowing in a coil of wire.

A17. Closing the key allows **current** to **flow** through a coil of wire.

A18. The magnetic force created by this **current flow** operates a buzzer.

A19. Magnetic forces can be developed by current flowing through a wire or a **coil.**

A20. When currents are passed through the coil of a speaker, **magnetic forces** are created.

A21. Magnetic force causes the coil and cone to be **attracted** or **repelled** by a permanent magnet, causing changes in air pressure.

WHAT YOU HAVE LEARNED SO FAR

1. Electricity is a combination of a force called voltage and the movement of invisible particles called current.
2. Voltage, as a force, is similar to the force developed by a water pump. Current flows through wires in much the same way that water travels through pipes.
3. All electrical or electronic devices make use of one or more of the effects produced by current flow.
4. Electrical current causes wires to heat. Toasters, irons, heaters, broilers, and lights are examples of devices which use this electrical effect.
5. Current flowing through a wire or coil develops a magnetic field. Such magnetic forces are used in motors, the telegraph, and speakers.
6. A magnetic (sometimes called electromagnetic) field can be used to move a metallic piece. Speakers and motors make use of two magnetic fields that either repel or attract each other. As a result, speaker cones vibrate to develop sound and motor armatures rotate.

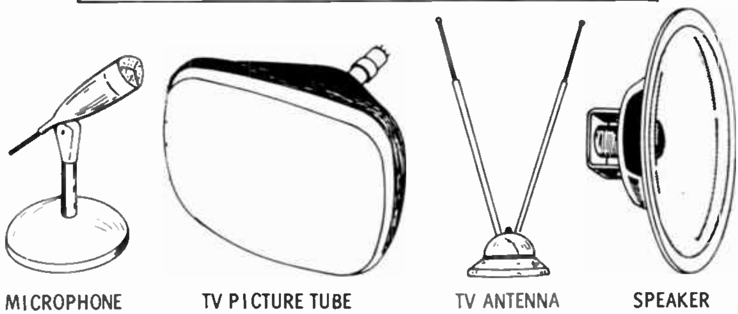
Current can cause other effects in addition to heating wires and producing magnetic forces. You will learn about these effects later.

HOW ELECTRICAL AND ELECTRONIC DEVICES ARE USED

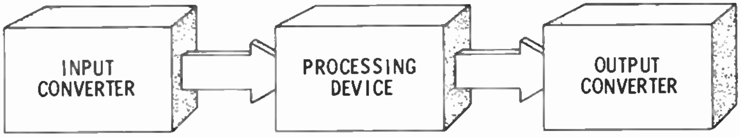
Jobs in which heat is necessary can be performed by using electric current to heat wires. Jobs calling for mechanical motion can be performed by the forces developed by magnetic fields. Transmitting telegraph messages makes use of the magnetic forces in a buzzer coil.

These simple jobs are accomplished by using simple devices. However, even complex jobs, such as sending and receiving telephone or radio messages, sending and receiving television pictures, and completely controlling manufacturing processes, are also accomplished by using simple devices.

DEVICES THAT PERFORM COMPLEX JOBS



Many complex jobs are performed by combinations of simple devices. That is, two or more simple devices work together to perform a complex job. These devices fall into three categories: (1) input converters, (2) processing devices, and (3) output converters.



Q22. Simple devices that can be combined to perform complex jobs are classified as ________________, ________________, and ________________.

Your Answer Should Be:

A22. Simple devices that can be combined to perform complex jobs are classified as **input converters, processing devices,** and **output converters.**

Input Converters

The purpose of the **input converter** in any electrical or electronic process is to convert some form of energy, such as sound, light, heat, pressure, etc., into voltage and current. These forms of energy can be processed by electrical or electronic devices after they are converted into voltage and current.

Processing Devices

A **processing device** changes the amount or form of current and voltage to that required by the output converter. Among the many functions these devices perform are: (1) creating radio waves, (2) changing small voltages into larger ones, (3) carrying telephone messages and connecting them to their intended destination, and (4) controlling furnaces, air conditioners, or industrial processes.

Output Converters

Very few end results are produced by voltages and currents alone. Therefore, devices are needed which convert voltage or current into some useful form, such as radio waves, sound, motion, heat, or pictures. These devices are called **output converters.**

WHAT YOU HAVE LEARNED

1. What electricity is.
2. How electrical and electronic devices operate.
3. How electrical and electronic devices are used.
4. Even the most complex jobs are accomplished by using three kinds of devices—input converters, processors, and output converters.
5. Any device which converts some form of energy into voltage and current performs the function of an input converter.

6. Processors change the input voltage and current into a form suitable for operating an output converter.
7. Output converters convert voltage and current from a processing device into some useful form.

Q23. The telephone mouthpiece is an input converter. It converts _____ into voltage and current.

Q24. A thermostat in a home heating system converts ____ into mechanical motion to open and close a switch.

Q25. The circuits of a radio receiver, which change electricity from radio waves (input) to the form of electricity required by the speaker (output), can be thought of as a(an) __________ ______.

Q26. Electric lamps convert voltage and current into _____.

Q27. A speaker converts voltage and current into _____.

Q28. Electric toaster filaments (wires) convert voltage and current into _____.

Q29. Television picture tubes convert voltage and current into _________.

Q30. Two results of current flowing through a wire are the development of ____ and ________ ______.

Q31. The flow of current through a wire is caused by an electrical characteristic called ________.

Q32. ________ and ________ are required to operer-erate electrical and electronic devices.

Your Answers Should Be:

A23. The telephone mouthpiece is an input converter. It converts **sound** into voltage and current.

A24. A thermostat in a home heating system converts **heat** into mechanical motion to open and close a switch.

A25. The circuits of a radio receiver, which change electricity from radio waves (input) to the form of electricity required by the speaker (output), can be thought of as a **processing device.**

A26. Electric lamps convert voltage and current into **light.**

A27. A speaker converts voltage and current into **sound.**

A28. Electric toaster filaments (wires) convert voltage and current into **heat.**

A29. Television picture tubes convert voltage and current into **pictures** (or images).

A30. Two results of current flowing through a wire are the development of **heat** and **magnetic fields.**

A31. The flow of current through a wire is caused by an electrical characteristic called **voltage.**

A32. **Voltage** and **current** are required to operate electrical and electronic devices.

2

Basic Electrical Circuits

What You Will Learn

You are now going to learn what electrical circuits are, what they consist of, and what each device in the circuit does. You will become more familiar with voltage and current and will learn the difference between direct current (DC) and alternating current (AC). You will become acquainted with electrical diagrams and construction of circuits.

COMPLETE ELECTRICAL CIRCUITS

If you look in a dictionary, you will find that **circuit** means to make a complete trip. In electricity, current makes a complete trip through an **electrical circuit.**

If the circuit is not complete, current does not flow. Current flows only if the path through the circuit is complete. A broken wire, a loose connector, or a switch in the OFF position will prevent current from flowing.

You have now learned two important facts regarding the flow of current. A **voltage source causes** current to flow, and a **complete circuit** allows current to flow.

Q1. In electricity, a circuit provides a path for _______ to make a ________ trip.

Q2. Current flow is caused by a(an) _______ ______ and permitted by a(an) ________ ________.

Your Answers Should Be:

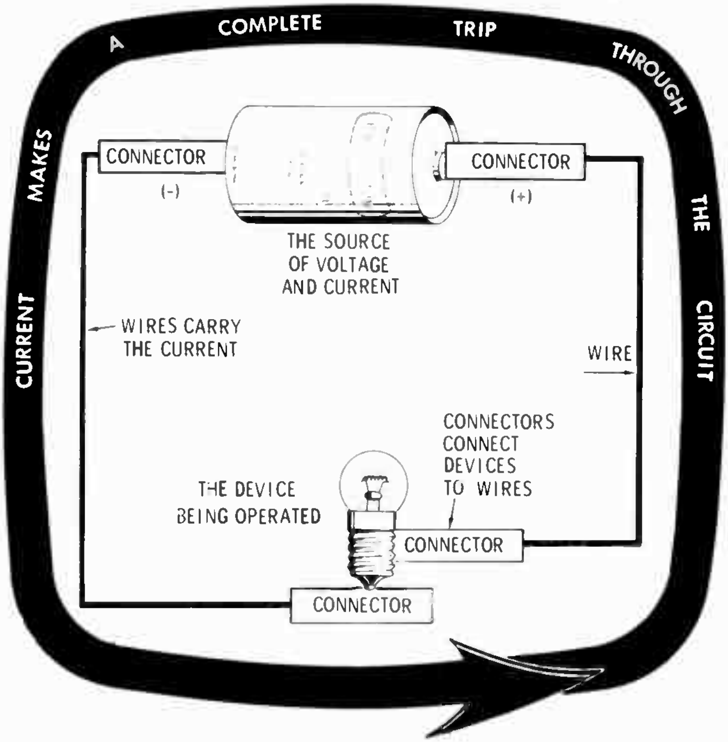
A1. In electricity, a circuit provides a path for **current** to make a **complete** trip.

A2. Current flow is caused by a **voltage source** and permitted by a **complete circuit**.

HOW ELECTRICAL CIRCUITS ARE MADE

All electrical circuits consist of the basic units shown in the illustration below. The device being operated, of course, may be any electrical or electronic device. In fact, many electrical circuits contain more than one device to be operated.

A BASIC ELECTRICAL CIRCUIT



Now that you are familiar with the basic units of an electrical circuit, you are ready to learn more about each part.

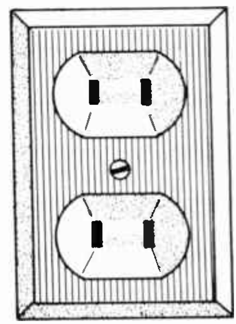
Voltage Source

A battery is an example of a voltage source. As you recall, a voltage source is also a source of current.

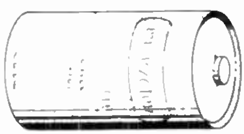
The electrical wall socket (or outlet) is another widely used source of voltage and current. The outlet is part of another circuit that has a generator as a voltage source. There may be many miles of wire between the generator and the outlet.

Familiar Sources of Voltage and Current

WALL OUTLET



FLASHLIGHT CELL



The battery shown in the illustration is more properly called a **cell.** A cell was originally considered to be a storage device. Cells, such as those used in a flashlight, develop 1.5 volts each. A **battery,** such as the 6- or 12-volt source in an automobile, is constructed of two or more cells. However, through long usage, a cell is often called a battery.

Q3. List the four basic units of an electrical circuit.

Q4. A lamp will light only when it is part of a(an) _________ ________.

Q5. A(an) __________ joins wires to a voltage source or operating device to make a complete current path.

Q6. A(an) ________ _______, such as a battery, is also a source of current.

Q7. Voltage sources of the type used in a flashlight are more properly called ______.

Q8. A single flashlight cell is a source of ______ volts.

Q9. If a 6-volt battery has four 1.5-volt cells, a 12-volt battery will have _____ 1.5-volt cells.

Your Answers Should Be:

A3. The four basic units of an electrical circuit are:
1. Voltage source.
2. Device being operated.
3. Wires.
4. Connectors (terminals).

A4. A lamp will light only when it is part of a **complete circuit.**

A5. A **connector** joins wires to a voltage source or operating device to make a complete current path.

A6. A **voltage source,** such as a battery, is also a source of current.

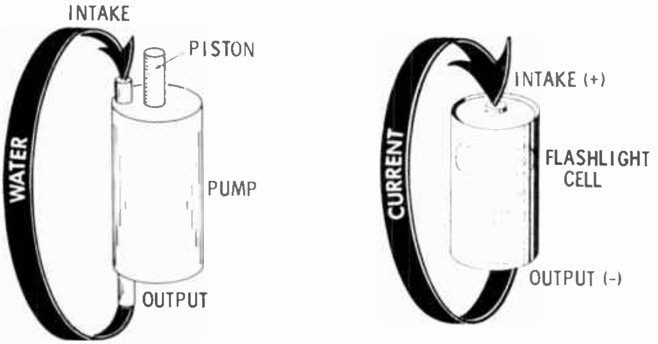
A7. Voltage sources of the type used in a flashlight are more properly called **cells.**

A8. A single flashlight cell is a source of **1.5** volts.

A9. If a 6-volt battery has four 1.5-volt cells, a 12-volt battery will have **eight** 1.5-volt cells. (If a 12-volt battery provides twice as much voltage as a 6-volt battery then it must have twice as many cells.)

Voltage Source Connections—All sources of voltage (and current) have at least two connections.

The source of voltage and current in an electrical circuit is similar to a pump in a water system. The **pump** provides



Electricity Is Like Water in Many Ways

both the **pressure** and the **water** to cause a flow through the **water system.** A **voltage source** provides **electrical pressure** (voltage) and **current** (electrical equivalent of water) to cause a flow through an **electrical circuit.**

Like the water pump, **the source of voltage and current requires an input connection and an output connection.**

SAFETY NOTE: Caution must always be observed when working near voltage sources or circuits. If you come in contact with both connections of the source, **your body becomes a circuit,** and current will flow through you. This can cause painful burns and even death. If you touch only one side of the source or a single wire leading to it, **be sure you do not touch a pipe or other metal surface in contact with the ground.** This precaution is necessary because many voltage sources have one connection wired to ground.

Conductors and Insulators

Wires provide a path for electric current just as pipes provide a path for water. Metals such as copper and aluminum are most commonly used in the manufacture of electrical wire. Their atomic structures make these metals good **conductors** of current. Silver is the best conductor but is much more expensive than other metals. Other more economical metals, such as copper and aluminum, are good conductors and are quite easily formed into wire. When connected into a circuit, wire is most often referred to as a **conductor.**

Most nonmetals are very poor conductors of electric current. These materials are called **insulators.** Rubber and plastic are two commonly used materials for insulators because they are flexible, easily molded, and can be readily cut when necessary. Because of their better insulating qualities, glass and ceramic material are used where high-voltage insulators are required.

Q10. How many connections must be made to a voltage source?

Q11. Materials which provide an easy path for current are called ___________. Those which do not provide an easy path are called ___________.

Your Answers Should Be:

A10. **At least two connections** must be made to **a** voltage source.

A11. Materials which provide an easy path for current are called **conductors.** Those which do not provide an easy path are called **insulators.**

Working With Wire

Practically all wire used in electrical and electronic work consists of a conducting metal (usually circular in cross section) covered with insulation. The insulation prevents **undesired connections** to and between conductors.

Exceptions include wire used for heating purposes. In these cases, the heating element (wire) is wrapped or formed on an insulating material or supported in air (a nonconductor) between insulators.

If a bare wire comes in contact with another conductor or other metal in an electrical unit, a **short circuit** develops. Current will flow through the **short** instead of the complete circuit containing the operating device. For this reason, wire should be handled with sufficient care to insure that its insulation is not damaged.

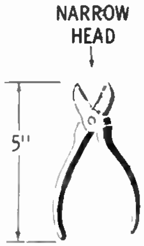
Wire Stripping—In order to join a wire to a connector, a length of insulation must be removed from the wire. A metal-to-metal connection is required to permit current flow.

The process of removing the insulation is called **wire stripping.** Both wire cutting and stripping are usually done with a type of pliers called **diagonal cutters.** The correct procedure is shown on the next page.

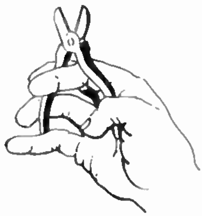
Precautions—When stripping wire, do not be discouraged if at first you cut the end of the wire while stripping it. Success will come with practice.

Do not squeeze the plier handles too tightly when attempting to remove the insulation from the wire. Just break the surface of the insulation with the cutting head. The cut need not go through to the wire. A steady pull should then part or tear the remaining insulation. Placing the index finger between the handles prevents the cutters from closing completely and nicking or cutting the wire.

CUTTING AND STRIPPING WIRE

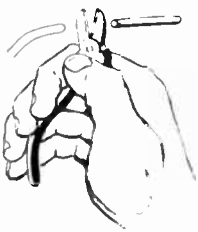


THE DIAGONAL CUTTER



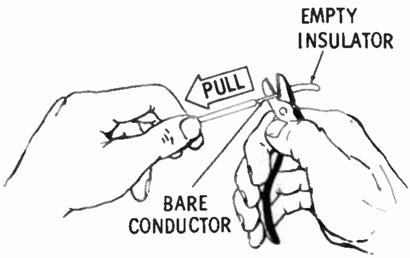
TO OPEN JAWS OF THE CUTTER:

Spread the handles using the index finger.



TO CUT WIRE:

Place the wire between the jaws of the cutter and squeeze the handles together.



TO STRIP WIRE:

1. Place the wire between the jaws (near the pivot).
2. Squeeze the handles just enough to cut the insulation.
3. Pull the long end of the wire away from the cutter. (Firmly grip the insulation with the jaws of the cutter).

Q12. Nearly all metals will conduct ________.

Q13. Copper or aluminum are used in electric wires because they are good ___________.

Q14. Materials that are nonconductors of current are called ___________.

Q15. Insulation is used on wires to (make, prevent) contact with other conductors of current.

Q16. Undesired contact between two conductors is called a(an) _____ ________.

Q17. ____ __________ is the process of removing insulation from a wire. It can be accomplished by pliers known as ________ _______.

Your Answers Should Be:

A12. Nearly all metals will conduct **current.**

A13. Copper or aluminum are used in electric wires because they are good **conductors.**

A14. Materials that are nonconductors of current are called **insulators.**

A15. Insulation is used on wires to **prevent** contact with other conductors of current.

A16. Undesired contact between two conductors is called a **short circuit.**

A17. **Wire stripping** is the process of removing insulation from a wire. It can be accomplished by pliers known as **diagonal cutters.**

Devices

Current from a voltage source operates devices such as electric light bulbs, heaters, and motors. Radio and television receivers are also operated by current from voltage sources. These devices process voltage and current contained in received radio waves by changing the input energy into sound and pictures. The voltage sources make it possible for these devices to perform this process.

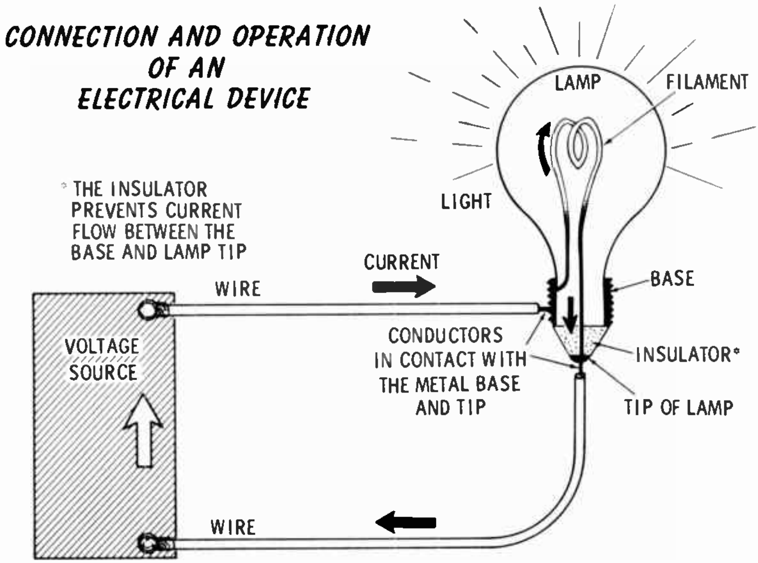
Connections—As stated earlier, all electrical devices must have **two or more** connections to a circuit. These connections are used to join conductors to the device, thus completing the circuit and permitting current to flow into and out of the device.

Operation—The voltage source operates the device by forcing current through the circuit. All connections must be made in the circuit, including those at the device and the source. Current will then be able to flow through the device and cause it to operate.

Connectors

The terms **connectors** and **terminals** are often used interchangeably. A **connector,** however, is normally thought of as being a mechanical part, such as a battery clamp, used to connect a conductor to a device. A **terminal,** on the other hand, is a point on a device where a connection can be made—a screw or other contact point.

The illustration below shows how connections are made to a voltage source and an operating device. The lamp will light with the bare conductors merely touching the lamp terminals. In practice, however, the lamp is placed in a socket and the wires connected to the socket terminals.



Wires, connectors, and terminals allow current to flow in a circuit because they are made of conducting metals. Care must be taken, however, when joining these parts to each other. Metal at the contact points must be clean and free from the insulating properties of dirt, grease, etc. Sandpaper or a small file can be used to clean these junction points when necessary. After a wire has been stripped, it should be cleaned of any remaining insulation.

When connecting a wire to a terminal, make sure the screw or clamp makes a tight connection. For current to flow, all parts of the circuit must be connected.

Q18. To permit current to flow into and out of a device, the device must have at least ___ connections.

Q19. That part of a device where a connection can be made is called a ________.

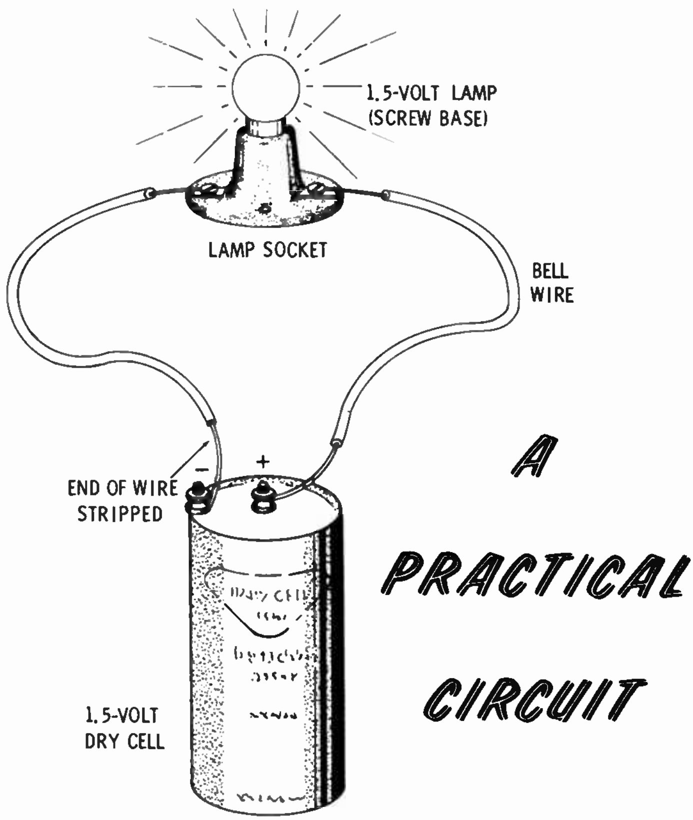
Your Answers Should Be:

A18. To permit current to flow into and out of a device, the device must have at least **two** connections.

A19. That part of a device where a connection can be made is called a **terminal.**

A PRACTICAL CIRCUIT

The circuit shown below demonstrates the way in which all basic circuits are connected. It contains a voltage source, wires, connectors (or terminals), and an operating device. The voltage source pictured is a large 1.5-volt dry cell used in some doorbell systems. This is a practical circuit because it will actually work and is often used.



Open Circuits

If all the connections are made as shown in the illustration, the lamp will light. If any of the connections are not properly made, the lamp will not light—a condition known as an **open circuit.** An open circuit represents a condition that prevents the flow of current. In other words, the circuit is not complete.

Closed Circuits

A **closed circuit** has all of its connections made and forms a complete path through which current can flow.

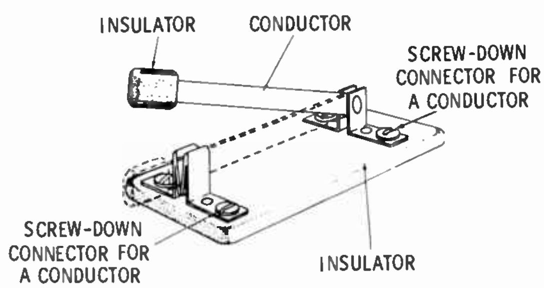
SWITCHES

Since it is often desirable to open and close a circuit, nearly all circuits contain some form of **switch.**

Knife Switch

The simplest type of switch is called a **knife switch.** It was given this name because it has an element resembling the blade of a knife.

A KNIFE SWITCH



Q20. The lamp in the illustration on the opposite page lights because it is a(an) (open, closed) circuit.

Q21. Disconnecting one of the wires will develop a(an) (open, closed) circuit.

Q22. To permit opening and closing a circuit, a(an) ______ can be connected into it.

Q23. A(an) _____ ______ is the basic type of switch.

Your Answers Should Be:

A20. The lamp lights because it is in a **closed** circuit.

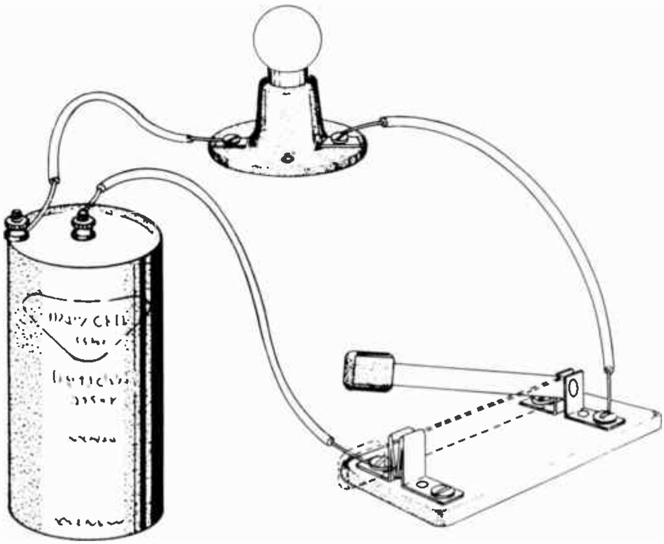
A21. Disconnecting one of the wires will develop an **open** circuit.

A22. To permit opening and closing a circuit, a **switch** can be connected into it.

A23. A **knife switch** is the basic type of switch.

The basic circuit just explained can be reconnected to include a knife switch. The illustration below shows how the connections are made. Be sure you understand what happens to the flow of current when the switch is open (position shown) and when it is closed.

A PRACTICAL CIRCUIT WITH SWITCH



There are many other types of switches, some of which you have used. For example, there are switches on the walls of your home, on the front of your appliances, and on the dashboard of your car. Nearly all operate on the knife-switch principle. In the closed position, a metal blade makes an electrical contact between at least two conductors.

WHAT YOU HAVE LEARNED ABOUT COMPLETE CIRCUITS

1. An electrical circuit provides a complete path for current flow.
2. Every electrical circuit consists of: (1) a source of voltage which causes current to flow; (2) conductors which provide a path for the current; (3) electrical devices which are operated by the current; (4) connectors (terminals) to join conductors to a source or a device.
3. Voltage sources and electrical devices always have at least two connections. All connections must be made in order for current to flow through them.
4. Most metals can conduct current and are called conductors. Most nonmetals provide a very poor path for current and are called insulators.
5. A wire consists of a conductor (usually copper) covered by insulation (usually rubber or plastic). Insulation may be stripped from the wire with diagonal cutters.
6. An open circuit is a condition in which the current path is interrupted. A closed circuit is the same as a complete circuit. A short circuit occurs when a conductor makes an undesirable contact with another conductor or metal part.
7. Switches are designed to open and close circuits. By operating the switch, a device may be turned on or off.

Review Questions (Mark them true or false.)

Q24. A voltage source causes current to flow if a complete circuit is provided.

Q25. Current will flow if there is a complete electrical path from the voltage source to the device, through the device, and back to the voltage source.

Q26. If otherwise complete, current will not flow in a circuit if its switch is closed.

Q27. When a wall switch is flipped to the ON position, the switch is open, permitting the lamp to light.

Q28. If the insulation on a wire is broken or damaged, it may cause a short circuit.

Your Answers Should Be:

A24. A voltage source causes current to flow if a complete circuit is provided. **True.**

A25. Current will flow if there is a complete electrical path from the voltage source to the device, through the device, and back to the voltage source. **True.**

A26. If otherwise complete, current will not flow in a circuit if its switch is closed. **False.**

A27. When a wall switch is flipped to the ON position, the switch is open, permitting the lamp to light. **False.**

A28. If the insulation on a wire is broken or damaged, it may cause a short circuit. **True.**

VOLTAGE AND CURRENT

In this section you will become acquainted with voltage and current measurement units. You will also become familiar with the commonly used values of these units.

Voltage

Voltage is measured in terms of a unit called a volt. A measurement unit indicates quantity or amount, as in gallons of water or pounds of sugar. As a similar unit, **volts** expresses a quantity contained in a voltage source. Although voltage is not visible like water and sugar, the number of volts expresses the amount of electrical pressure available from the source. As you remember, it is this pressure that causes current to flow. The greater the pressure (number of volts), the greater the current will be.

Current

Current is measured in terms of a unit called an **ampere.** The number of amperes defines the amount of current that is flowing in a circuit. A flashlight lamp (bulb), for example, draws 0.25 **ampere** (abbreviated as **amp**) from the voltage source.

A 100-watt lamp draws approximately 1 amp from the 115-volt home electrical system. Ten amps flow through some electric irons, toasters, and heaters. A car battery supplies 100 amps or more to a starter motor.

Large and Small Values

Values of voltage and current can be very large or very small. Since it is awkward to talk and write about 500,000 volts or 0.003 amp, units which are more easily handled have been developed. With this system the quantities mentioned become 500 kilovolts and 3 milliamps, respectively. A **kilovolt** represents 1,000 volts and a **milliamp**, 0.001 amp.

The following table will help you convert from one unit to another.

CONVERSION TABLE

When You See	Do This to Convert	Example
Mega or M	Multiply by 1,000,000	2 Megavolts is 2,000,000 volts
Kilo or K	Multiply by 1,000	5 Kiloamps is 5,000 amps
Milli or m	Divide by 1,000	7 Millivolts is 0.007 volt
Micro or μ	Divide by 1,000,000	9 μamps is 0.000009 amp
Nano or n	Divide by 1,000,000,000	5 nano volts is 0.000000005 volt
Pico or p	Divide by 1,000,000,000,000	4 pico-amps is 0.000000000004 amp

Q29. Voltage is measured by a unit called a(an) ____.

Q30. The number of volts indicates the quantity of __________ ________ contained in a voltage source.

Q31. An ampere is a unit that indicates the quantity of ________.

Q32. Assuming that the voltage source can provide the current, what determines the number of amps that will flow in a circuit?

Q33. 3 kilovolts is (larger, smaller) than 100 millivolts.

Q34. How much of an amp is 15 microamps?

Q35. Convert 16 megavolts to volts.

Your Answers Should Be:

A29. Voltage is measured by a unit called a **volt.**

A30. The number of volts indicates the quantity of **electrical pressure** contained in a voltage source.

A31. An ampere is a unit that indicates the quantity of **current.**

A32. The **operating device** determines the number of amps that will flow in a circuit, assuming the voltage source can provide it.

A33. 3 kilovolts is **larger** than 100 millivolts.

A34. 15 microamps is **0.000015 amp.**

A35. 16 megavolts is equivalent to **16,000,000 volts.**

DIRECT CURRENT

A current that always flows in the same direction is called a **direct current.** Dry cells and batteries are sources of direct current. Some types of electric generators also supply direct current. Later you will learn about a power supply which provides direct current for use within radio and TV receivers.

Is There a Direct Voltage?

Yes. A voltage which provides direct current is considered to be a direct voltage. Since direct current is abbreviated DC, the abbreviation is used to identify direct voltage as DC voltage. Direct current is often shortened to DC current, or merely DC.

Direction of Current Flow

Marking the terminals of a voltage source with plus (+) and minus (—) signs indicates the direction in which current flows in a circuit. There are two systems describing the direction of current flow—**conventional** and **electron.**

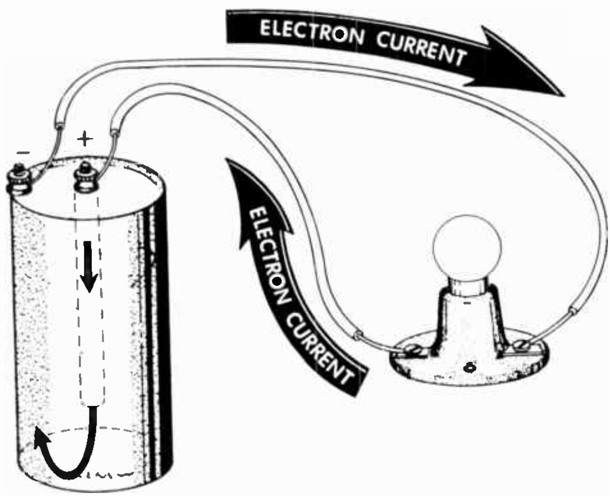
The conventional current theory was the first to be developed. Benjamin Franklin is considered to be its originator, and it is still being used in many electrical engineering texts. **Conventional current** is said to flow **from the positive** (+) voltage terminal, through the circuit, and to return **to the negative** (—) voltage terminal.

The **electron current** theory, of more recent origin, permits a clearer explanation of how current flows through electronic circuits. For this reason, the electron current direction of flow will be used in this text. This theory states that current **leaves the negative** (—) terminal, flows through the circuit, and **returns to the positive** (+) terminal of the voltage source.

If you learn the rules of electron flow, conventional flow should not be confusing. You will find it easy to mentally reverse directions.

Current flow does all the work involved in the operation of any electrical or electronic device, whether it is a simple lamp or a complicated electronic computer. In any application a continuous path must be provided between the two terminals of a voltage source before current can flow.

The Direction of DC Electron Current Flow



Q36. The connecting posts on the cell in the illustration are marked (+) and (—). The (+) post is the _________ terminal.

Q37. Inside the cell, electron current flows from the _________ terminal to the _________.

Your Answers Should Be:

A36. The (+) post is the **positive** terminal.

A37. Inside the cell, electron current flows from the **positive** terminal to the **negative** terminal. (Although the text did not provide this information, the illustration reveals the proper direction. Current must flow in this direction inside the battery if it is to move from negative to positive through the circuit.)

ALTERNATING CURRENT

A current that reverses its direction of flow at regular intervals is called **alternating current (AC).** You might ask, "Why should we have a current that is constantly changing its direction?" The answer is fairly simple. AC has certain features that make it desirable. The two main reasons are:

Reason 1. Wall outlets in your home supply an AC voltage. This voltage is produced by generators located many miles away. During the earliest days of electricity, DC was supplied to homes. However, DC can be sent through lines for only short distances.

AC can be easily changed to a higher or lower value. This characteristic makes possible its economical transmission over long distances—hundreds of miles in some cases. As a result, AC generating plants can be located at remote sources of water power and still be able to supply customers miles away. A good example of this application is the generating equipment at Hoover Dam in Arizona supplying power to cities on the West Coast, hundreds of miles distant.

Reason 2. The preceding chapter described input converters which convert other forms of energy into voltage and current. Many of these forms, such as sound and radio waves, occur in alternating cycles. Sound waves, for instance, are alternating areas of maximum and minimum air pressure. When converted into electricity, as in the telephone, the resulting current is also alternating, thus the sound is faithfully transmitted.

WHAT YOU HAVE LEARNED

1. The measurement unit of electrical pressure is the volt. It defines the amount of electrical pressure available in a voltage source.
2. The measurement unit for current is the ampere, abbreviated amp. Assuming that a sufficient amount of current can be supplied by the voltage source, the number of amperes that flow in a circuit is determined by the needs of the operating device. Operating devices are designed for a specified number of volts, and are so constructed as to draw the required number of amps when operated at that voltage.
3. Volt and ampere quantities are often expressed in very large and very small numbers. To ease the task of writing or speaking of very large or very small numbers, prefixes, such as mega-, kilo-, milli-, and micro-, have been added to the basic units of volts and amperes.
4. A current that always flows in the same direction is direct current. Its abbreviation is DC, which can be used to specify DC current or DC voltage.
5. Current flows from the negative terminal of a voltage source, through the circuit, and returns to the positive terminal. Inside the voltage source, current flows from the positive to the negative terminal. This is in accordance with the electron current theory.
6. A current that reverses its direction of flow at regular intervals is called alternating current (AC). AC voltage and current can be transmitted over long distances, but DC cannot. AC is also the only means of converting certain types of energy into useful electrical representations.

Q38. A volt is a measurement of _______, and an ampere is a measurement of _______.

Q39. According to the electron current theory, current flows from the ________ voltage terminal, through the circuit and returns to the ________ terminal.

Your Answers Should Be:

A38. A volt is a measurement of **voltage,** and an ampere is a measurement of **current.**

A39. According to the electron current theory, current flows from the **negative** (—) voltage terminal, through the circuit, and returns to the **positive** (+) terminal.

3

How To Use Meters

What You Will Learn

Since volts and amperes are units of measurement, some device must be used to measure them. Devices used for this purpose are called meters. You are now going to learn about the different types of meters and how to use them to measure voltage and current. The precautions to take when handling these instruments are also discussed.

HOW DO METERS WORK?

Meters, like motors, convert electrical energy (current) into mechanical motion. In a motor, current-generated magnetic fields cause the armature to rotate. In a meter, similar magnetic fields cause a pointer to move across a scale. The position of the pointer (sometimes called a needle or indicator) when it comes to rest on the scale indicates the amount of current flowing through the meter.

Most homes and cars have meters similar in principle to those that will be discussed. An electrical meter measures consumption of house current. The gasoline, temperature, and other automobile gauges are all basically meters measuring current flow. The quantities being measured are converted into current.

Q1. Voltage and current are measured by ______.

Q2. The reading of a meter is taken where a pointer comes to rest on a _____.

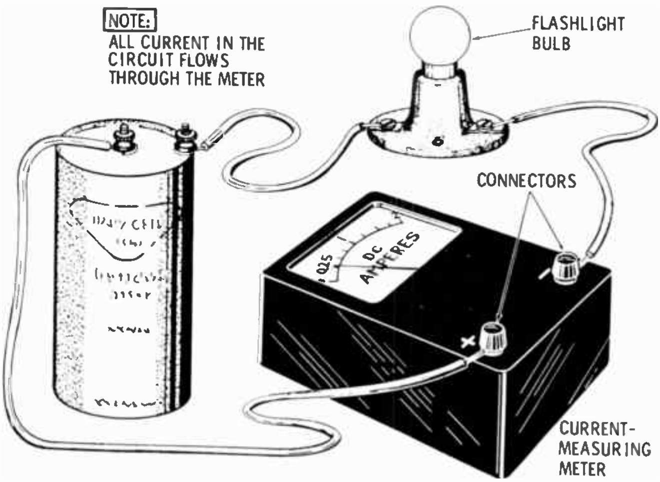
Q3. ________ in the meter moves the pointer.

> **Your Answers Should Be:**
>
> **A1.** Voltage and current are measured by **meters.**
>
> **A2.** The reading of a meter is taken where a pointer comes to rest on a **scale.**
>
> **A3.** **Current** in the meter moves the pointer.

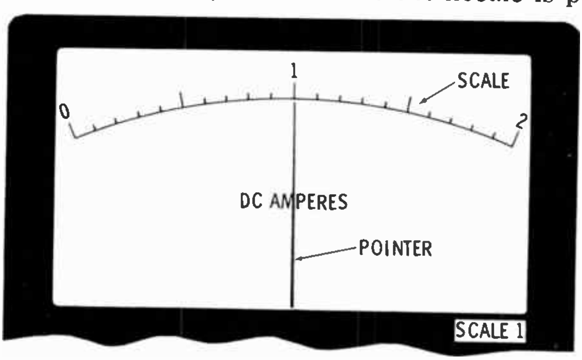
READING METERS

The illustration below shows how a meter is connected to a circuit to measure the amount of current flowing.

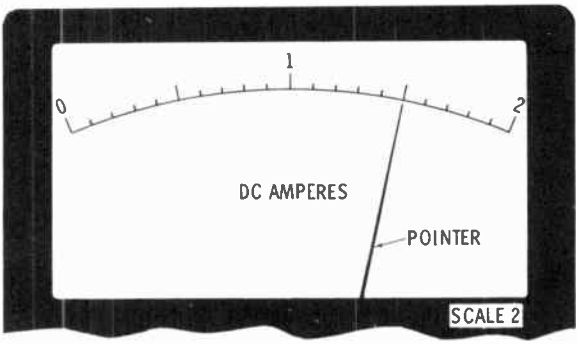
MEASURING THE CURRENT DRAWN BY A LAMP

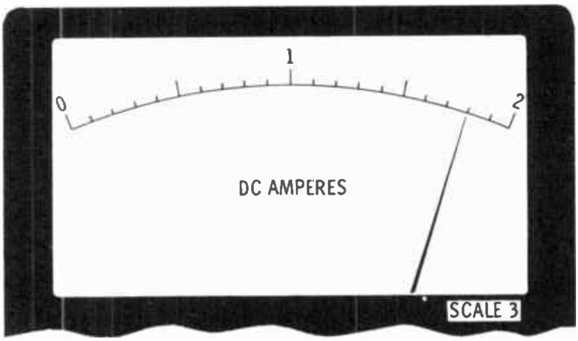


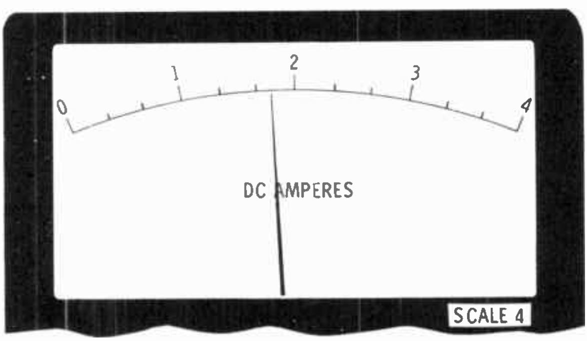
Meters are read by noting to which number (or division mark between numbers) on the scale the needle is pointing.



If the needle points to a division mark between two numbers, the decimal value of the division is added to the lower number.







Q4. **What is the reading for scale 1?**

Q5. **What is the value read on scale 2?**

Q6. **How many amps according to scale 3?**

Q7. **What does scale 4 read?**

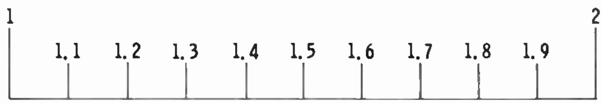
Your Answers Should Be:

A4. The reading for scale 1 is **1 amp.**

A5. The value read on scale 2 is **1.5 amps.** (Note the pointer is halfway between 1 and 2 on the scale.)

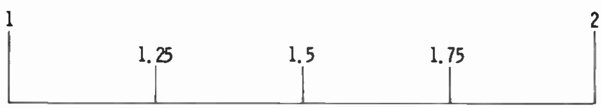
A6. There are **1.8 amps** registered on scale 3. (There are ten equal division marks between numbers 1 and 2. The pointer rests on the eighth division, indicating a current of 1.8 amperes. Counting of the divisions is shown in the illustration below.)

The Value of the Ten Divisions Between 1 and 2 on the Meter Scale



A7. Scale 4 reads **1.75 amps.** (This scale has four divisions between the numbers. Thus, each division has a value of ¼ or 0.25 amp as shown in the following illustration. Since the pointer is on the third division between 1 and 2, its reading is 1.75 amps.)

The Value of the Four Divisions Between 1 and 2 on the Meter Scale



VOLTMETERS

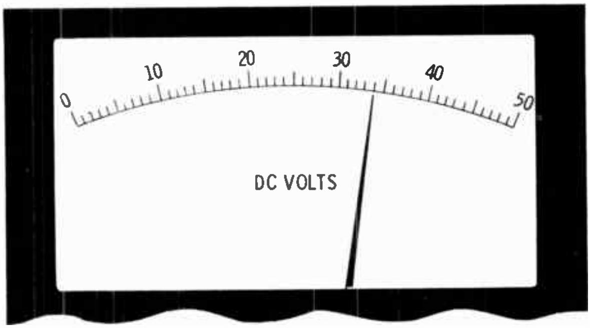
Voltmeters are used to measure voltage. When the voltmeter is connected across the terminals of a voltage source, a current proportional to the source voltage flows through the meter mechanism. The meter scale is calibrated (drawn) to give a reading in volts. The procedure for reading a voltmeter scale is similar to the current scales you have just read.

Precautions

There are two basic types of voltmeters—one for measuring DC voltage and the other for AC voltage. Be sure to use the correct one for the type of voltage to be measured. When a DC voltmeter is applied to an AC source, an incorrect measurement will occur. But when an AC meter is used to measure DC voltage, **the meter may be damaged.**

Reading a Voltmeter

As shown in the following illustration, a voltmeter scale is similar to a current-measuring scale. A value between numbers is read in the same manner as a current reading.



Voltage Ranges

Voltmeters are designed to read to certain maximum values. From zero to a maximum voltage is called the **range** of a voltmeter. Some commonly used ranges are 0-10 volts, 0-50 volts, 0-250 volts, and 0-1,000 volts.

Always be sure that any voltage to be measured is within the range of the voltmeter you are using. A meter will be damaged if used to measure a voltage greater than the maximum value for which it is designed. Excess voltage will cause excess current to flow. As a result, the pointer may be bent in trying to move beyond the end of the scale, or meter circuits may overheat and damage delicate parts.

Q8. What type of meter is used to measure DC voltage?

Q9. How many volts are indicated in the above illustration?

Q10. What may happen if a voltmeter is used to measure voltages beyond its range?

Your Answers Should Be:

A8. A **DC voltmeter** is used to measure DC voltage.

A9. The illustration indicates a reading of **34 volts DC.**

A10. **A meter may be damaged** if used to measure voltages beyond its range. Either the pointer will be bent and/or delicate parts within the meter will be ruined.

AMMETERS

A current-reading meter is called an **ammeter.** It can only be used to measure amperes.

Current Ranges

Commonly used current ranges for work on electrical appliances are 0-10 amps and 0-30 amps. When working with electronic devices, ranges such as 0-500 microamps, 0-10 milliamps, and 0-250 milliamps may be required.

Precautions

Ammeter precautions are the same as for voltmeters.

1. Never use DC meters for AC, or AC meters for DC.
2. Do not measure a current value that is beyond the range of the meter.

The first rule can be observed if you know the type of voltage source supplying the current. For example, you know that batteries supply DC current (and voltage), and most wall outlets supply AC current (and voltage).

The second rule can be followed as you gain experience. If your meter has a selection of ranges, always use the highest range first. Then switch to the appropriate range to obtain the most accurate reading. Quickly remove the meter leads if the pointer swings beyond the limits of the scale.

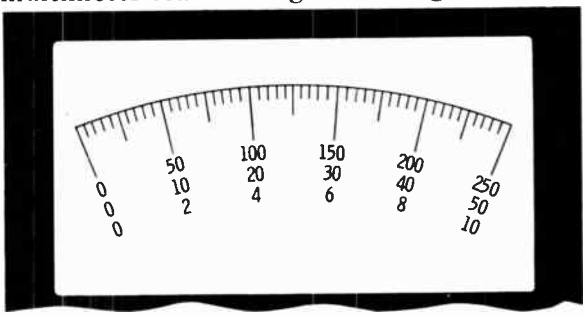
A third rule must be added to the above. Never use an ammeter to measure voltage nor a voltmeter to measure current. Each meter is designed to measure only certain electrical values. If either type of meter is used for measuring other values, it will be damaged.

MULTIMETERS

A **multimeter** is a combination voltmeter and ammeter. It can be used to measure either AC or DC voltages and currents. A multimeter is also called a **volt-ohm-milliameter** (VOM) or a **circuit analyzer.**

Reading Multimeters

A multimeter face has a combination of scales that may include several ranges of voltage and current readings. A typical multimeter scale having three ranges is shown below.

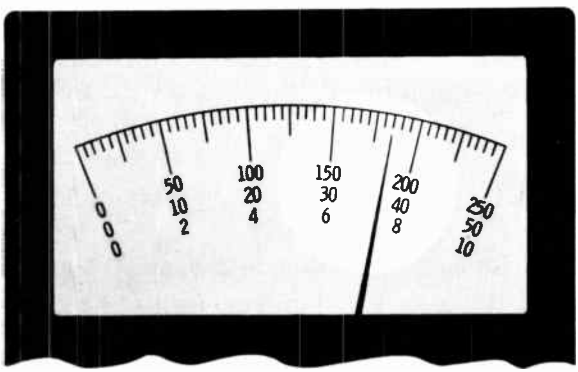


By proper front-panel settings, a multimeter can be used to measure AC and DC current and voltage.

Q11. To measure current, use a(an) ________.

Q12. State three precautions that must be observed when using ammeters or voltmeters.

Q13. Shown here is a portion of the scale illustrated above. What is the reading on the 0-10 range?



Q14. What is the reading on the 0-250 range?

Your Answers Should Be:

A11. To measure current, use an **ammeter.**

A12. Brief statements of the three meter precautions are:

1. **Never use DC meters for AC, or AC meters for DC.**
2. **Do not measure a value beyond the range of the meter.**
3. **Do not use a voltmeter to measure current or an ammeter to measure voltage.**

A13. The reading is 7.4 on the 0-10 range.

A14. The reading is 185 on the 0-250 range.

Multimeter Characteristics

Several experiments are described in this volume. Most of them require the use of a multimeter. You need not work these experiments unless you wish to do so since the text describes the results of each one. However, you can obtain a better understanding of principles and a great deal of experience working with electrical parts and tools by performing the experiments.

Although you may not desire to purchase a multimeter until a later date, you should have some knowledge of what to look for. A good multimeter can be purchased in most electronic parts stores for under $25.00. Or it can be ordered from one of the catalogs of the many mail order companies.

A multimeter from which you can obtain suitable accuracy and which has useful ranges should have the following characteristics. Each characteristic is explained in detail in Volume 4.

Sensitivity: 5,000 to 10,000 ohms/volt on AC and 20,000 ohms/volt on DC.

Voltage Ranges: 0-10, 0-50, 0-250, and 0-500.

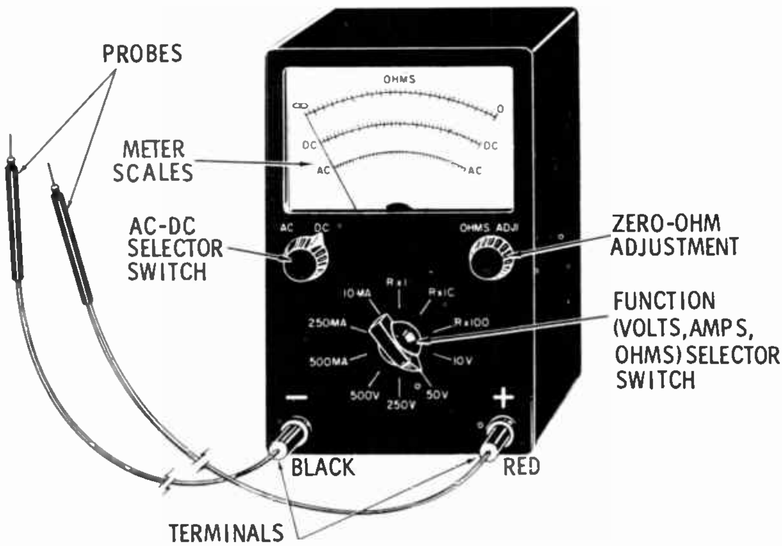
Current Ranges: 0-500 microamps, 0-10 milliamps, and 0-250 milliamps.

Current and Voltage: Both AC and DC.

Resistance Ranges: 0-10K, 0-100K, and 0-1 Meg.

A typical multimeter is shown below. Study the drawing to become familiar with the location and names of the various parts, controls, and scales. The next few pages describe each in detail.

A TYPICAL MULTIMETER



The front panels of some multimeters do not look like this one. Each, however, has a similar means of accomplishing the same measuring tasks.

Q15. A good multimeter can generally be purchased for less than ____________.

Q16. A multimeter having an AC sensitivity of 10,000 ohms/volt will have (greater, lesser) accuracy than one of 1,000 ohms/volt.

Q17. If the AC-DC Selector Switch in the above illustration were set on DC, you would read the position of the pointer on the (top, middle, bottom) scale.

Q18. What is the meaning of the "10V" marking on the Function Selector Switch? Make a guess.

Q19. To serve their purpose, should the tip ends of the two probes be bare metal or insulated?

Your Answers Should Be:

A15. A good multimeter can be purchased for less than **$25.00.**

A16. A multimeter having an AC sensitivity of 10,000 ohms/volt will have **greater** accuracy than one of 1,000 ohms/volt.

A17. You would read the position of the pointer on the **middle** scale.

A18. It indicates a setting at which a voltage **between 0 and 10 volts** may be read.

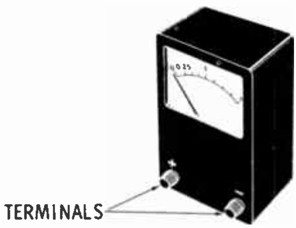
A19. The tip ends of the two probes must be **bare metal.**

VOLTAGE MEASUREMENTS

The term "multimeter" means literally "many meter." It is, in fact, a many-metered instrument performing many measuring functions. The typical multimeter shown on the preceding page measures AC volts, AC amps, DC volts, DC amps, and ohms (to be discussed shortly).

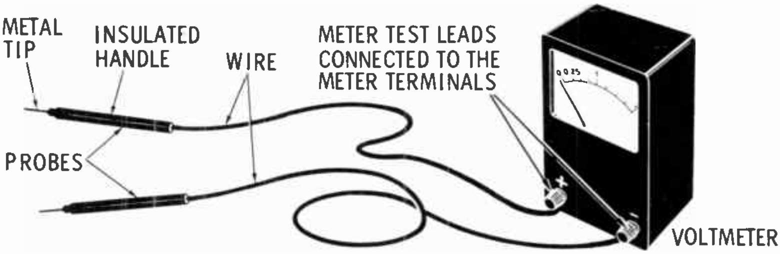
Learning to use a multimeter well requires you to think only of the particular function for which you are using the instrument. If you are measuring DC voltage, think DC voltmeter. If the next measurement is AC amperes, change your thinking to an AC ammeter. By concentrating in this manner, you are more certain to make the proper settings and observe the appropriate measuring precautions. For this reason, the multimeter will be discussed in terms of its separate measuring functions.

Voltmeter Connections



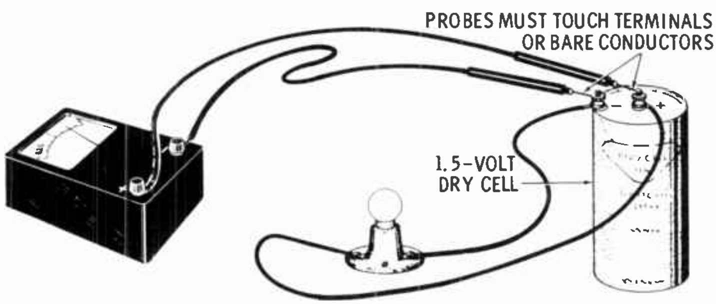
Terminals — The voltmeter, like other electrical devices, has two terminals. Both terminals are connected into a circuit when using the instrument. The terminals are sometimes colored red (+) and black (—) to identify the positive (+) and negative (—) connections.

Test Leads—A voltmeter requires a pair of test leads to connect the meter to the circuit being tested. Test leads are lengths of flexible insulated wire. One end has a means of joining the lead to the voltmeter terminal. The other end has a metal probe encased in an insulated handle.



Connections—When measuring voltage, the probes are touched to the terminals of the voltage source or device. A voltage measurement is always taken across the terminals, and is never made between a terminal and an open wire.

VOLTMETER CONNECTIONS



Q20. List the five electrical quantities that a typical multimeter will measure.

Q21. How is AC and DC current different?

Q22. When measuring battery voltage, how should you think of a multimeter?

Q23. How are the positive and negative terminals of some voltmeters identified?

Q24. What part of a test lead is placed in contact with the circuit being tested?

Q25. A voltage is always measured ______ the terminals of a source or a device.

Your Answers Should Be:

A20. **AC volts, AC amps, DC volts, DC amps, ohms.**

A21. AC current changes its direction of flow periodically; DC current flows in only one direction.

A22. When measuring battery voltage, think of the multimeter as **a DC voltmeter.** (You will be more certain to safely make the correct measurement.)

A23. The positive and negative terminals of some voltmeters are colored **red** and **black** to indicate **positive (+)** and **negative (—)** connections.

A24. The **probe end** of a test lead is placed in contact with the circuit being tested.

A25. A voltage is always measured **across** the terminals of a source or a device.

DC Voltmeter Connections

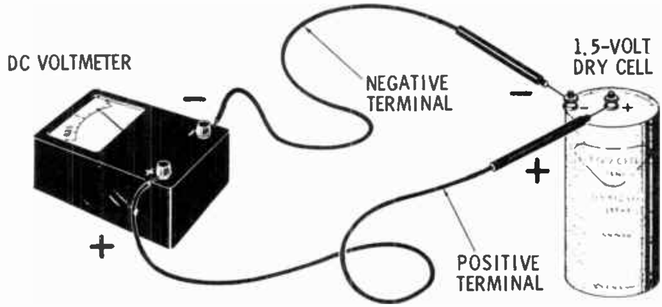
As you recall from the preceding chapter, a DC voltage source has both a negative and a positive terminal. The distinction between negative and positive voltage is identified by the term, "polarity." The **polarity** of a DC voltage source (a battery, for example) is usually indicated in some way at its terminals. One is negative and the other positive. In a DC circuit, the terminal polarity of an operating device is the same as the supply source.

The terminals of a DC voltmeter are either colored or marked to indicate the polarity. A red color or a plus (+) mark identifies a positive terminal. Black or minus (—) indicates a negative terminal. The negative terminal of a DC voltmeter is connected through a test lead to the negative terminal (source or device) of the circuit. The other test lead is connected to the corresponding positive terminal of the meter and of the circuit.

Always observe this rule: **The polarity marking of the DC voltmeter terminal must be the same as the polarity of the voltage being measured.**

If you disobey the rule, the scale pointer will move opposite to its normal direction and may be damaged. The rule does not apply when measuring AC voltage.

The following illustration shows the proper connections to be made when measuring DC voltage.

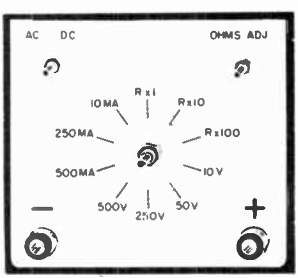


Voltage Measurements With a Multimeter

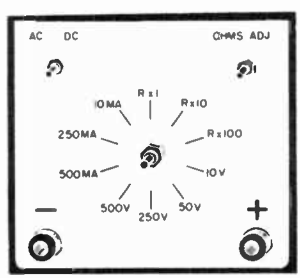
A multimeter can be adjusted by means of selector switches to measure either AC or DC voltage.

TO MEASURE 30 VOLTS AC, THE MULTIMETER SETTINGS SHOULD BE MADE LIKE THIS

Q26. Mark this figure to show the switch settings required to measure 6 volts DC.



Q27. Show the settings for measuring the voltage of a wall outlet.



Your Answers Should Be:

A26.

A27.

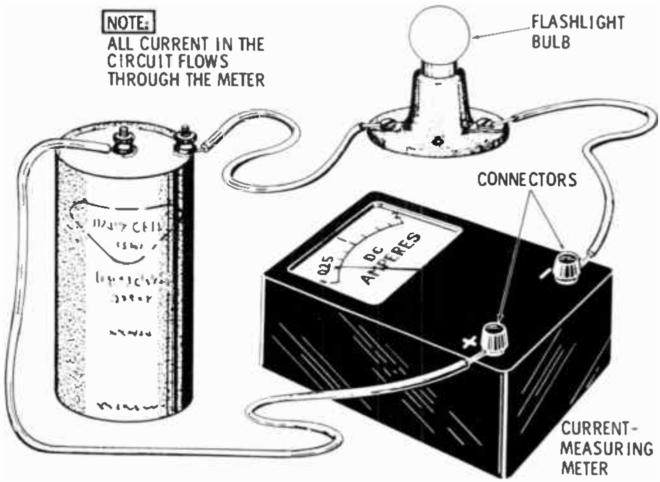
CURRENT MEASUREMENTS

Methods used to measure current with an ammeter or multimeter are different from those used to measure voltage.

Ammeter Connections

Terminals—An ammeter, like a voltmeter, has two terminals. Both terminals must be connected into the circuit when using the meter.

Connections—To measure current, the ammeter must be connected in the circuit in such a way as to allow the current being measured to **flow through** the meter.



CONNECTING AN AMMETER IN A CIRCUIT

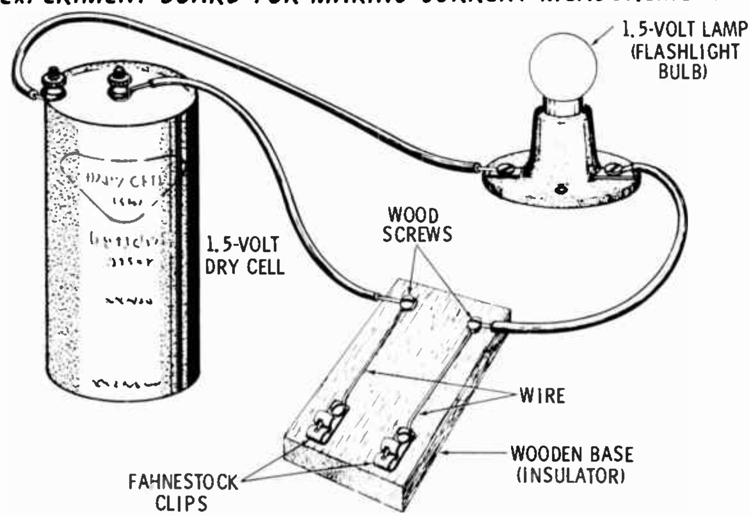
Current Measurements With a Multimeter

Connections—Multimeter connections for measuring current are made as if the instrument were an ammeter. The circuit must be opened (usually at a terminal) and the probes inserted, one on either side of the break.

When measuring DC current, a polarity rule must be observed: **DC current should enter the negative terminal of a DC ammeter and leave by its positive terminal.** Since you know that DC current flows through a circuit from the negative to the positive terminals of a voltage source, current direction can easily be determined.

If you plan to do many experiments that require measuring currents, the board shown below should be worth constructing. The ammeter probes are inserted into the Fahnestock clips.

EXPERIMENT BOARD FOR MAKING CURRENT MEASUREMENTS



Settings—When a multimeter is used as an ammeter, the function switch is set to the appropriate range. In addition, the AC-DC switch is set for the kind of current (AC or DC) to be measured.

Q28. What is the difference between connecting a voltmeter and an ammeter into a circuit?

Q29. DC current should enter the ________ terminal of a DC ammeter.

Your Answers Should Be:

A28. Voltmeter measurements are made **across** the terminals of a device or source. Ammeters are inserted into a circuit so that the circuit current **flows through** the meter.

A29. DC current should enter the **negative** terminal of a DC ammeter.

MULTIMETER SAFETY RULES AND PRECAUTIONS

Rule 1: **When not in use, always set the function selector switch to the highest DC voltage position.**

There are two reasons for this rule. First, as you will learn later, a multimeter contains batteries; at the highest DC voltage position the batteries are disconnected from the internal circuits and will not be supplying current. Second, this position of the selector switch provides the best protection for the delicate meter movement in the event the probes should accidentally come in contact with an energized circuit.

Rule 2: **When in use, forget that the instrument is a multipurpose meter and think of it only in terms of the function for which you are using it.**

A multimeter with its many switch positions and multiple scales can be confusing and can lead even the best technician into making unnecessary errors. Regard the instrument each time time as a particular single-purpose meter.

Rule 3: **When measuring any voltage or current, always use the highest range available first.**

This advice not only provides the best protection to the meter, but it also quickly identifies the best range scale you should use. If the quantity being measured on this or any range causes the needle to move past the end of the scale, immediately remove the probe from the circuit.

Q30. A multimeter should be stored with the switches in what position?

Q31. Make all measurements first at the ------- ----- setting.

WHAT YOU HAVE LEARNED

1. Meters are used to indicate the quantity or value of voltages and currents.
2. Meters are read by noting the position of a pointer on a marked scale.
3. Voltmeters are used to measure voltage.
4. Ammeters are used to measure current.
5. DC meters should not be used to measure AC, and AC meters should not be used for DC.
6. The range of a meter is indicated by the highest marking on the scale. The range is read as "zero to some number." For example, 0-150 volts DC.
7. Never connect a meter to measure a quantity known to be above the meter range. Meter damage will result. You should have some idea of the maximum value of the quantity before making the measurement.
8. A multimeter is a multipurpose meter. A typical instrument will measure AC volts, AC amps, DC volts, DC amps, and ohms. It will measure each of these functions in several ranges.
9. Voltage measurements are made by connecting the voltmeter probes across the terminals of the voltage source or device to be measured.
10. If DC voltage is being measured, observe the polarity rule. The terminals of the meter and the circuit should be connected negative to negative and positive to positive.
11. Current measurements are made by connecting the ammeter into the circuit in a manner which allows the circuit current to flow through the meter. This normally requires breaking the circuit and connecting the ends to the meter terminals.
12. If DC current is being measured, observe the polarity rule. Connect the ammeter into the circuit in a manner which allows current to enter the negative terminal of the meter.
13. Switches are provided on the front panel of a typical multimeter. An AC-DC switch prepares the meter for

Your Answers Should Be:

A30. Before storing a multimeter, **set the AC-DC switch to DC** and **the function selector switch to the highest voltage range.**

A31. Make all measurements first at the **highest range** setting.

the type of voltage or current to be measured. A function selector switch sets the meter to the function (volts, amps, ohms) to be measured and the desired range.

14. When not in use, a multimeter should be set at its highest DC-voltage position.
15. When working with a multimeter, forget its many purposes. Think only of the specific function for which you are using it.
16. When measuring voltage or current, always use the highest range first. Remove the probes immediately if the pointer moves past the end of the scale.

4

The Basic Telephone System

What You Will Learn

You will find that a telephone system is a simple electrical circuit which operates in accordance with the principles you have learned earlier. Parts of the telephone circuit convert sound into electrical signals. Other parts change the electrical signals back into sound. As a result, conversations can be transmitted through wires for extremely long distances.

You are familiar with the mouthpieces and earpieces of a telephone. When you finish this chapter, you will understand how these parts work. You will also learn how they are connected in an operating system.

THE MECHANICAL TELEPHONE

Have you ever built a mechanical telephone using a pair of tin cans and a length of string? If you have, you know sound can be transmitted through a string. As crude as this mechanical system is, it demonstrates many of the principles used in the modern telephone.

Q1. Vibrations, representing sound, travel down the string of a(an) ___________ telephone system.

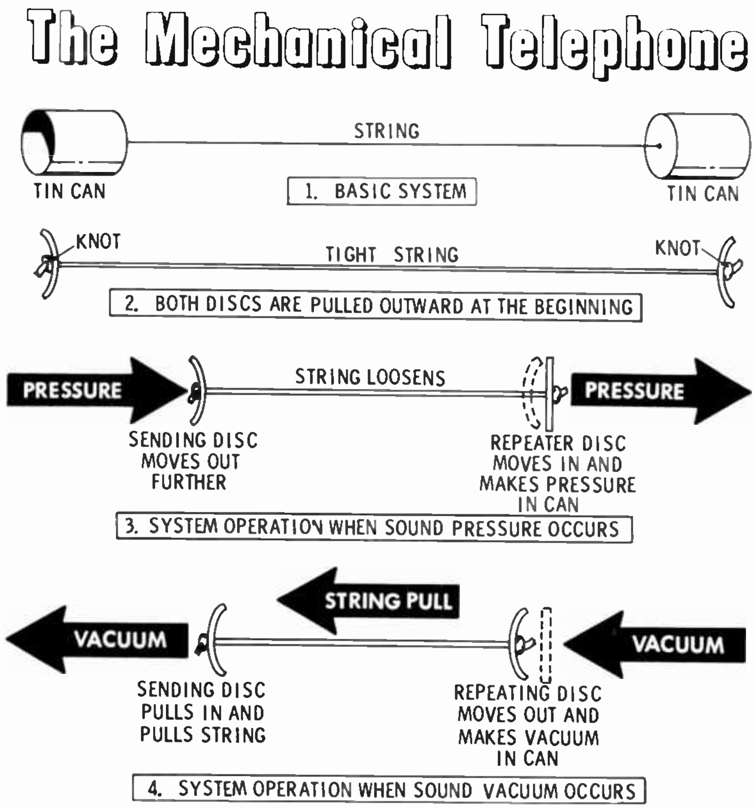
Q2. ____________, representing sound, travels down the wires of an electrical telephone system.

Your Answers Should Be:

A1. Vibrations, representing sound, travel down the string of a **mechanical** telephone system.

A2. **Electricity** (or electrical signals), representing sound, travel(s) down the wires of an electrical telephone system.

The figures below illustrate how a mechanical telephone system operates.



Note that the key part of the mechanical telephone system is the flexible metal disc at the bottom of each can. Speaking into the can causes sound waves to strike the disc and make it vibrate.

The vibrations from one disc are carried to the other disc by a tightly stretched string. The second disc repeats the in-and-out motions of the sending disc and develops varying air pressures in the can. These are sound waves which are crude reproductions of the original sound waves.

Principles of Sound

A study of the basic principles of sound reveals how a mechanical (or electrical) telephone system works. Sound is made up of vibrations. Differences in sound are determined by their **frequency**—the number of times per second a sound vibrates. A high tone (a shriek) has a high frequency—several thousand vibrations per second. A low tone (deep bass voice) has a frequency of only a few hundred vibrations in a second.

All tones have a specific frequency. A tuning fork, for example, vibrates and creates a sound tone at the frequency for which it was designed. The same is true of piano or violin strings, the skins of a drum, or your vocal cords.

Air consists of a large number of extremely tiny particles, several million per cubic inch. When sound causes these particles to vibrate, they alternately pack together and fly apart at the frequency of the sound. Packing together creates instantaneous areas of high pressure and flying apart develops a condition of less-than-normal pressure (approaching a vacuum).

As the areas of changing air pressure strike other adjacent air particles, the process is continued. This is the manner in which sound travels through air. When the changes in air pressure strike a flexible disc (or **diaphragm**), it vibrates. The vibrations are at the same frequency as the original sound.

In the mechanical telephone, the sending disc transmits its vibrations to a tightly stretched string which, in turn, sets up the same vibrations in the receiving disc. In the modern telephone, proper design and the use of electricity result in excellent reproduction of sound.

Q3. Frequency of a sound indicates the number of times it will _______ in a ______.

Q4. Sound vibrations set up corresponding changes of air ________.

Your Answers Should Be:

A3. Frequency of a sound indicates the number of times it will **vibrate** in a **second.**

A4. Sound vibrations set up corresponding changes of air **pressure.**

THE ELECTRICAL TELEPHONE SYSTEM

The basic telephone system consists of a **mouthpiece** connected to an **earpiece** by electrical wires. This system permits conversation in one direction only. For two-way conversation, each end of the system requires a mouthpiece and an earpiece.

Sound Into Electricity

There are two basic methods of converting sound into electrical signals. One method causes current already flowing in a circuit to vary in accordance with the frequency of the sound. The other method converts sound into a varying voltage which, in turn, causes a varying current to move through the circuit. How each method is accomplished will be discussed further.

When the current signals (varying at the rate of the sound) arrive at the earpiece, the process is reversed. If the signal is the type superimposed on an existing current, the variations are received by a material that expands and contracts with the signal frequency. If the mouthpiece develops a voltage to cause a fluctuating current, the current develops a similar voltage in the earpiece.

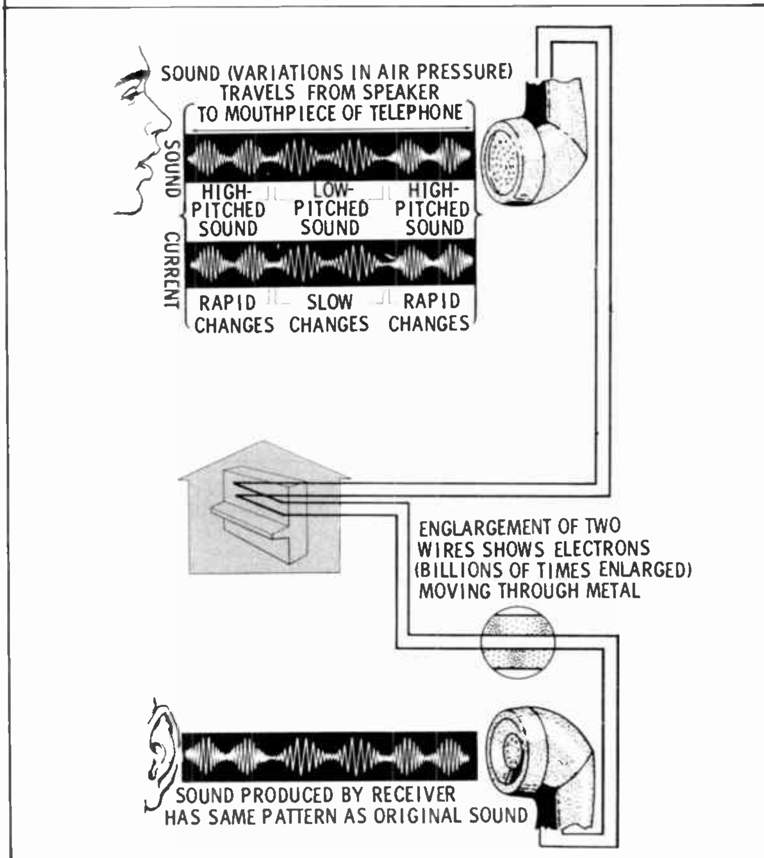
Basic Parts of a Telephone

The working parts of a telephone mouthpiece (often called a **transmitter)** and an earpiece (sometimes called a **receiver)** are usually identical. The mechanism or material used to produce a varying current depends on the method used. Since all vibrations enter or leave the telephone as changes in air pressure, the transmitter and receiver both contain a diaphragm. Other parts of the mouthpiece include wires, terminals, and materials to hold the parts together.

Connections

In a large telephone system, several lines are connected through a switchboard.

Electricity Carries the Pattern of Sound From One Telephone to Another



Q5. **A(an) ___________ connected to a(an) _________ by wires is the simplest telephone system.**

Q6. **________ in a telephone line varies at the frequency of the original sound.**

Q7. **Vibrating air pressure strikes a(an) __________ in the (mouthpiece, earpiece).**

Your Answers Should Be:

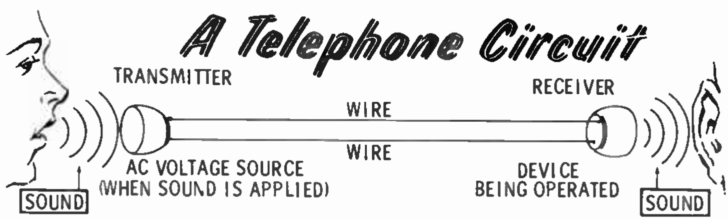
A5. A **mouthpiece** (or transmitter) connected to an **earpiece** (or receiver) by wires is the simplest telephone system.

A6. **Current** in a telephone line varies at the frequency of the original sound.

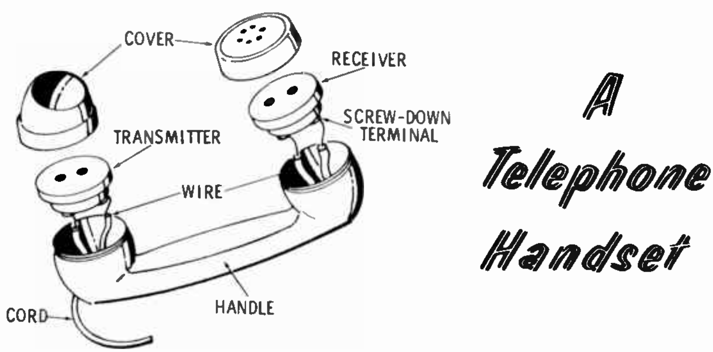
A7. Vibrating air pressure strikes a **diaphragm** in the **mouthpiece.** (The earpiece diaphragm causes vibrating air pressure.)

COMMERCIAL TELEPHONES

As you can see in the illustration below, a telephone system is actually a simple circuit.



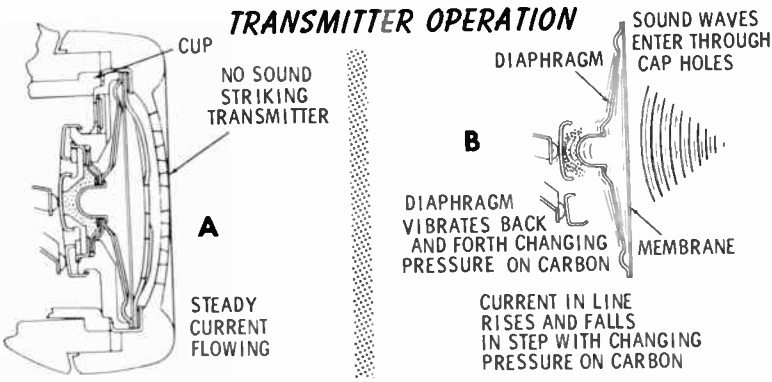
In most commercial (home) telephones, the mouthpiece and earpiece are contained in a single handset. An exploded view of the main parts of a handset is shown below.



The transmitter contains a diaphragm resting against **carbon granules** (grains). The granules are loosely packed with enough freedom to expand and contract in volume.

Transmitter Operation

Part A in the illustration below shows a drawing of the transmitter with no sound applied. Part B demonstrates what happens when sound strikes the diaphragm.



When the handset is lifted from its cradle, a steady current from the phone system starts to flow through the carbon granules. Sound striking the diaphragm places a varying pressure on the carbon. When the granules are packed tightly, current in the circuit increases. When the diaphragm releases its pressure, the granules become loose and less current flows.

The transmitter diaphragm vibrates in response to the frequency of the sound. Packing and loosening of the carbon follow the vibrations of the diaphragm, and current in the phone line varies with the density of the carbon. Therefore, the current varies at the same rate (frequency) as the original sound.

In a commercial system, the varying current is routed to the desired receiver through a central telephone office.

Q8. When a commercial telephone handset is lifted from its cradle, a(an) ------ ------- flows through the transmitter.

Q9. When the carbon granules in the transmitter become more densely packed, (more, less) current flows.

Q10. At what rate does the current vary in the phone lines during a conversation?

Your Answers Should Be:

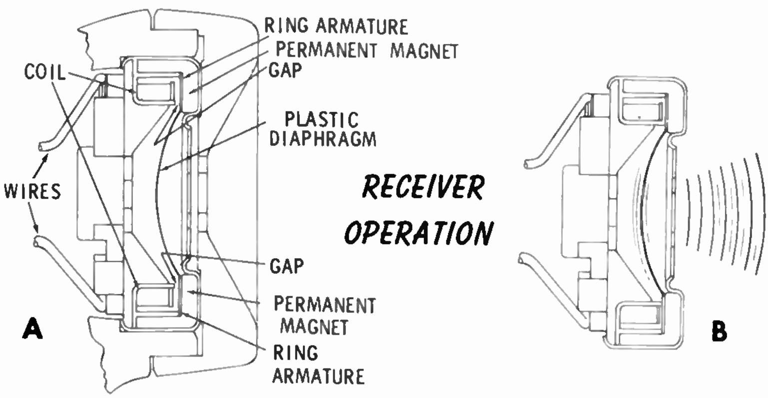
A8. When a commercial telephone handset is lifted from its cradle, a **steady current** flows through the transmitter.

A9. When the carbon granules in the transmitter become more densely packed, **more** current flows.

A10. During a conversation, **current varies at the same rate, or frequency, as the original sound.**

Receiver Operation

The method of converting the current back into sound is slightly different. Part A in the illustration below shows a typical receiver used in a commercial phone system.



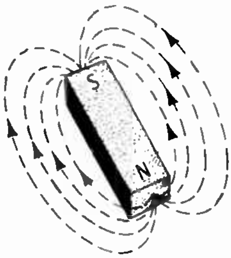
Part B shows that the diaphragm vibrates when a sound-varying current passes through the receiver. The current passing through the coil develops a magnetic field which varies in strength with the changes in current. Thus, the field developed by the current periodically repels and attracts the steady magnetic field of the permanent magnet, causing the magnet to which the diaphragm is fastened to move back and forth. This action reproduces the original sound.

SOUND-POWERED TELEPHONES

Another application of a simple electrical circuit is the sound-powered telephone system. It is used only for short distances because of its limited range.

Induced Current

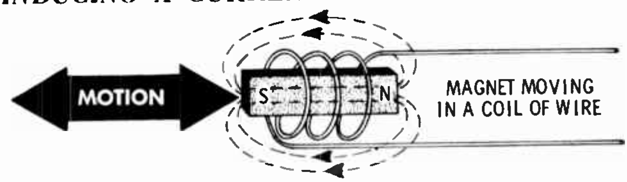
Transmission takes place in sound-powered phones because of the ability of a magnet to **induce** current in a coil of wire. A bar magnet has a north (N) and a south (S) pole. Actually,



when the magnet is suspended in air, the north end of the magnet points toward the north geographic pole. Such a magnet has a magnetic field existing in the space surrounding it, with the lines of magnetic force taking the directions shown.

The illustration below shows a bar magnet being moved back and forth inside a wire coil. As the magnet moves, its magnetic lines of force cut across the turns of the coil. This causes an induced current which will actually flow if the ends of the coil are connected to a circuit.

INDUCING A CURRENT IN A COIL OF WIRE



The current reverses direction each time the motion of the magnet changes direction. The amount of current that flows depends on the strength of the magnetic field, the number of turns in the coil, and the speed at which the magnet is moving. Increasing any of these factors increases the amount of current.

Q11. Current flowing in phone lines at the time when no sound is present is (DC, AC).

Q12. Current flowing during sound transmission is (DC, AC).

Q13. What causes a receiver diaphragm to vibrate?

Q14. A magnet is surrounded by magnetic _____ of _____.

Q15. A magnet moving inside a coil _______ current in the coil.

Your Answers Should Be:

A11. Current flowing in phone lines at the time when no sound is present is **DC.**

A12. Current flowing during sound transmission is **AC.**

A13. A varying current develops a changing magnetic field which repels and attracts a magnet connected to a diaphragm.

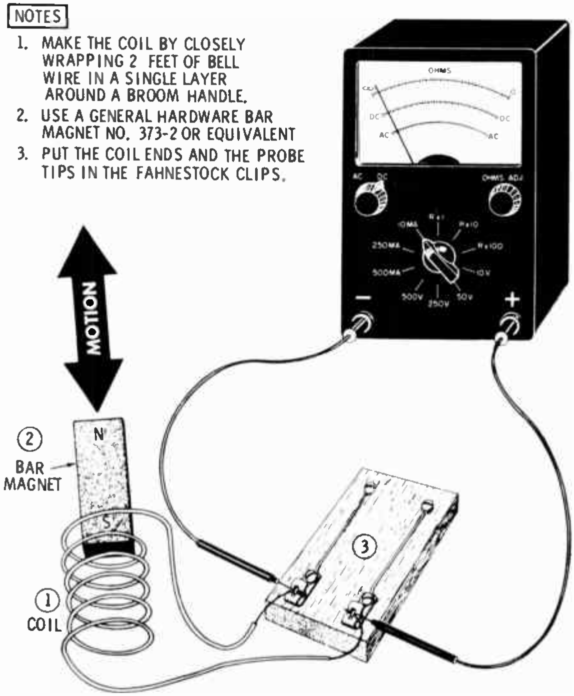
A14. A magnet is surrounded by magnetic **lines of force.**

A15. A magnet moving inside a coil **induces** current in the coil.

The induced current theory can be proved by performing the experiment shown below. A few microamps of current will be developed.

NOTES

1. MAKE THE COIL BY CLOSELY WRAPPING 2 FEET OF BELL WIRE IN A SINGLE LAYER AROUND A BROOM HANDLE.
2. USE A GENERAL HARDWARE BAR MAGNET NO. 373-2 OR EQUIVALENT
3. PUT THE COIL ENDS AND THE PROBE TIPS IN THE FAHNESTOCK CLIPS.

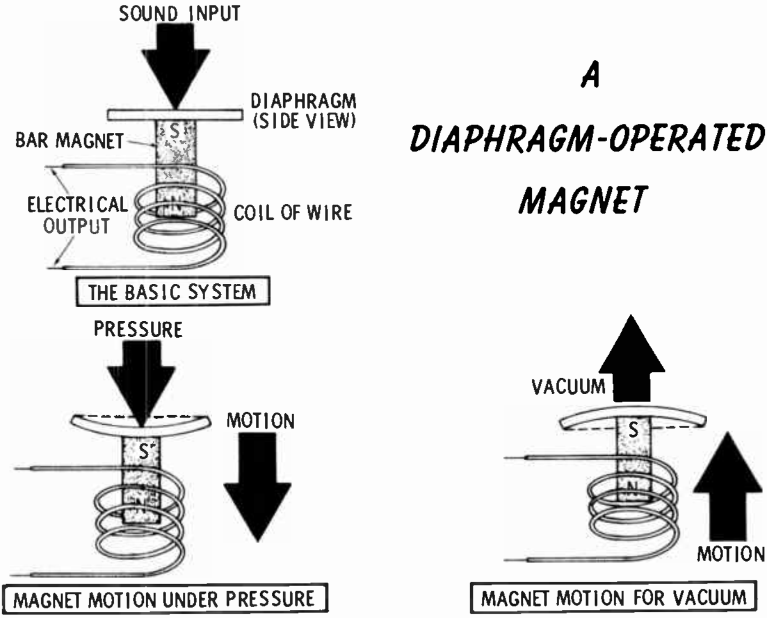


CREATING VOLTAGE AND CURRENT WITH A MAGNET

Sound-Powered Transmitter

The transmitter of a sound-powered phone makes use of the induced-current principle.

As shown below, a bar magnet is fixed to the center of a diaphragm. The diaphragm is fastened to the transmitter in such a way that the magnet is over the center of the coil.



A DIAPHRAGM-OPERATED MAGNET

As in other phones, this diaphragm vibrates at the frequency of the sound waves striking it. As it vibrates, the bar magnet moves back and forth within the coil. This induces a current which changes direction at the same frequency as the sound. If the transmitter is connected to a sound-powered receiver, current will flow back and forth through the circuit.

Q16. The amount of current induced in a coil can be increased in two ways. Describe them.

Q17. A sound-powered phone system (does, does not) have current flowing in the connecting lines during a silent period.

Q18. Why will the induced current in this system change at the same frequency as the sound?

Your Answers Should Be:

A16. Induced current can be increased by **adding more turns to the coil** or **increasing the magnetism of the magnet.**

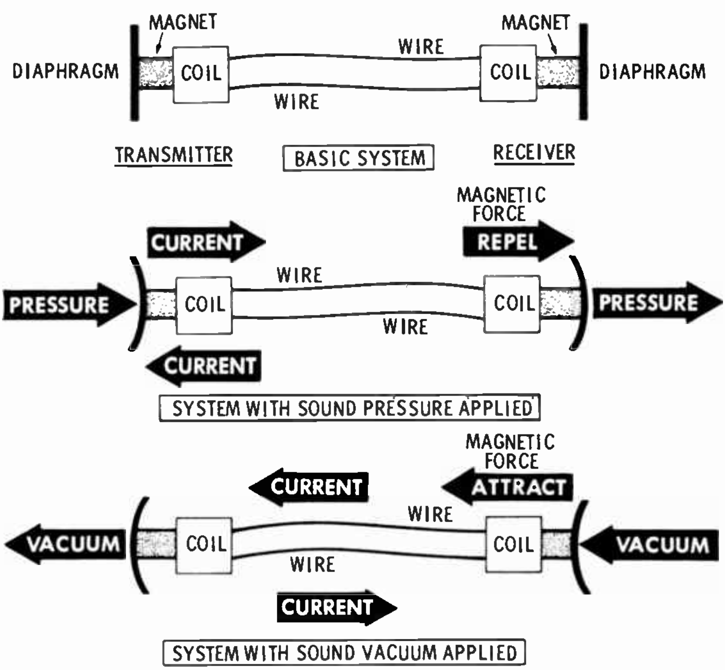
A17. A sound-powered phone system **does not** have current flowing in the connecting lines during a silent period.

A18. Induced current changes at the rate of the moving bar magnet. Since the magnet is fastened to the diaphragm, the induced current will change at the same frequency as the sound.

Sound-Powered Receiver

The mechanism in the receiver is identical to that in the transmitter—a coil, a magnet, and a diaphragm. Current flowing back and forth in the receiver coil develops a chang-

A BASIC SOUND-POWERED TELEPHONE SYSTEM



ing magnetic field. The bar magnet responds by moving back and forth at the same frequency as the current, causing the diaphragm to reproduce the original sound.

Sound-Powered System

The illustration on the opposite page shows the transmitter and receiver connected together as a working system.

The two bottom figures demonstrate how the induced current changes direction with the motion of the transmitter diaphragm. The corresponding effect upon the receiver diaphragm is also shown.

WHAT YOU HAVE LEARNED

1. A basic telephone system uses all the principles of a simple circuit.
2. The operating principle of any telephone system is the ability of the transmitter and receiver diaphragms to vibrate in unison. The transmitter is the cause and the receiver is the effect.
3. Sound vibrates at a frequency determined by its pitch.
4. Sound vibrations cause changes in air pressure.
5. Changes in air pressure cause a thin metal or plastic diaphragm to vibrate. A vibrating diaphragm also causes changes in air pressure, producing sound.
6. In a commercial phone system, a steady current flows through the circuit during periods of silence. This current is varied when sound waves strike the diaphragm, the resulting vibrations exerting and releasing pressure on carbon granules.
7. At the receiver end, the changing current produces a varying magnetic field which repels and attracts a magnet connected to a diaphragm. This action reproduces the original sound.
8. Another type of phone is the sound-powered system. This type uses induced current for signal transmission.
9. An alternating current is induced in a coil by the back-and-forth motion of a magnetic field.
10. A sound-powered transmitter develops an induced current caused by the vibrations of a diaphragm.

11. A sound-powered receiver uses a changing current to develop a varying magnetic field about a coil. The field vibrates a magnet connected to a diaphragm, the latter reproducing the original sound.

5

Reading Diagrams

What You Will Learn

Before proceeding with more complex circuits, you should learn how to read and draw diagrams used in electricity and electronics. There are many varieties of diagrams, but they have all grown from two basic types—wiring and schematic. The fundamentals of both will be explained.

THE REASON FOR DIAGRAMS

A textbook can be written without illustrations, but very few are. Words alone cannot fully describe the idea or thought the author wants the reader to understand. A writer uses drawings or illustrations with his words to make sure his descriptions are more completely understood.

Most of the illustrations used thus far in this book have been in three-dimensional form. A dry cell was drawn as it actually looks—in the shape of a cylinder and with its terminals in the correct positions. A lamp appeared similar to those in your home. Wires were drawn to look as natural as possible. The artwork was time-consuming but necessary.

However, can you imagine the task required to draw all of the circuits, parts, wires, and terminals of a television set in three-dimensional form?

The illustrations would not only be difficult to draw, but also awkward to use. Technical drawings are needed by engineers who design equipment, workers who construct it, and technicians who service it. They are also required by persons who study electricity and electronics.

Two-Dimensional Diagrams

Two-dimensional (flat instead of shaped) diagrams are now used almost exclusively because they are easier to "read." Reading a diagram means obtaining information from it, such as following the path of current through a circuit. Reading a two-dimensional diagram is simplified by eliminating unnecessary and confusing details. But reading this type of diagram is easy only if you understand the language.

The Language of Symbols

Electrical and electronic diagrams have symbols that either resemble or represent the real item. There are symbols (most of them rather simple) for every electrical or electronic part. When new parts are invented—such as the transistor—a corresponding, identifiable symbol is also developed.

Using symbols instead of cumbersome pictures is not new. Shortly after man emerged from the Stone Age, he found it difficult to work with his counting and numbering system. Making marks on the ground or stacking pebbles in a pile became fairly tedious when he wished to indicate "how many" of anything. Numeral symbols were invented to show how many. This permitted the ancient Arab who owned nine sheep and four horses to show on his inventory record the symbols "9" and "4" instead of a number of marks.

Learning electrical and electronic symbols requires the same process you used to learn the meaning of numerals. Learn what the symbols stand for and how to use them.

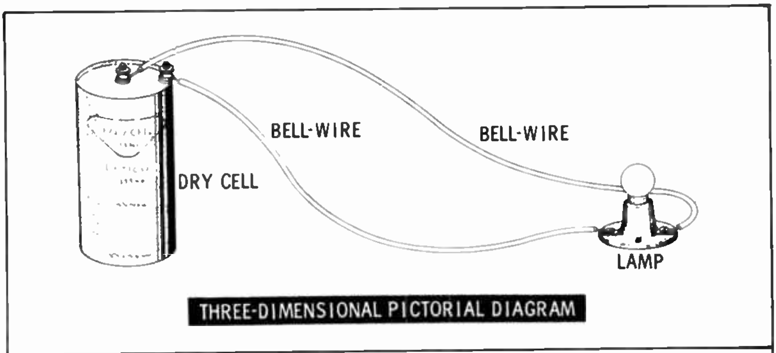
WIRING DIAGRAMS

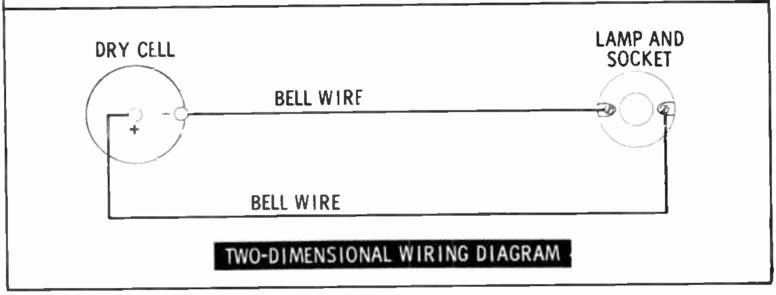
Wiring diagrams are used as a guide when constructing a circuit or equipment. They are also useful for locating wires or connections when servicing or troubleshooting.

Basic Wiring Diagrams

The fundamental wiring diagram shows a symbol for each part. Emphasis is placed on displaying the terminals of each part and the wire connections between them. A circuit can be easily put together by following a wiring diagram. As an example, compare the two diagrams on the next page.

LAMP CIRCUIT DIAGRAMS





Note how easy it would be to follow the two-dimensional diagram if you were to construct the circuit. The symbols are easily identifiable. The dry cell is a flat circle (top view) with terminals in the correct positions and polarity markings shown. The lamp symbol is two circles, a bulb in a base, plus two terminals. Wires are straight lines, and the parts are labeled.

Q1. The two basic types of electrical/electronic diagrams are ______ and __________.

Q2. Why are two-dimensional diagrams used in electricity and electronics? Give two reasons.

Q3. Reading a technical diagram requires an understanding of _______.

Q4. How does one learn the meaning of symbols?

Q5. Name two purposes of a wiring diagram.

Q6. Redraw the wiring diagram at the top of the page showing a knife switch placed in the circuit between the lamp and cell. Draw a side view of the switch.

Your Answers Should Be:

A1. The two basic types of electrical/electronic diagrams are **wiring** and **schematic.**

A2. Two-dimensional diagrams are used because they are **easier to draw** and **easier to read** than a three-dimensional diagram.

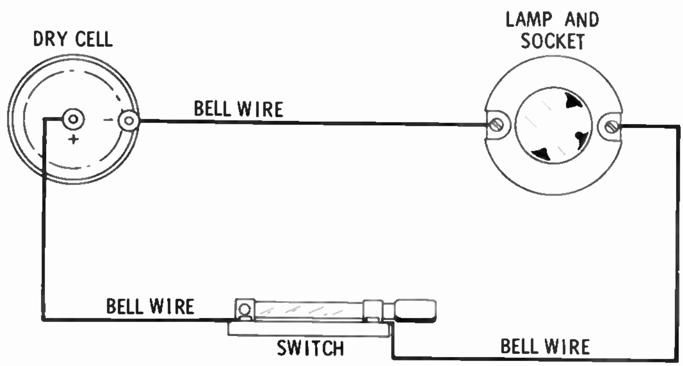
A3. Reading a technical diagram requires an understanding of **symbols.**

A4. One learns the meaning of symbols by learning what they stand for and then using them.

A5. Two purposes for a wiring diagram are:

1. **A guide for constructing a circuit or equipment.**
2. **A means of locating wires or connections in equipment.**

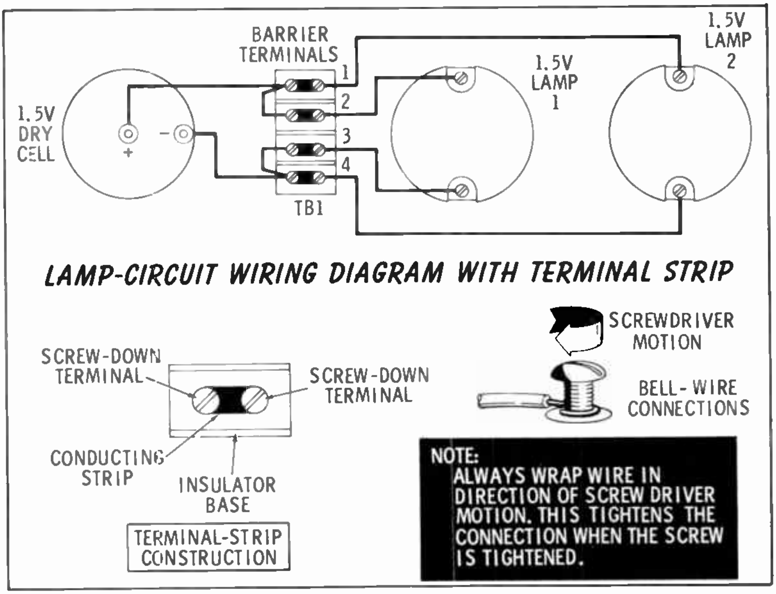
A6. Your drawing should be similar to this:



No two manufacturers will necessarily use identical symbols for the same part. Each symbol however, will be a close representation of the real thing. The switch symbol thus should show the terminals and make clear the difference between the open and hinged ends.

The illustration on the next page shows a wiring diagram for two 1.5-volt lamps connected to a 1.5-volt dry cell. You may construct it if you wish. The circuit is intended to demonstrate a principle of electricity.

You will note that the lamp symbol has been changed. A single circle is often used for this purpose.



LAMP-CIRCUIT WIRING DIAGRAM WITH TERMINAL STRIP

A new part has been added—a terminal board (TB1). As shown in its construction detail, a terminal board has a metal strip with two screws on either end, mounted on an insulating material. These boards serve as connecting points for wires.

The electrical principle demonstrated in the diagram above is that two lamps can be connected to a single voltage source. Since both lamps are connected across the voltage source (the top terminal of each lamp is wired to the positive pole and the bottom terminal to the negative pole), the lamps are said to be in **parallel**. This means the same voltage (1.5 volts) is being applied to each lamp.

Q7. What is the purpose of a terminal strip?

Q8. Two devices connected across a voltage source are in _________.

Q9. Redraw the above circuit, showing by means of arrows the direction of current flow in each wire.

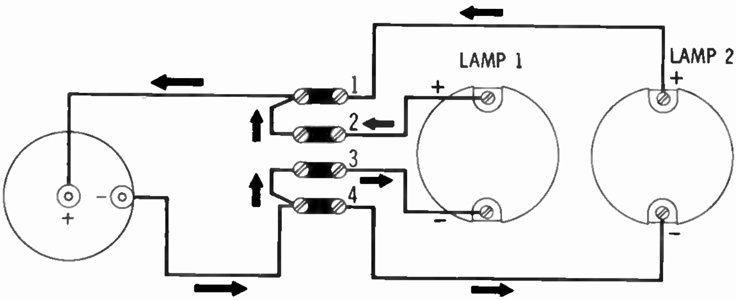
Q10. Remove lamp 1 from the circuit by disconnecting the wire at terminal 3. Will lamp 2 go out?

Your Answers Should Be:

A7. A terminal strip provides a means of securely joining two or more wires.

A8. Two devices connected across a voltage source are in **parallel.**

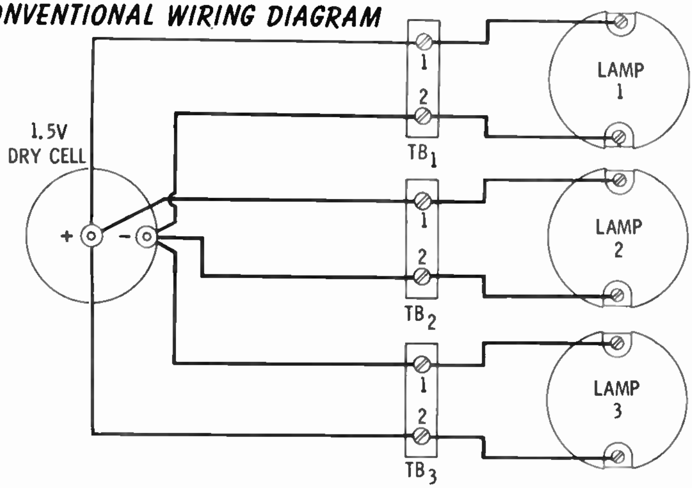
A9. Your drawing should look like this:



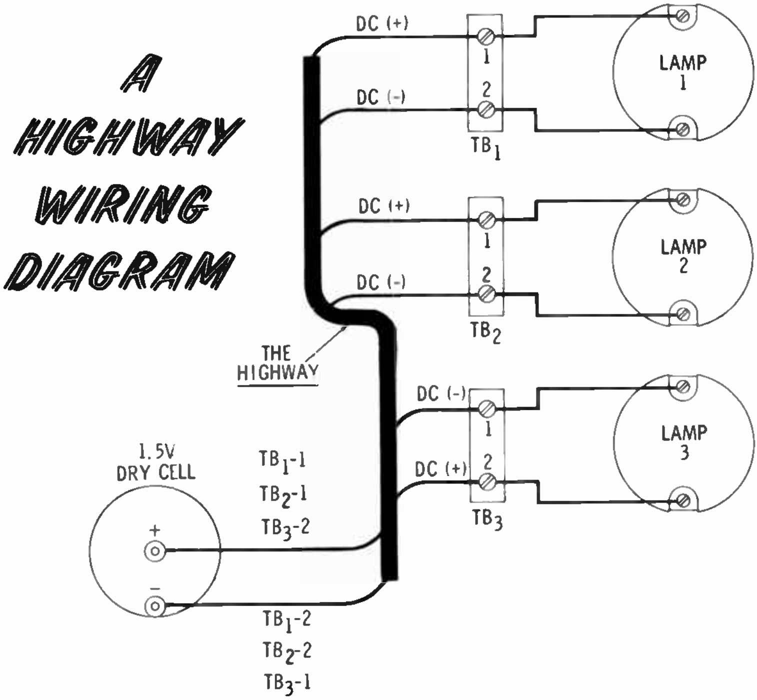
A10. **Lamp 2 will remain lit.** (Even though lamp 1 is removed from the circuit, lamp 2 is still across the source. If you guessed wrong, trace the path of current through the circuit.)

Multiwire Diagrams—The wiring diagram below shows three lamps in parallel.

CONVENTIONAL WIRING DIAGRAM



The Highway Wiring Diagram—Even with three lamps, the diagram is cluttered, and the lines are difficult to follow. **A highway wiring diagram** (it looks like a highway with secondary roads leading from it) removes the clutter. The same three lamps are redrawn below. Each wire entering the "highway" has its destination marked.



TB1 is the abbreviation for terminal board 1. TB2-1 (terminal 1 of terminal board 2) is positive and therefore connected to the positive pole of the cell. Although only two wires are shown connected to the cell, there are actually three at each pole as indicated by the TB listings.

Q11. To which pole of the dry cell is the wire from TB3-2 connected?

Q12. Which dry-cell terminal is connected to TB2-2?

Q13. What would the abbreviation TB4-3 mean?

Q14. Draw a wiring diagram showing only lamp 4 connected to TB4 with TB4-1 positive.

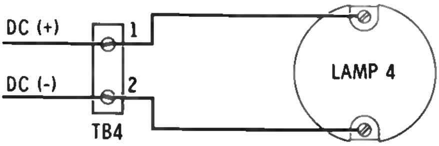
Your Answers Should Be:

A11. TB3-2 is connected to the **positive pole.**

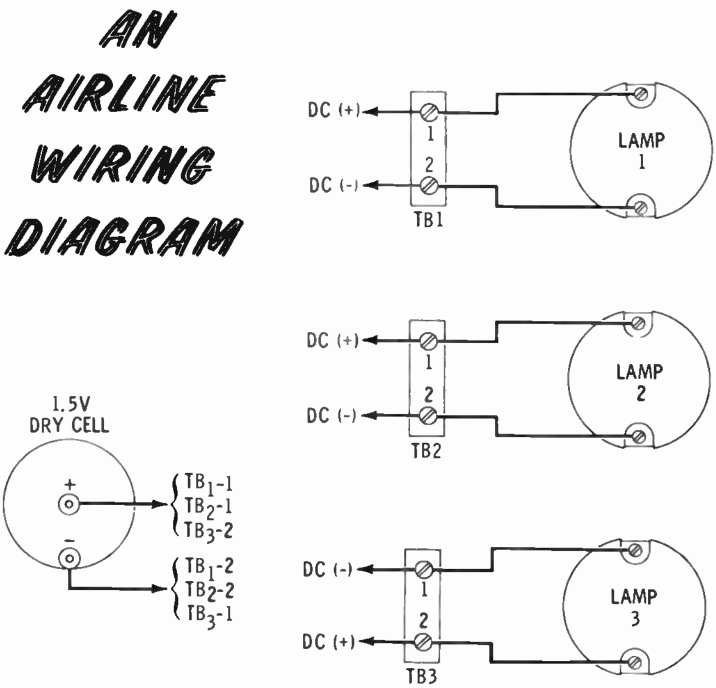
A12. The **negative terminal** of the dry cell is connected to TB2-2.

A13. TB4-3 would mean the **third terminal of terminal board 4.**

A14. Your wiring diagram should look like this:



The Airline Wiring Diagram—The airline wiring diagram shows wire destinations without a connection between terminals. This type of diagram is used in the same manner as the highway diagram.



SCHEMATIC DIAGRAMS

Schematic diagrams are used more than any other technical diagram in electronics. Engineers use **schematics** (the term "diagram" is usually dropped) when designing equipment and testing its performance after construction. Technicians and repairmen constantly refer to a schematic while servicing or troubleshooting equipment.

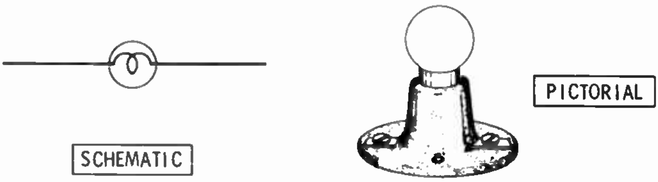
Information including a schematic is available for nearly every television set, radio, and other electronic equipment ever manufactured. These can be purchased at electronic supply stores and from mail order companies—the same source from which you purchase electronic components to repair or construct equipment.

The schematic is used in nearly all electricity/electronics textbooks. The reason for using this kind of diagram, of course, is the need for all future technicians and engineers to become familiar with the type of diagrams they will be using most often. Another reason is the clarity with which the schematic provides information. The many parts of a circuit, or group of circuits, can be drawn in a limited amount of space. The symbols used are fairly standard and do not vary as the representations do in wiring diagrams.

Symbols

Shown below is the schematic symbol for a lamp.

SYMBOLS FOR A LAMP



Q15. What is the difference between highway and airline diagrams?

Q16. Technicians use schematic diagrams to _______ and _____________ equipment.

Q17. Engineers use schematics to ______ and ____ equipment.

Q18. What does the curved line inside the symbol for a lamp represent?

Your Answers Should Be:

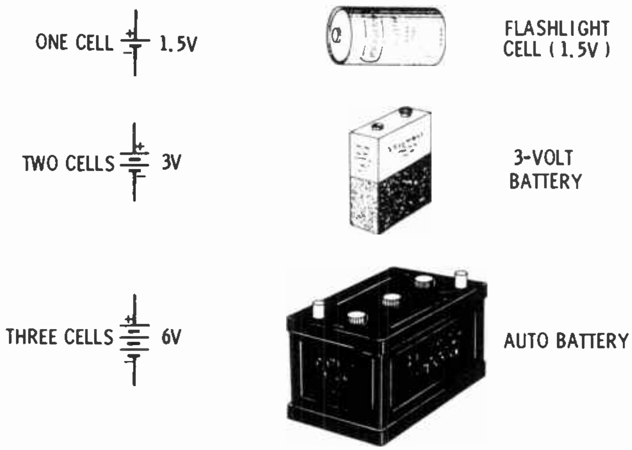
A15. A highway wiring diagram has a broad line (highway) drawn to each of the wires in the circuit. An airline diagram does not.

A16. Technicians use schematic diagrams to **service** and **troubleshoot** equipment.

A17. Engineers use schematics to **design** and **test** equipment.

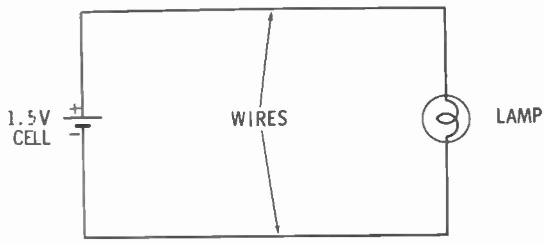
A18. The curved line inside the symbol for a lamp represents its **filament.**

Cells and Batteries—The symbol for a cell is two broad parallel lines, one shorter than the other, each with a perpendicular line attached. The broad lines represent the negative and positive materials (plates) in a cell. Since a battery contains two or more cells, its symbol is two or more pairs of plates—the standard symbol usually used is either two or three pairs. Since a battery may have any number of volts, the symbol is usually labeled with the voltage. It is also good practice to mark the polarity of the battery on the symbol, (—) for negative and (+) for positive.



SYMBOLS FOR CELLS AND BATTERIES

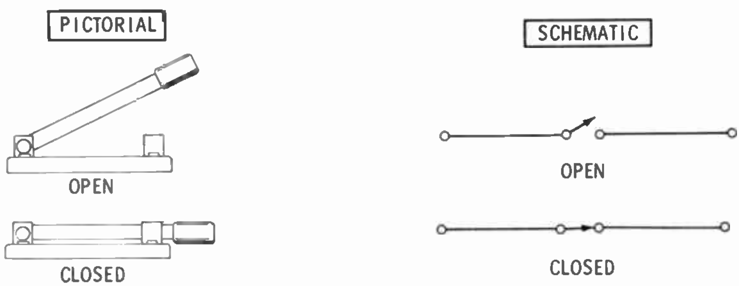
A Circuit Schematic—Now that you are familiar with the symbols for a voltage source and an operating device, you should be able to draw the schematic of a simple circuit. It should look like this:



The lamp and cell symbols are connected by lines representing wires. Note that the lines run in only two directions—horizontal and vertical. Slanted or curved lines lessen the clarity of a diagram. Also note that a voltage value and polarity markings appear on the cell.

Switches—The symbol for a simple switch is also suggestive of the original article.

SYMBOLS FOR A SWITCH



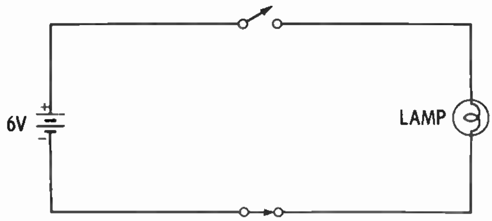
The arrowhead has no real significance other than helping to identify the symbol as a switch when it is shown in a closed position. Without the arrowhead, the symbol would look like a wire between two terminals.

Q19. Draw a schematic of a 6-volt battery and a lamp. Place an open switch in the line attached to the positive terminal and a closed switch in the line to the negative terminal.

Q20. Will current flow in this circuit?

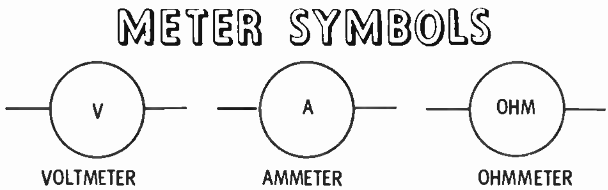
Your Answers Should Be:

A19. Your schematic should look like this:



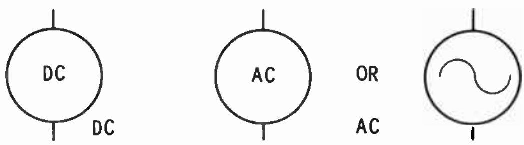
A20. Current will **not** flow in this circuit. The open switch breaks the path through which current would flow.

Meters—Meters are quite often inserted into circuits to monitor voltage and current. The **wattmeter** (a combination of a voltmeter and an ammeter) in your home is an example. It is often necessary to show on a schematic where a meter reading is being taken. The symbols for three types of meters are shown below.



You should recognize these meters as the three types built into a multimeter. They are also available as separate meters.

Voltage Sources—The battery symbol obviously represents a source of DC voltage. There are also other types of DC sources. The symbol for one of these, in addition to symbols for AC sources, is shown below.



SYMBOLS FOR AC AND DC VOLTAGE SOURCES

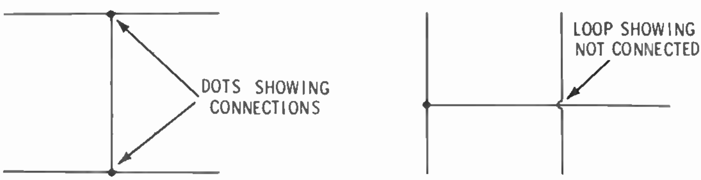
DC and AC voltages can be supplied by generators or developed by other methods. An example is the AC voltage developed by the vibrating diaphragm of a telephone. The basic symbol is the circle, with the letters DC or AC (to designate the type of voltage) placed inside. The second AC symbol includes a **sine wave** instead of letters. The sine wave in the circle represents the rise and fall of alternating voltage.

Coils—A coil symbol actually looks like the several turns of wire it represents. The symbol on the left is the most common version.

SCHEMATIC SYMBOLS FOR A COIL

Wire Connections and Crossings—Quite often one wire is connected to another. In a wiring diagram the terminal where the connection is made is shown. In a schematic, however, terminals are usually not indicated. In addition, it is sometimes necessary to show lines crossing each other. The following illustration shows how connections and crossings are indicated.

SYMBOLS FOR CONNECTING AND CROSSING WIRES



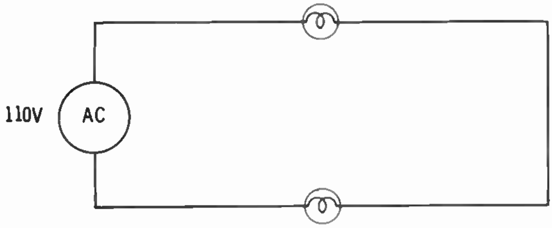
Series and Parallel Connections—In the discussion on wiring diagrams, two lamps were connected in **parallel.** Both were connected **across** the battery terminals. Devices can also be connected in **series,** like knots in a string. If two lamps are connected in series with a battery, the same current flows through both lamps.

Q21. Draw a schematic of two lamps and a 110-volt AC source, all connected in series.

Q22. Draw two lamps in parallel across a 12V DC generator. The second lamp is to be switched out of the circuit.

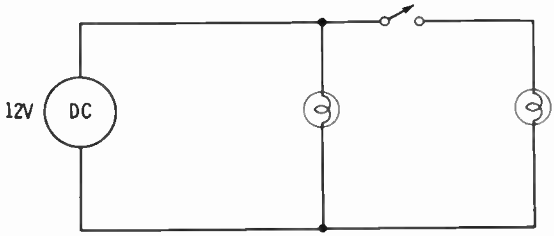
Your Answers Should Be:

A21. Your series circuit should look like this:



You may have used the other symbol for an AC source.

A22. Your parallel circuit should look like this:



The two lamps are in parallel across the generator. The open switch disconnects the second lamp. With the switch closed, both lamps will light. The dots show the points at which the wires are connected.

There are dozens of other symbols which will be shown at the time new parts or devices are introduced. The purpose of this chapter was to teach you the basic principles of how to read and draw simple diagrams. More complicated diagrams which include many different components will be used later as you gain more experience and become familiar with simple schematics.

As a summary of the fundamentals of schematics, how would you draw this circuit?

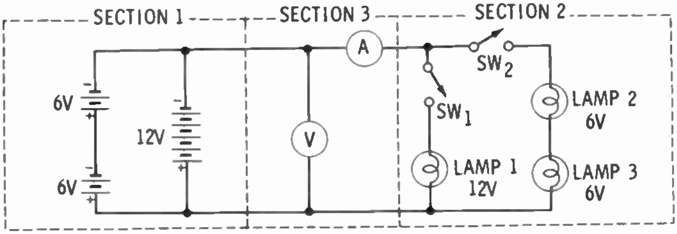
1. The voltage source is two 6-volt batteries (series-connected) in parallel with a 12-volt battery. The polarity of all three batteries is in the same direction.

2. The **load** (another term for operating devices) is two 6-volt lamps (connected in series) in parallel with a 12-volt lamp. The load is to be connected across the voltage source.
3. Switches are placed in the circuit so that each parallel **leg** (a separate current path) of the load can be switched on and off individually.
4. An ammeter and a voltmeter are placed in the circuit between the load and source.

The easiest and most accurate way to draw the schematic from the above description is in sections.

1. Section 1—the voltage source.
2. Section 2—the load with its switches.
3. Section 3—the meters between the load and source.

DRAWING A SCHEMATIC BY SECTIONS



As you recall, an ammeter is always connected in the circuit path. Therefore, the ammeter in the above illustration is placed in series with the source and the load. A voltmeter is always placed across (in parallel with) the load or source.

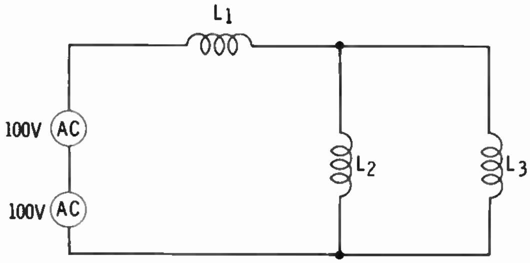
Q23. Draw a schematic for the following:

1. **Load—A coil in series with two coils in parallel. "L" is the symbol for a coil. Label the coils L_1, L_2, and L_3 in the order of their distance from the source.**
2. **Source—Two 100-volt AC generators in series.**

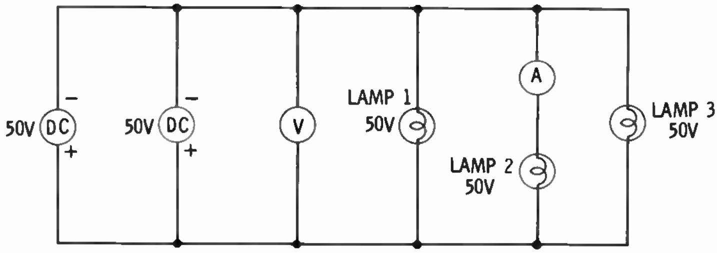
Q24. Draw a schematic for two 50-volt DC generators (in parallel) supplying voltage for three 50-volt lamps, also in parallel. Show a voltmeter to measure the source voltage and an ammeter to measure the current through lamp 2.

Your Answers Should Be:

A23. Your schematic should be similar to this:



A24. Your schematic should be similar to this:



WHAT YOU HAVE LEARNED

1. Technical diagrams are drawn with symbols to clearly present a great deal of information in a limited amount of space.
2. There are two basic types of diagrams generally used in electrical and electronic work. These two types are wiring and schematic diagrams.
3. Wiring diagrams are useful as a guide when detail is required for construction purposes.
4. Schematic diagrams with their simple symbols are widely used by engineers for designing and testing equipment, and by technicians for servicing and troubleshooting.
5. A fundamental or conventional wiring diagram shows each wire and a representative symbol for each part, and clearly defines each terminal.

6. When several parts must be included, an airline or highway wiring diagram is drawn. A highway diagram uses a broad line representing the many wires going to each terminal. All terminals are marked. An airline diagram contains the same details without the broad line.
7. Wiring diagrams usually contain too much detail for general use, other than construction. The most widely used diagram is called a schematic.
8. Symbols for circuit parts have been fairly well standardized. They are simple in detail and represent the actual article.
9. New electrical terms introduced were the circuit relationships of series and parallel connections. Parts are in parallel when their respective terminals are connected to the same point. Parts are in series when they are connected together in line.
10. Symbols were shown for several different parts or devices—lamps, cells, batteries, switches, meters, AC and DC sources, coils, and connecting wires.
11. You were shown how to draw schematics of both simple and complex circuits.

6

Understanding Resistors

What You Will Learn

Voltage, current, and resistance are closely related within a circuit. Where you find current, you find the other two. Current cannot flow unless there is voltage. How much will flow is determined by how much voltage and how much resistance are present in the circuit. You will learn what resistance is, what it does, and how it is used.

WHAT LIMITS CURRENT FLOW?

You have learned that voltage is a pressure which forces current to flow through a circuit. You also have learned that current has the ability to heat a lamp filament white-hot and thus produce light. But have you ever wondered why a 40-watt lamp produces less light than one rated at 100 watts? The amount of voltage pushing current through both lamps is the same. The answer, of course, is the individual characteristic of each lamp which limits the amount of current that will flow.

The 100-watt lamp glows more brightly because more current is allowed to pass through the filament, heating it to a higher degree, thus causing it to give off more light. Less current is allowed to flow through the 40-watt filament. The reason for the different amount of current through each of the two lamps is an electrical characteristic called **resistance.** Resistance **limits** or **controls** the flow of current.

WHAT IS RESISTANCE?

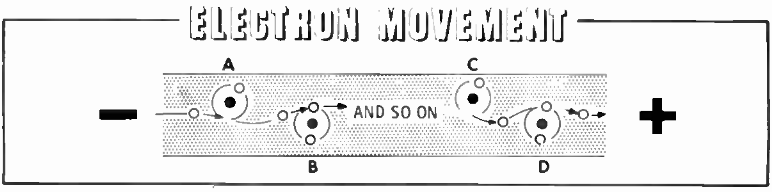
Resistance is a physical property of all materials and is directly responsible for the amount of current which will flow through a material with a given voltage applied.

Atomic Structure

All matter is made up of invisible particles called **atoms.** There are over 90 different atoms, or **elements,** as the physicist calls them. One of the features that makes one atom different from another is the number of **electrons** each contains. A hydrogen atom has one electron, an oxygen atom has eight, and an atom of uranium has 92.

You know that current is a flow of electrons and that electrons are made to move by a voltage. This does not mean that an electron leaves the negative pole of a battery and speeds around the circuit to the positive terminal. Instead, there is a general movement or drift of electrons throughout the complete circuit.

Below is a greatly magnified and exaggerated drawing of a length of wire with four atoms shown—A, B, C, and D. In the shortest possible length of a very thin wire there are actually many millions of atoms.



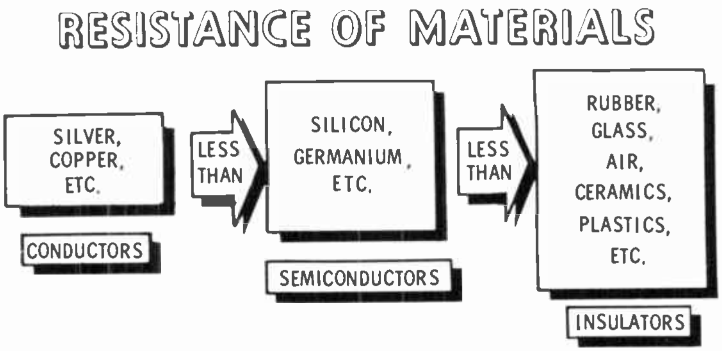
Electron Flow

As shown above, electrons orbit about the center of an atom. At the instant voltage is applied, two things happen simultaneously—negative voltage at one end of the wire pushes against the electrons, and positive voltage at the other end of the wire pulls them toward that end. In moving, electrons strike other electrons. One electron is bumped out of atom A, and it in turn pushes another out of atom B. At the positive end, an electron is pulled from atom D and another leaves atom C to replace it. The atoms of some materials give up their electrons more easily than the atoms of other materials.

Resistance of Materials

There is no perfect conductor. Even the best conductors, such as those having silver or copper atoms, resist the pressure to release electrons. On the other hand, the best insulators have atoms which, under conditions of sufficiently high voltage, give up some electrons. The resistance of a material, then, is **determined by its atomic structure.**

The size of the columns in the illustration below shows the comparative resistance of certain materials. Keep in mind that no material is a perfect conductor or a perfect insulator.



Most metals contain atoms that release electrons very easily. These materials, therefore, offer the least resistance to current flow. Insulators have the greatest resistance because their atoms resist the release of electrons. The in-between materials are neither good conductors nor insulators. Among these are certain materials, the **semiconductors**, from which **transistors** are manufactured.

Unit of Measurement—Resistance is measured in **ohms.** The resistance of the 1.5-volt lamp in the preceding experiment, for example, is approximately 6 ohms. In other words, the lamp offers 6 ohms of resistance to the electrical pressure of the 1.5-volt cell, and the result is a current flow of 0.25 amp.

Q1. What is the difference between a conductor and an insulator?

Q2. The resistance of a material is determined by its ______ structure.

Your Answers Should Be:

A1. Conductor atoms give up their electrons more eas- than insulator atoms.

A2. The resistance of a material is determined by its **atomic** structure.

Volts, Ohms, and Amperes

Since resistance limits the amount of current that flows and voltage forces an amount to flow, there must be some numerical relationship between them.

You would see current decrease to half its former amount when a second lamp is added in series with the lamp circuit. Current is divided by two when resistance is multiplied by two. Mathematicians say, then, that current is inversely proportional to resistance. In other words, **current decreases** by the same amount that **resistance increases.**

You can also discover, by experimenting, what happens to current when voltage increases. You will find they increase together (they are directly proportional to each other). This makes sense because the pressure of voltage causes current to flow. If the pressure increases, flow increases.

These relationships of voltage and resistance to current can be expressed in an arithmetic statement as:

$$\text{Current in a circuit} = \frac{\text{voltage applied to a circuit}}{\text{resistance of a circuit}}$$

Using mathematical symbols, this statement becomes:

$$I = \frac{E}{R}$$

where,

I is the current in amperes,
E is the voltage in volts,
R is the resistance in ohms.

If voltage (**E**) is increased, current (**I**) will increase. When **E** decreases, **I** also decreases. The relationship between **I** and **R** is just the reverse. A decrease in **R** causes **I** to increase. The larger **R** becomes, the smaller **I** will be.

Now that you know what resistance is, you are ready to learn about a device called a **resistor.**

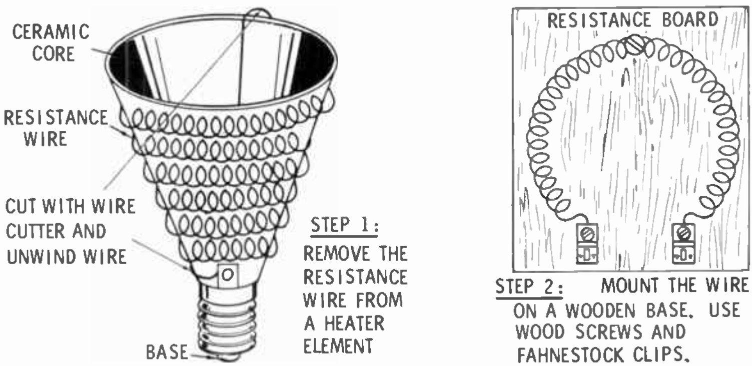
What Is a Resistor?

A resistor not only offers resistance to current flow but also has a specific value of resistance. A resistor has many uses, but its main purpose is to control current.

Making a Simple Resistor—Since you know that all materials have some resistance, you should be able to make a resistor having a desired value. The wire from a heating element is an economical material to use.

The element with its wire can be purchased from hardware or most variety stores. Unstretched lengths of the coiled wire can be obtained at an appliance repair shop. Replacement wire for heating elements is tightly coiled and looks very much like a spring. If you make the resistance board shown below using the tightly coiled wire, cut off a 2- or 3-inch length. Grasp the last turn on each end with pliers and gently stretch the coil until it is a foot long.

MAKING A SIMPLE RESISTOR



Q3. The unit used in measuring resistance is the ____.

Q4. When resistance remains the same, current will (increase, decrease) when voltage decreases.

Q5. With E constant, I will (increase, decrease) if R decreases.

Q6. Fifty volts is applied across 100 ohms. How much current will flow through the resistance?

Your Answers Should Be:

A3. The unit used in measuring resistance is the **ohm.**

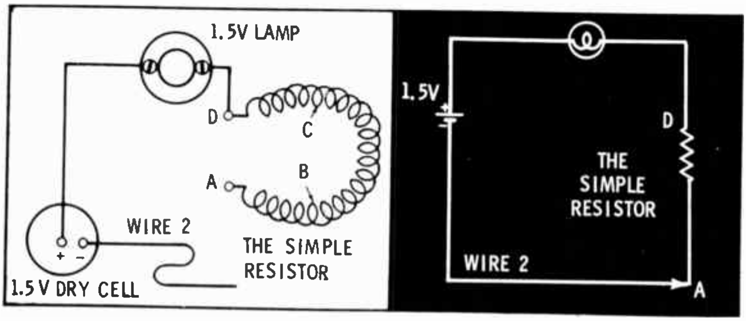
A4. When resistance remains the same, current will **decrease** when voltage decreases.

A5. With E constant, I will **increase** if R decreases.

A6. Fifty volts is applied across 100 ohms. The current that will flow is:

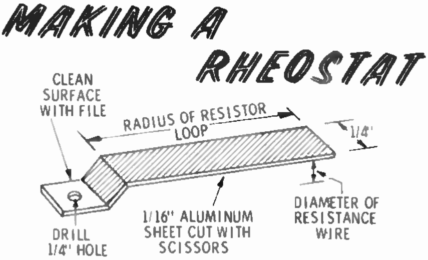
$$I = \frac{E}{R} = \frac{50 \text{ volts}}{100 \text{ ohms}} = 0.5 \text{ amp}$$

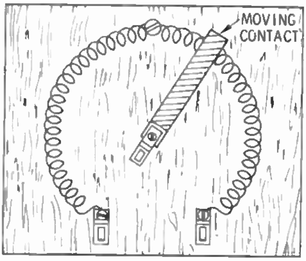
A Lamp-Control Circuit—The resistance board can be used as a means of controlling current in the familiar lamp circuit. Note the schematic symbol for resistance.



A Rheostat—A device that can be adjusted to provide a desired amount of resistance is called a **rheostat.** It has a moving contact that performs the function of moving wire 2 across the resistance from point A to D.

The diagram shows how the simple resistor would look if it were converted into a rheostat.

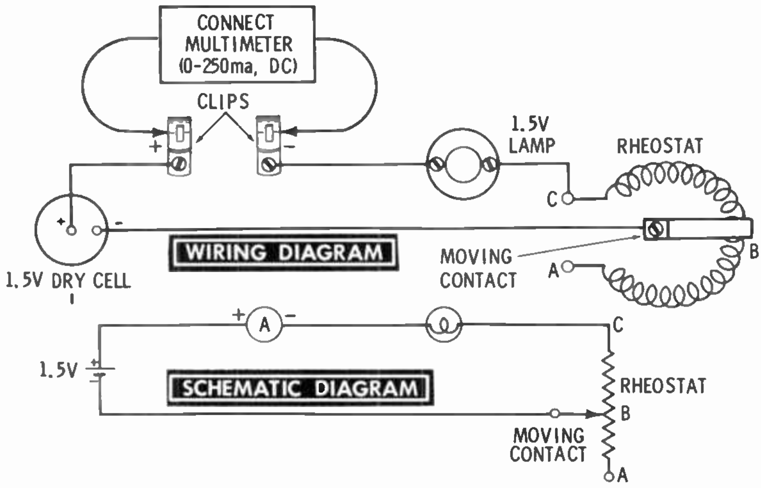




By inserting the rheostat into a circuit with one wire connected to the rotating arm and the other to one of the terminals, a desired value of resistance can be selected.

As you can see, the schematic symbol for a rheostat (variable resistor) is a combination of switch and resistor symbols. The arrow indicates that the value of resistance can be varied.

A Lamp-Control Circuit With Rheostat and Ammeter



Q7. A rheostat is a _________ resistor.

Q8. Draw the symbol for a rheostat.

For the remaining questions, use these data:

(a) The lamp and rheostat are the circuit load.

(b) Lamp resistance is 6 ohms; rheostat, 12 ohms.

(c) The resistance from point B to point C (see illustration above) is half the rheostat resistance.

Q9. What is the total resistance of the load?

Q10. Circuit current will be minimum when the moving contact is at point (A,B,C).

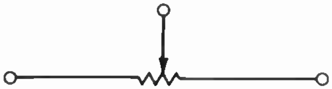
Q11. The lamp will glow brightest when the contact is at point (A,B,C).

Q12. How much current will be registered by the ammeter when the contact is at point B?

Your Answers Should Be:

A7. A rheostat is a **variable** resistor.

A8. The rheostat symbol is:



A9. The total resistance of the load is **18 ohms.** Six ohms (lamp) in series with 12 ohms (rheostat) equals 18 ohms.

A10. Circuit current will be minimum when the moving contact is at point **A.** (The entire resistance of the rheostat becomes part of the load.)

A11. The lamp will glow brightest when the contact is at point **C.** (The rheostat is no longer in the circuit and therefore offers no resistance.)

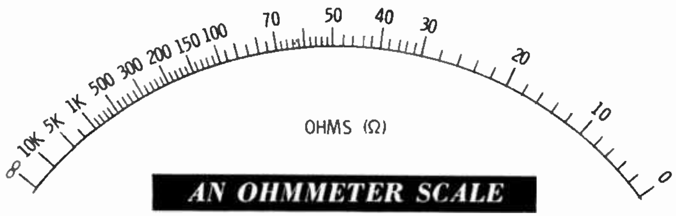
A12. **0.125 amp, or 125 milliamps.** (The contact selects six ohms of rheostat resistance which, when added to the six ohms of the lamp, produces a total load resistance of 12 ohms. 1.5 volts divided by 12 ohms equals the answer.)

MEASURING RESISTANCE

Like voltage and current, resistance can be measured with a meter. In fact, you have already learned that an **ohmmeter** is part of a multimeter.

The Ohmmeter Scale

An ohmmeter scale is labeled either OHMS or with the Greek letter omega (Ω). Instead of writing the word "ohm" after the numerical value of a resistance, the omega symbol is often used. A typical OHMS scale is shown below.



AN OHMMETER SCALE

Meter Scale—The meter scale reads from zero to infinity, as indicated by the symbol ∞. Because it is so great, infinity has no numerical value. The "K" on the scale stands for 1,000; therefore, 5K equals 5,000 ohms.

Zero is on the right of the scale instead of the left as it is for voltmeter and ammeter readings. As you remember, the meter pointer moves across the dial a distance that is proportional to the amount of current flowing through the meter. If there is zero current when taking a current or voltage measurement, the pointer remains at the left on 0. Maximum voltage or current readings cause the pointer to rest on the right end of the respective scales.

How the Meter Measures—The ohmmeter measures the value of a resistance by passing current through the resistance. The amount is measured by the meter. The smallest resistance allows the most current to flow. Therefore, zero ohms is at the maximum position of pointer swing—at the right. Maximum resistance permits the least meter current to flow. Therefore ∞ is on the left.

> NOTE: As mentioned previously, there are no resistances that are perfect insulators or perfect conductors. Zero and ∞ have been selected arbitrarily as the two extreme scale markings. Each scale must have a maximum and a minimum point. These points are 0 to ∞.

Reading the Scale—The ohmmeter scale is read in the same manner as the voltage and current scales. If the pointer stops on a numbered division, that number represents the value in ohms. Between numbers, you determine the value of each division mark. Multiply this by the number of marks to the pointer and add to the lower number. For example, there are five divisions between 40 and 50. The pointer rests on the third division past 40. The entire distance is 10, so each division is worth 2. Three 2's are 6 which, when added to 40, provide a meter reading of 46 ohms. Near the left (upper) end of the scale, numbers are close together. A reading here can only be an estimate.

Q13. The pointer rests on the second of five divisions between 500 and 1K. What is the value of resistance?

Your Answer Should Be:

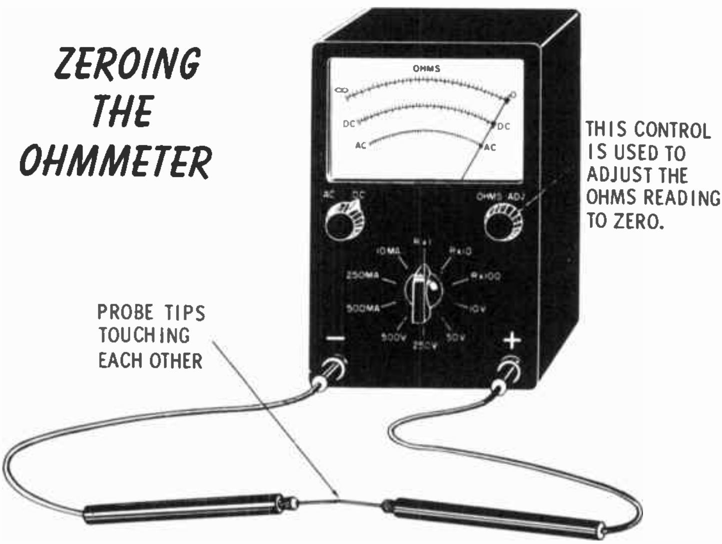
A13. The resistance is **700 ohms.** The value between the numbers is 500 (1000 — 500). Each of the five divisions is therefore worth 100. Two divisions of 100 each added to the lower number (500) equals 700.

Calibrating the Ohmmeter

The ohmmeter must be calibrated, or "zeroed," before accurate resistance measurements can be made.

The zeroing procedure is as follows:

1. Set the function selector to R × 1.
2. Touch the meter probes together. The pointer will rest close to, but not at 0 on the scale.
3. Slowly vary the OHMS ADJ control until the pointer rests on 0.



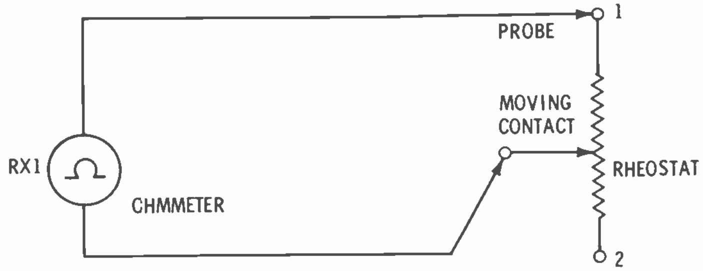
The ohmmeter is now zeroed and a resistance measurement can be made. The pointer should swing back to infinity when the meter is not in use and the probes are not touching each other.

Resistance Measurements

Resistance measurements are made by touching the meter probes to the terminals of the unit to be measured. **Never make a resistance measurement when the circuit under test is operating.** Current from the operating circuit will enter the test leads and damage the meter.

The schematic diagram below shows how an ohmmeter is used to measure the resistance of a rheostat.

MEASURING THE RHEOSTAT RESISTANCE



If the rheostat contact is at terminal 1 and the meter has been properly zeroed, the resistance reading should be zero ohms. Leaving the probes connected, the meter will show the gradual increase of resistance as the contact is moved toward terminal 2. At terminal 2 the total resistance of the rheostat will be read on the meter scale.

If this experiment is conducted with a properly designed rheostat, ¼ of the total resistance will be read when the contact travels ¼ of its total rotation, ½ at the halfway point, and so on. This shows that resistance is proportional to the length of the material. If a 12-inch length of wire measures 12 ohms, a 1-inch piece of the same wire will measure one ohm.

Q14. After you set the function selector switch to the proper position, how do you complete the procedure of zeroing an ohmmeter?

Q15. Before making a resistance measurement in a circuit, what should you determine first about the circuit?

Q16. One yard of wire measures two ohms. How many ohms will 10 yards of the wire measure?

Your Answers Should Be:

A14. The remainder of the zeroing procedure is: **Touch meter probes together and slowly adjust the OHMS ADJ control until the pointer reads 0.**

A15. Check the circuit to be sure that it is **not operating.** If it is, turn it off or disconnect it from the voltage source.

A16. If one yard of wire measures two ohms, 10 yards will measure **20 ohms.**

Hot and Cold Resistance

In some cases a resistance taken with an ohmmeter will not be the true resistance of the device when it is operating in a circuit. A lamp is a good example. It gives off light because current has raised the temperature of the filament to a white-hot level. The physical structure of most materials is such that their resistances will increase with a rise in temperature.

This is particularly true of wire used for lamp filaments. When hot, the resistance of the wire to current flow is higher than it is at room temperature. In materials where heat is a factor, there is a hot and a cold resistance.

Cold Resistance—Cold resistance is an ohmmeter measurement. It is taken when operating current is not passing through the device and therefore not heating the resistance. Cold resistance cannot be used to determine current that will be drawn by a heat-generating device.

Hot Resistance—Hot resistance is the true operating resistance of the heated wire or material. It is this resistance that determines the amount of current flow. Because current is determined by the hot resistance, and because current and resistance are inversely proportional to each other, the value of hot resistance can be determined by:

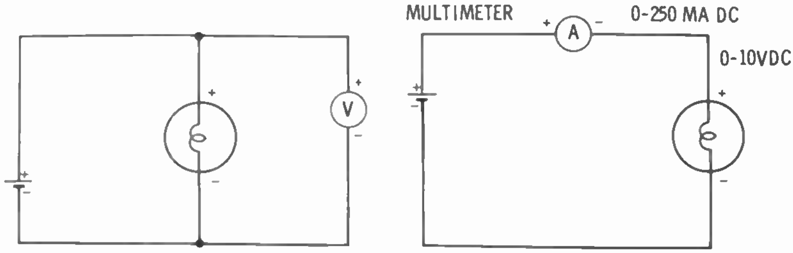
$$\text{Hot (operating) resistance} = \frac{\text{voltage applied}}{\text{current flowing}}$$

You should note that this is just another way of stating the formula, current equals voltage divided by resistance.

Determining Hot Resistance

Since you must know voltage and current values to determine hot resistance, use the following method.

THE VOLTMETER-AMMETER METHOD OF MEASURING RESISTANCE



STEP 1. MEASURE THE VOLTAGE APPLIED TO THE DEVICE

STEP 2. MEASURE THE CURRENT DRAWN BY THE DEVICE

STEP 3. COMPUTE:

$$\text{OPERATING RESISTANCE} = \frac{\text{VOLTAGE APPLIED}}{\text{CURRENT DRAWN}}$$

This method of measuring resistance is called the **voltmeter-ammeter method.** Using this method you will find that the dry cell measures very close to 1.5 volts and the current very near 200 milliamps (0.2 amp). In this case, the resistance will be 7.5 ohms. The arithmetic statement says that if you divide volts by amperes the answer will be the value of the heated resistance in ohms.

Using the cold-resistance method (ohmmeter measurement) you would probably find the lamp resistance to be 6 ohms or less.

Q17. Cold resistance is usually (higher, lower) than hot resistance.

Q18. A heated wire will pass (more, less) current than the same wire when it is cold.

Q19. Redraw the two schematics above into one to show the voltmeter-ammeter method with both meters in the circuit at the same time.

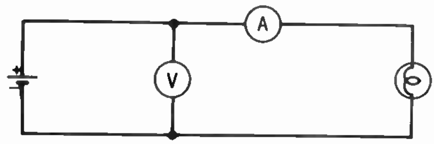
Q20. If the ammeter reads 0.5 amp and the voltmeter 9 volts, what is the hot-resistance value?

Your Answers Should Be:

A17. Cold resistance is usually **lower** than hot resistance.

A18. A heated wire will pass **less** current than when it is cold.

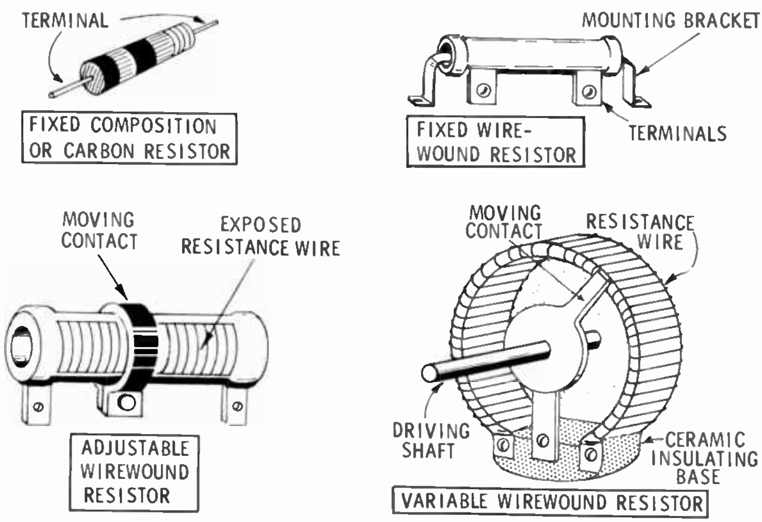
A19. Your schematic should look like this (voltmeter in parallel and ammeter in series with the circuit):



A20. Operating $R = \frac{E\ \text{applied}}{I\ \text{drawn}} = \frac{9}{0.5} = \mathbf{18\ ohms}$

TYPES OF RESISTORS

Resistors are classified in two ways: (1) in terms of their construction (wirewound and composition), and (2) in terms of their type or function (fixed, adjustable, variable).



TYPES OF RESISTORS

Wirewound Resistors

Wirewound resistors are made by wrapping resistance wire around a ceramic or other high-insulation cylinder. The assembly is then covered with enamel glaze and baked. The wire has a known value of ohms per inch. The resistance value desired is then merely a matter of wrapping on the required length of wire.

Composition or Carbon Resistors

Composition or carbon resistors are molded from a paste consisting of carbon (a conducting material) and a filler. Terminal wires (sometimes called **pigtails**) are inserted into the paste before it hardens. The resistor is then covered with a plastic coating. The resistance of a composition resistor is determined by the ingredients (percentage of carbon) and its diameter and length.

Fixed Resistors

A fixed resistor has only one nonvariable ohmic value.

Adjustable Resistors

Adjustable resistors provide a range of resistance within the limits of their total value. When placed in a circuit, the sliding contact can be positioned and secured to accurately provide the required resistance value. This type of resistor is not designed to be continuously variable.

Variable Resistors

Variable resistors are designed for continuous adjustment. A shaft to control the resistance value is usually connected to a knob on the front panel of an electrical or electronic device. The volume control of your radio or TV set is an example.

A rheostat is a variable resistor. The material that the moving contact presses against may be either resistance wire or a carbon mixture.

Q21. Composition resistors are made from a ______ and ______ mixture.

Q22. The control that dims the dashboard lights in an automobile is a(an) _________ resistor.

Q23. _____ and ___________ resistors are not designed to be continuously variable.

Your Answers Should Be:

A21. Composition resistors are made from a **carbon** and **filler** mixture.

A22. The control that dims the dashboard lights in an automobile is a **variable** resistor.

A23. **Fixed** and **adjustable** resistors are not designed to be continuously variable.

Resistor Applications

Typical applications for each kind of resistor are presented below.

RESISTOR APPLICATIONS

Type	Applications
Composition or Carbon	Composition resistors are the least expensive of the types discussed. They are, therefore, the type most widely used. However, composition resistors have certain limitations. They cannot handle large currents, and their measured values may vary as much as 20% from their rated resistance.
Wirewound	Wirewound resistors are more expensive to manufacture. They are used in circuits which carry large currents or in circuits where accurate resistance values are required. Wirewound resistors can be made to within 99% or better of the desired value.

RESISTOR POWER RATINGS

As you already know, current passing through a resistor generates heat. If too much heat is generated, the resistor will be damaged. Wire in the wound resistor will melt and become open, or some of the carbon in the composition resistor will burn away.

The current-carrying capacity of a resistor is rated according to the amount of heat it can safely release in a given period of time. A resistor cannot be used in a circuit where current causes heat to build up faster than the resistor can dissipate it. When such a condition exists, the resistor may become so hot that it will be destroyed. Even if the resistor doesn't melt and become open, the excessive heat may cause a permanent change in its resistance value. In addition, heat from the overloaded resistor may damage other components that are near by.

Since heat is a form of energy, the heat-releasing rate of a resistor is measured in energy units. The unit is a watt. A 100-watt lamp dissipates 100 watts of heat. In the process, the lamp also gives off light.

Heat energy depends on the amount of current flowing through a resistor. The arithmetic involved is:

$$\text{Heat energy in watts} = (\text{current in amps})^2 \times (\text{resistance})$$

This means that the number of watts dissipated by a resistor can be found by multiplying the resistance in ohms times the square (a number multipled by itself) of the current in amperes. The electrical term for heat energy is **power.**

For example, a 10-ohm resistor has three amps flowing through it. What must be its power rating in watts?

$$\text{Power} = (\text{amps})^2 \times (\text{ohms}) = (3)^2 \times (10) = 90 \text{ watts.}$$

Composition resistors usually come in power ratings of ¼ watt, ½ watt, 1 watt, and 2 watts. If larger power ratings are required, wirewound resistors are used.

A design engineer determines the value of resistance needed and the amount of current that will flow through it. He then specifies the resistor wattage that must be used. If the value falls between two of the ratings mentioned above, he selects the higher rating.

Q24. Which of the standard composition-resistor ratings would you select for a resistor of 10 ohms through which 1/10 of an amp flows?

Q25. A 1-watt wirewound resistor (will, will not) safely carry more current than a 2-watt composition resistor.

Your Answers Should Be:

A24. Power $= \left(\frac{1}{10}\right)^2 \times 10 = \frac{1}{100} \times 10 = \frac{1}{10}$ watt

The next highest standard rating is a **¼-watt** resistor.

A25. A 1-watt wirewound resistor will **not** safely carry more current than a 2-watt composition resistor.

RESISTOR TOLERANCE

As mentioned previously, a resistor will rarely measure the exact number of ohms specified by its label. The amount it will vary is called **tolerance.** Every resistor has a tolerance rating.

Resistor tolerance is given as a **percentage value** which indicates the amount that a resistor may vary above or below its labeled value. Standard tolerances for composition resistors are 5%, 10%, and 20%. Wirewound resistors may have tolerances as low as one or two percent.

Try a 1,000-ohm, 10% tolerance resistor as an example. Ten percent of 1,000 is 100 ohms. The tolerance factor thus indicates this resistor will measure somewhere between 100 ohms above and 100 ohms below the labeled value of 1,000 ohms. This is a range from 900 to 1,100 ohms. The same resistor with a 20% tolerance will have a true ohmic value somewhere between 800 and 1,200 ohms.

If you have trouble working with percentages, here is another way of computing tolerance:

$$\text{Resistance variation} = \frac{\text{rated resistance} \times \text{tolerance}}{100}$$

The answer will be the number of ohms the resistor may vary above and below its labeled value. For example:

$$\text{Resistance variation} = \frac{2{,}000 \text{ ohms} \times 10}{100}$$

$$= \frac{20{,}000}{100} = 200 \text{ ohms}$$

A 2,000-ohm resistor with a 10% tolerance may vary as much as 200 ohms above or below—1,800 to 2,200 ohms.

Resistor tolerance is not an indication of poor manufacturing. Closer tolerances can be achieved, but at greater expense. As you will discover, for a given ohmic value a 20% tolerance resistor costs less than one rated at 10%. And a 10% tolerance resistor is less expensive than one rated at 5%.

Required resistor tolerance depends on circuit design. If current flow must be controlled within very close limits, the engineer specifies a 1% resistor. On the other hand, a 20% tolerance is satisfactory for circuits which have less critical operating requirements. Your radio or television set, for example, has more 20% resistors than all the other tolerances combined.

PURCHASING RESISTORS

When purchasing fixed-value resistors, describe each by its four characteristics:

1. Type (composition or wirewound).
2. Value (in ohms).
3. Tolerance (5%, 10%, or 20%; 1% if wirewound).
4. Power rating (¼, ½, 1, or 2 watts). For higher wattages, wirewound resistors must be used.

Q26. Resistance limits the flow of _______ in a circuit.

Q27. Conductors have (low, high) resistances. Insulators have (low, high) resistances.

Q28. A resistor is a device that has a specific value of __________.

Q29. If 100 volts is applied across a 25-ohm resistor, how much current will flow?

Q30. A(an) ________ is used to measure resistance.

Q31. If 100 volts will force 2.5 amps through a device, what is the resistance of the device?

Q32. If 0.2 amp flows through a 50-ohm resistor, how much power (in watts) will it dissipate?

Q33. What is the lowest value in ohms you would expect to measure in a 5K resistor having a 5% tolerance?

Your Answers Should Be:

A26. Resistance limits the flow of **current.**

A27. Conductors have **low** resistances. Insulators have **high** resistances.

A28. A resistor is a device that has a specific value of **resistance.**

A29. **4 amps.**

A30. An **ohmmeter** is used to measure resistance.

A31. **40 ohms.**

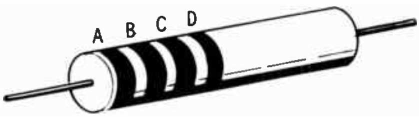
A32. **2 watts.**

A33. **4,750 ohms.** (K = 1,000)

RESISTOR COLOR CODES

Wirewound resistors normally have their value in ohms and tolerance in percent stamped on them. For carbon or composition resistors a **color code** is used.

For several years, resistance values have been coded by three colored bands painted around the body of the resistor. If the tolerance is either five or ten percent, a fourth color band is added. Position of the bands is shown below.



COLOR BANDS INDICATE RESISTANCE VALUE

Colors and Numbers—Each of the colors represents one of the ten digits—0 through 9.

Color	Number	Color	Number
Black	0	Green	5
Brown	1	Blue	6
Red	2	Violet	7
Orange	3	Gray	8
Yellow	4	White	9

The order of reading the bands is from the end of the resistor toward the middle.

The first two colors (A and B in the illustration) indicate the first two digits in the resistance value. The third band (C) indicates the number of zeroes that follow the first two digits. Sometimes a fourth band (D) is present. This band indicates tolerance and will be either gold or silver. A gold band denotes 5% tolerance, silver 10%, and no fourth band, 20%. Here is an example in reading the first three bands:

Band	A	B	C
Color	Blue	Red	Orange
Numbers	6	2	3 zeroes

The blue-red-orange bands signify 62 followed by three zeroes and would be read as 62,000 ohms. Another example:

Band	A	B	C
Color	Violet	Green	Red
Numbers	7	5	2 zeroes

Digits seven and five are to be followed by two zeroes. Combined to form a number, they read 7,500 ohms. Although rare, you may find a resistor with the following colors:

Band	A	B	C
Color	Violet	Green	Black

The resistance value is not 750 ohms. The third band specifies the number of zeroes. Black decoded is zero. So there are **no** zeroes after the first two digits, indicating a value of 75 ohms.

If black appears as the second color, it is read as a digit. Brown-black-red, for example, reveals that the composition resistor has a value of 1,000 ohms.

Q34. The color bands are read from the ___ toward the ______ of a resistor.

Q35. The first two bands are decoded as ______.

Q36. The third band indicates the number of _____.

Q37. Decode brown-black-green.

Q38. Decode blue-red-red.

Q39. What is the color code for a 10K resistor?

Q40. Decode orange-green-brown-silver.

Your Answers Should Be:

A34. The color bands are read from the **end** toward the **middle** of a resistor.

A35. The first two bands are decoded as **digits.**

A36. The third band indicates the number of **zeroes.**

A37. Brown-black-green decoded is **1,000,000 ohms.**

A38. Blue-red-red decoded is **6,200 ohms.**

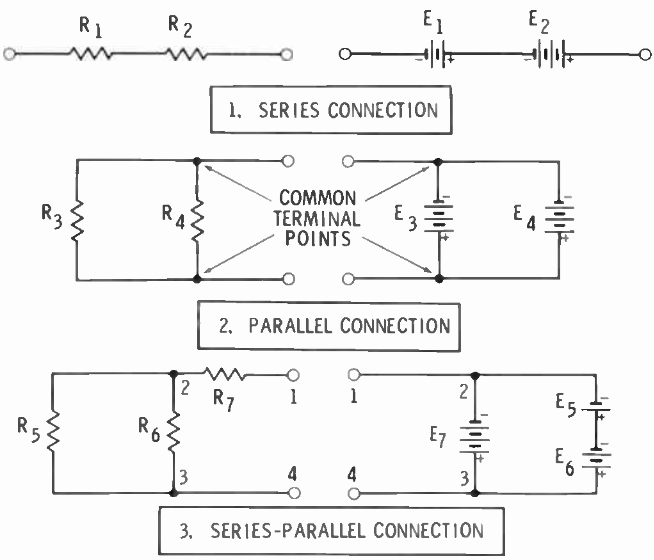
A39. **Brown-black-orange.**

A40. **350 ohms, 10% tolerance.**

RESISTOR CONNECTIONS AND CIRCUITS

There are only three different ways in which electrical or electronic parts may be connected—**series, parallel,** and **series-parallel.**

THE THREE BASIC CIRCUIT CONNECTIONS



The illustration shows the three different connections and also the accepted method for labeling components. R stands for resistor; E designates a voltage source. Numbers are used with the letters to identify a specific component.

Series Connection

The first figure on the opposite page shows components in series. A terminal of one component is connected to a terminal of the other. Since they are connected together in a line, R_1 is in series with R_2. Voltage sources may also be series-connected. E_1 is in series with E_2.

Parallel Connection

The second figure shows components connected in parallel. Each terminal of one component is connected to a terminal of the other. The connections are called **common terminal points.** R_3 is in parallel with R_4; E_3 is in parallel with E_4. In parallel, one component is connected **across** the other.

Series-Parallel Connection

As the third figure shows, series and parallel connections are combined to form a series-parallel arrangement. Two different combinations are illustrated. R_7 is in series with the parallel combination of R_5 and R_6. E_7 is in parallel with the series combination of E_5 and E_6.

Circuit Tracing

The method of determining the manner in which parts are connected within a circuit is called **circuit tracing.** Visualize how current would flow as you follow its path.

In the first figure on the opposite page, the same current that flows through R_1 must also flow through R_2. Current supplied by E_2 must flow through E_1 and add to the current generated by E_1. In the second figure, current is traced to one of the common terminal points. Here it must divide and flow through each **leg,** the name given to a parallel circuit path. Some of the current flows through R_3 and the rest through R_4, both currents joining again at the other terminal. Current from the E_3 and E_4 legs unite at one terminal and separate upon returning to the other terminal.

Q41. In the third figure on the opposite page, current flows through R_7. At terminal 2 it divides and flows through both ____ of the ________ connection.

Q42. In the voltage source portion, __ and __ are connected in series.

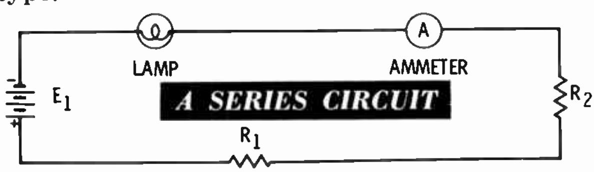
Your Answers Should Be:

A41. At terminal 2 the current divides and flows through both **legs** of the **parallel** connection.

A42. In the voltage source portion, E_5 and E_6 are connected in series.

SERIES CIRCUITS

If all the components in a circuit are connected one after the other, it is called a **series circuit.** By circuit tracing, you can show that in the circuit below, the same current that leaves E_1 flows through the lamp, the ammeter, R_2, R_1, and returns to E_1 again. Therefore, the circuit must be a series type.



A SERIES CIRCUIT

Current in a Series Circuit

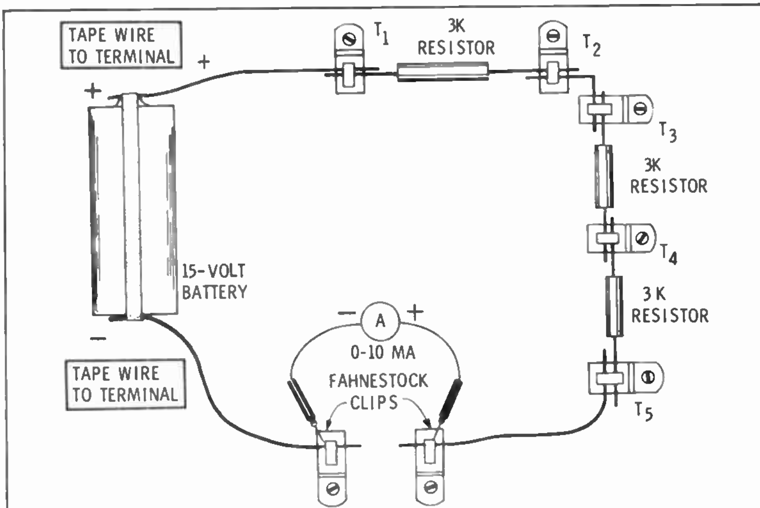
It can be proved that the value of current remains the same in all parts of a series circuit by constructing the circuit on the next page. Fahnestock clips are used as terminal connections.

If the current is measured by connecting the ammeter as shown, the reading should be between 1.6 and 1.7 milliamps. This is the value of the current entering terminal 5.

Connecting the ammeter in series with the two resistors at terminal 4, another reading may be taken. Remember, an ammeter must always **be in series** with the circuit in which current is being measured. In this case, T4 is disconnected and each resistor terminal reconnected to one of the ammeter clips. The reading will again be 1.6 or 1.7 milliamps. The same results will be obtained at terminals T3, T2, and T1.

Resistance in a Series Circuit

Total resistance in a series circuit is equal to the **sum of the resistances** of each of its parts.



RESISTANCES IN SERIES

This is logical, because the total resistance in the circuit determines the amount of current allowed to flow with a given voltage source. Therefore, to find the total resistance in a circuit, add the values of the individual resistances.

In the above circuit, the resistances are 3,000 ohms each. Their sum is 9,000 ohms. The ammeter also adds resistance in series. But since this resistance is normally less than 1 ohm, it adds so very little to the total that it can be disregarded.

Q43. In a series circuit, all of the parts are connected in ------.

Q44. R_1 and R_2 are connected in series. Their values are 3,000 ohms and 1,500 ohms, respectively. If current through R_1 is 2 milliamps. what is the value of current flowing through R_2?

Q45. Draw a schematic of the three resistors as they are connected in the above diagram. Show how an ohmmeter (schematic symbol) would be connected to read total resistance of the three.

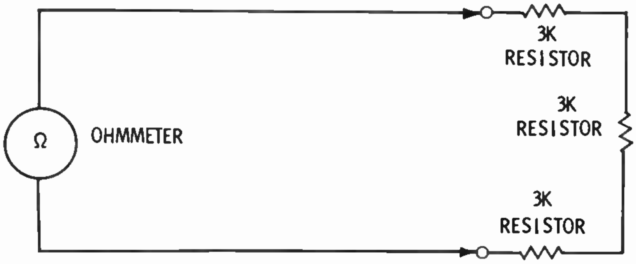
Q46. If the ohmmeter measures 9,000 ohms, how much current will flow if the three resistances are connected across a 15-volt battery?

Your Answers Should Be:

A43. In a series circuit, all of the parts are connected in **series.**

A44. **Current through R_2 is also 2 milliamps.** (Current through all parts of a series circuit is the same.)

A45.

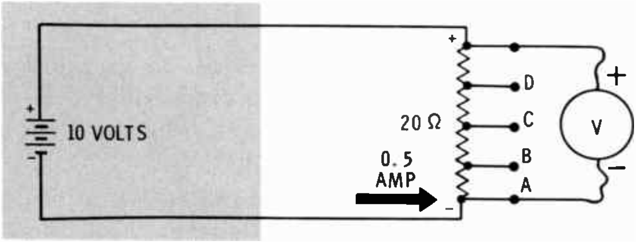


A46. $$\text{Current} = \frac{\text{voltage applied}}{\text{total resistance}} = \frac{15}{9{,}000}$$
$$= \textbf{0.00167 amp, or 1.67 milliamps}$$

Voltage Distribution in a Series Circuit

The voltage of a source is distributed **across and within** any load connected to it. Although this is a simple statement, the concept is often misunderstood.

VOLTAGE DISTRIBUTION IN A SERIES CIRCUIT



If a 20-ohm resistor is connected across a 10-volt source, as shown in the illustration, a voltmeter reading across the resistor will be **10** volts. This means that the voltage of the source is not only applied **across** the load, but it also exists **within** it.

The **taps** (connections) shown are equal distances apart. If the lower test probe is moved to tap B, the voltmeter will be across ¾ of the resistor. And ¾ of the total voltage is 7.5 volts. Half the resistance (between C and E) will result in a measurement of 5 volts. From D to E is ¼ of the resistance and ¼ of the voltage, or 2.5 volts.

Can voltage distribution be estimated without making the measurements? Yes, and the reason is based on the familiar relationship that exists between voltage, current, and resistance:

$$\text{Current} = \frac{\text{voltage}}{\text{resistance}}, \text{ or } I = \frac{E}{R}$$

If you do not know the value of voltage applied across a resistance of 20 ohms, but you do know the current through it is 0.5 amperes, how would you determine the voltage? You can find the value of voltage by reasoning that E/R must be a ratio that equals ½. Since R is 20, E would have to be 10 volts. Or you can restate the relationship to read **E = IR,** meaning current multiplied by resistance. To prove that it is the same equality, ½ amp times 20 ohms does equal 10 volts.

Voltage developed across a resistance is termed an **IR drop,** or, substituting E for IR, it may be called a **voltage drop.** "Drop" does not indicate voltage has been lost. Instead, it identifies the amount of voltage existing between two points of a resistance when current is flowing.

The IR (or voltage) drop between points A and E in the illustration is 10 volts. IR equals 10 volts. What is the voltage (IR drop) between taps A and B? I is still 0.5 amp, but the value of R is different. It is ¼ of the total resistance or 5 ohms. Therefore, $E = IR = 0.5 \times 5 = 2.5$ volts.

Q47. What is the value of voltage between taps A and C?

Q48. What is the voltage drop between taps B and E?

Q49. What is the IR drop between taps B and D?

Q50. The sum of the resistances in a series circuit is equal to the total ___________ of the load.

Q51. The sum of the _______ _____ in a series circuit is equal to the total voltage across the load.

Your Answers Should Be:

A47. 5 volts between taps A and C.

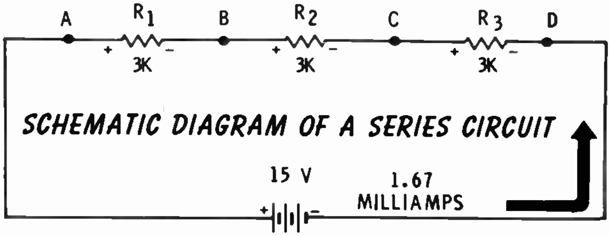
A48. 7.5 volts between taps B and E.

A49. 5 volts between taps B and D.

A50. The sum of the resistances in a series circuit is equal to the total **resistance** of the load.

A51. The sum of the **voltage** (or IR) **drops** in a series circuit is equal to the total voltage across the load.

Examples—The schematic for three 3,000-ohm resistors and a 15-volt battery circuit can be drawn to look like this.

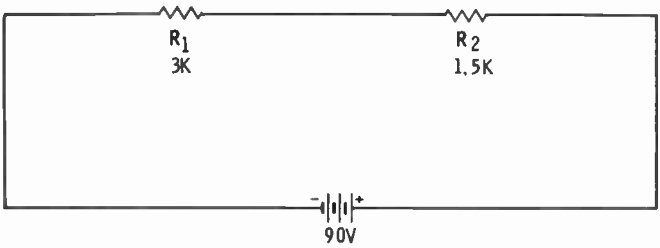


Voltage distribution principles are the same for this circuit as they were for the tapped resistor. Since the load contains three resistors of equal value, the voltage drop across each will be ⅓ of the source voltage, or 5 volts. To prove this, multiply the resistance of one of the resistors times the current in the circuit to give the voltage. This voltage will not be exactly 5 volts because 1.67 milliamps was rounded off to the next highest whole number. If you make the measurements with a voltmeter, you will find the distribution principle correct by a reading of 5 volts.

Note that each resistance is marked with polarity signs (minus and plus). The voltage across the resistor is just as real as that of the voltage source and, if the voltage is DC, the resistor has negative and positive terminals. When taking voltmeter readings, resistor polarity must be known. Circuit tracing is the best way to determine the polarity. The terminal that current enters is minus, and the one from which it leaves is plus.

Try the same reasoning on a series circuit containing resistors of unequal value.

A SERIES CIRCUIT WITH UNEQUAL RESISTANCE VALUES



R_1 is twice the value of R_2 in the above circuit. Both are in series across 90 volts. How do you find the voltage drop across each resistor?

This can be done by either of the two methods discussed—determining proportional distribution across each resistor, or by using E = IR. By the proportion method it is necessary to determine what ratio (or fraction) one resistance is of the total.

$$\frac{R_1}{R\ (\text{total})} = \frac{3{,}000}{4{,}500} = \frac{2}{3}$$

Two-thirds of 90 volts is 60 volts. So the drop across R_1 is 60 volts and across R_2, 30 volts.

By the IR method, current must be determined first.

$$I = \frac{E\ (\text{total})}{R\ (\text{total})} = \frac{90}{4{,}500} = 0.02 \text{ amp}$$

Then, by using the IR relationship:

$$E = I \times R_1 = 0.02 \times 1{,}500 = 30 \text{ volts}$$

Since the two methods are based on the same voltage distribution principle, either method provides the correct answer.

Q52. The (left, right) end of R_1 is negative.

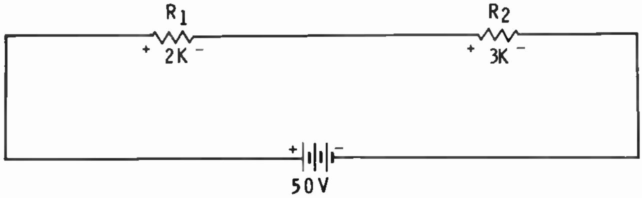
Q53. Draw a schematic of two resistances in series and supplied by 50 volts DC. R_1 is 2K and R_2 is 3K. Show all polarity marks.

Q54. What is the voltage drop across R_1?

Your Answers Should Be:

A52. The **left** end of R_1 is negative.

A53.

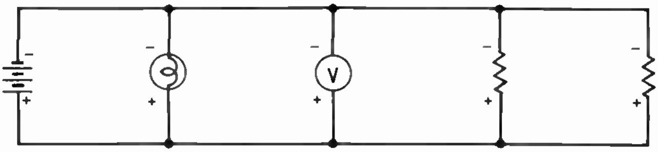


A54. Voltage across R_1 is 20 volts.

PARALLEL CIRCUITS

If all the components are connected across each other, the circuit is a **parallel circuit.** In the example shown below, the components are all connected to the same terminal (a wire in this case) and are therefore in parallel.

A PARALLEL CIRCUIT



Polarity across each component is determined by circuit tracing. The terminal that current enters is negative.

Voltage Distribution in a Parallel Circuit

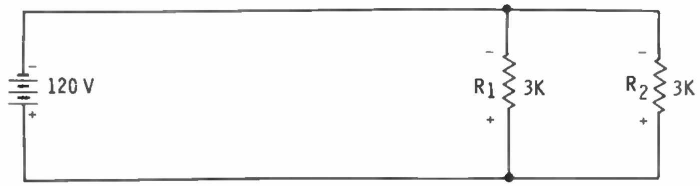
Each component (the lamp, the voltmeter, and each resistor) is connected across the voltage source. Thus the voltage drop across each part is the same value as the source. This is true even though the resistance of each component may be different.

Current in a Parallel Circuit

Each component in a parallel circuit draws its own separate current. Each leg is connected directly to the voltage source, which means each leg can be considered as a separate circuit to determine its current.

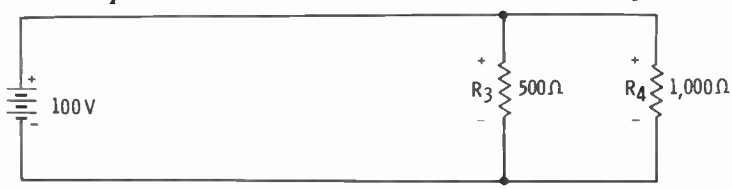
In the diagram below, two equal resistors are shown as being in parallel across a single voltage source.

Two Equal Resistances in Parallel With a Voltage Source



To find the current through R_1, divide the voltage across the resistor by the value of R_1. The result of this calculation is 0.04 amp. Since both resistances are equal and have the same voltage source, the current through R_2 must also be 0.04 amp. Both currents are supplied by the same voltage source, so the total current drawn must be 0.08 amp.

Two Unequal Resistances in Parallel With a Voltage Source



Using the same reasoning ($I = E/R$), it will be found that the current through R_3 in the above circuit is 0.2 amp. The current through R_4 is 0.1 amp. The total current is 0.3 amp.

Q55. In a parallel circuit, voltage across each leg is (the same as, different from) the voltage at the source.

Q56. In a series circuit, voltage across each resistor is (the same as, different from) the source voltage.

Q57. In a parallel circuit, total current is the (same as, sum of) currents in each leg.

Q58. In a series circuit, total current is the (same as, sum of) currents in each resistance.

Q59. R_1 (20 ohms), R_2 (40 ohms), and R_3 (60 ohms) are in parallel across a 12-volt DC source. Draw the schematic.

Q60. Find the total current and the current in each leg.

Your Answers Should Be:

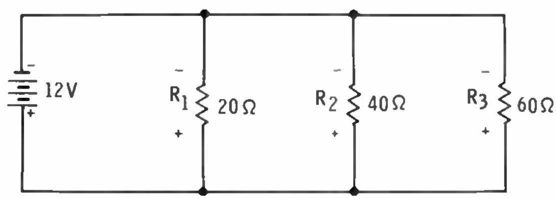
A55. In a parallel circuit, voltage across each leg is **the same** as the source.

A56. In a series circuit, voltage across each resistor is **different from** the source.

A57. In a parallel circuit, total current is the **sum of** currents in each leg.

A58. In a series circuit, total current is the **same** as currents in each resistance.

A59.



A60. I in R_1 = 0.6 amp. I in R_2 = 0.3 amp. I in R_3 equals 0.2 amp. Total I = 1.1 amps.

Resistance in a Parallel Circuit

How would you find the total resistance in the parallel circuit you drew in A59 above?

At this point you have used two of the three arithmetic statements that express the relationship existing between voltage, current, and resistance. To find current:

$$I = \frac{E}{R}, \text{ or current} = \frac{\text{voltage}}{\text{resistance}}$$

To find voltage:

$$E = IR, \text{ or voltage} = \text{current} \times \text{resistance}$$

The third way the relationship can be stated is:

$$R = \frac{E}{I}, \text{ or resistance} = \frac{\text{voltage}}{\text{current}}$$

You know the total voltage across the circuit (12 volts), and you found the total current through the circuit (1.1

amps). What is the total resistance of the circuit? Using the resistance formula above, the answer is approximately 10.9 ohms.

As you suspected, total resistance is smaller than the smallest resistance in the parallel network. Total current is the sum of the parallel currents and is therefore an amount that can flow only if the total resistance is smaller than that in any of the legs.

Total resistance cannot be found by adding the values of the individual resistances. The sum would be a resistance much larger than any one of the resistances. This would mean the total current would be smaller than any of the leg currents. Obviously, such a solution cannot be correct. For those who like to work with numbers, total resistance can be obtained by adding reciprocals:

$$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \text{etc.}$$

The electrical wiring in your home consists of parallel circuits. This includes the ceiling fixtures, wall outlets, and whatever else is energized electrically. Each parallel circuit is fused. If you plug one too many appliances into a circuit, the fuse blows. You have just learned the reason why. You added one more resistive path that draws current. As a consequence, total current increased beyond the capacity of the fuse, and it performed its job.

Comparisons between series and parallel circuits are shown below:

	Series Circuit	**Parallel Circuit**
Voltage	Divides across resistances	Same voltage across all resistances
Current	Same current through all resistances	Divides through each resistance
Total Resistance	Sum of all the individual resistances	Less than the smallest resistance

Q61. Two 6-ohm resistors are in parallel across a 6-volt battery. What is the total resistance?

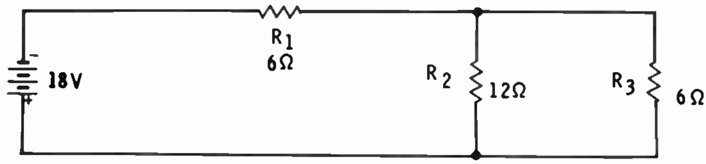
Your Answer Should Be:

A61. Three ohms. Current through each leg is 1 amp. Total current of 2 amps divided into 6 volts (total voltage) is 3 ohms.

SERIES-PARALLEL CIRCUITS

A **series-parallel circuit** contains a combination of series- and parallel-connected components. The simplest example is the one shown below.

A SIMPLE SERIES-PARALLEL CIRCUIT



The best way to work with a series-parallel circuit is to reduce all parallel combinations to an equivalent resistance. When this is done, the total current or the total resistance for the resulting series circuit can be readily found.

In the example shown above, how would you find the total resistance? Think about it before you continue reading. Yes, you could do it with reciprocals, but there is another method that is more easily applied, even when the resistance values are difficult.

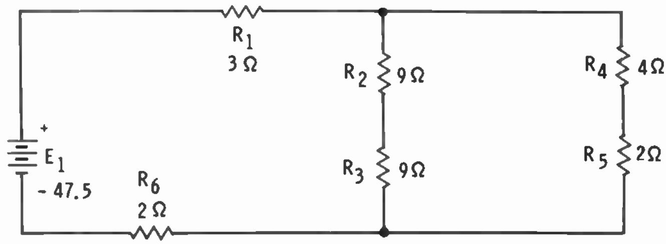
Cover all the circuit except for the parallel network. Apply a mythical voltage, the value of which is easily divisible by either resistance. Perform the E/R division to find the mythical current flowing in each leg. Divide the sum of the currents into the mythical voltage to find the **real** total resistance. The following tables uses three different voltages to show it will work with any assumed voltage.

Mythical Voltage	**6 Volts**	**12 Volts**	**24 Volts**
$I = E/R_2$ (12 ohms):	0.5 amp	1 amp	2 amps
$I = E/R_3$ (6 ohms):	1.0 amps	2 amps	4 amps
Total I is:	1.5 amps	3 amps	6 amps
$R = E/I$:	**4 ohms**	**4 ohms**	**4 ohms**

The total resistance (4 ohms) is the equivalent resistance of the parallel network. The 4 ohms is in series with 6 ohms for a total circuit resistance of 10 ohms (add resistances in a series circuit). The total circuit current (E/R) is 1.8 amps.

There are many different combinations of series-parallel circuits. One that is slightly more complex is shown below. Some of the questions at the bottom of the page refer to this circuit.

A MORE COMPLEX SERIES-PARALLEL CIRCUIT



Q62. Current in the above circuit flows through R_1 (before, after) it flows through the parallel network.

Q63. Total series-parallel circuit resistance is readily solved by reducing ________ resistances to an equivalent ______ resistance.

Q64. In a series circuit _______ divides among the resistances.

Q65. In a parallel circuit _______ divides among the resistances.

Q66. In a series circuit _______ is the same for all resistances.

Q67. In a parallel circuit _______ is the same for all resistances.

Q68. What is the total current in the above circuit?

Q69. What is the arithmetic statement for finding current?

Q70. For finding resistance?

Q71. For finding voltage?

Your Answers Should Be:

A62. Current in the above circuit flows through R_1 **after** it flows through the parallel network.

A63. Total series-parallel circuit resistance is readily solved by reducing **parallel** resistances to an equivalent **series** resistance.

A64. In a series circuit **voltage** divides among the resistances.

A65. In a parallel circuit **current** divides among the resistances.

A66. In a series circuit **current** is the same for all resistances.

A67. In a parallel circuit **voltage** is the same for all resistances.

A68. The total current for the circuit is **5 amps.** If you missed it, do it again. Guidance is on the preceding pages.

A69. $\mathbf{I} = \frac{\mathbf{E}}{\mathbf{R}}$ which means: current $= \frac{\text{voltage}}{\text{resistance}}$

A70. $\mathbf{R} = \frac{\mathbf{E}}{\mathbf{I}}$ which means: resistance $= \frac{\text{voltage}}{\text{current}}$

A71. $\mathbf{E} = \mathbf{IR}$ which means: voltage = current $\times$ resistance

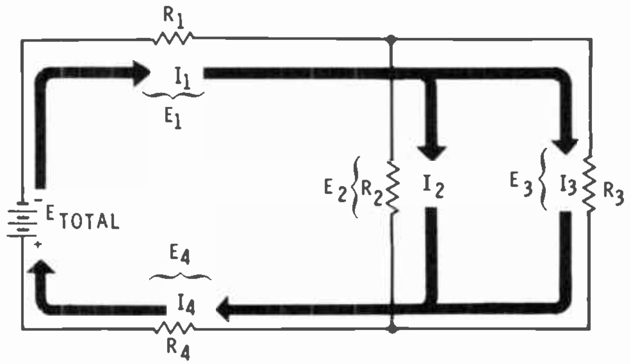
You have now accumulated quite a bit of experience working with the current-voltage-resistance relationship that exists in all DC circuits. This same relationship also holds true for any portion of a circuit.

You were guided very closely when solving for current, voltage, or resistance, so you may not recall or be aware of the care that must be taken in applying the three different arithmetic statements. For this reason, the necessary precautions are summarized.

1. The correct algebraic forms of the arithmetic statements are:

$$I = \frac{E}{R},\ R = \frac{E}{I},\ E = IR$$

2. When using any one of the three formulas, I must be expressed in amperes, E in volts, and R in ohms. When values appear with milli-, kilo-, mega-, or other prefixes, they must be converted to the basic units of amperes, volts, or ohms.
3. When using any one of the three formulas, values must be taken from the same portion of the circuit. Study this diagram for a few moments.



If you are solving for **total current,** you must use only the values that truly represent **total voltage** and **total resistance.** You cannot use E_1 (voltage across R_1) because it is not the total voltage. You cannot use the equivalent parallel resistance because it is not the total circuit resistance.

There is danger also in selecting incorrect values when seeking a solution for a portion of the circuit. If you are working with R_1, be sure the current you use is I_1 and the voltage is E_1 (volts across R_1).

Always label values to identify the circuit areas to which they belong (R_1, E_1, I_1, etc.).

OHM'S LAW

You probably have heard of or read about **Ohm's** law. Do you know what it is? Your answer should be yes. You have been working with it ($E = IR$; $I = E/R$; $R = E/I$) throughout this entire chapter.

Q72. In the above circuit, E_2 is 6 volts and I_1 is 120 milliamps. What is the value of R_1?

Your Answer Should Be:

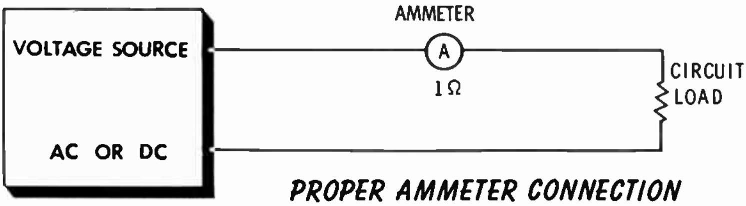
A72. Your immediate answer should have been: "I don't know; **there is not enough information available.**"

METER RESISTANCE

All meters have resistance between their terminals. When you connect a meter into or across a circuit, you add resistance to that circuit.

Ammeters

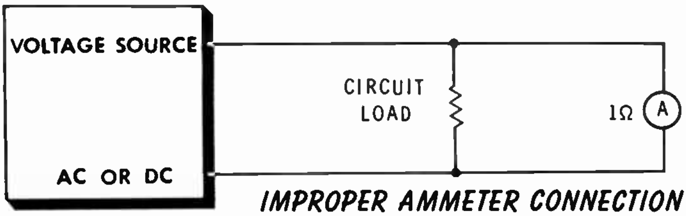
Ammeters are always connected in **series** with the circuit through which current is to be measured. As a result, the same current flows through the ammeter that flows through the circuit. The familiar connection is shown below.



PROPER AMMETER CONNECTION

The resistance of most ammeters is less than 1 ohm. Added in series with the load resistance, very little change is made to the total resistance. If the load were 10,000 ohms, for example, the new total resistance would be 10,001 ohms—hardly enough change to make a significant difference in the current. If the load were only 1 or 2 ohms, however, a difference would be noted.

Ammeters are never connected in parallel. What would happen if an ammeter were connected like this?

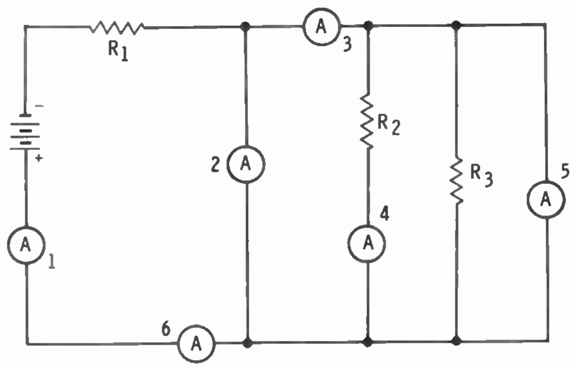


IMPROPER AMMETER CONNECTION

You are right, it would be damaged. But do you know why? The full voltage of the source is applied across the 1-ohm resistance of the meter. Even if the source were only a 1.5-volt dry cell, more than an ampere of current would flow through the meter. Some meters are designed to handle that amount of current, but a multimeter is not.

If an ammeter is connected to a wall outlet (115 volts AC) how much current would try to flow through the meter? More than 115 amps! However, when the current increased to 20 amps, the protective fuse in the house circuit would break the circuit. But the 20 amps would certainly damage the meter, and under certain conditions, the person holding the meter could be injured.

FIND THE ERRORS IN THIS CIRCUIT



Q73. There are six ammeters connected into the above circuit. Some are connected improperly. Which numbers are they?

Q74. A DC ammeter has a polarity that must be observed. The negative test lead must be connected to the _________ side of the circuit.

Q75. This means that circuit current must enter the _________ terminal of the meter and leave by the _________ terminal.

Q76. The (left, right) side of ammeter 3 in the above circuit is the negative terminal.

Q77. Current to be measured should not exceed the _______ _____ of the meter.

Your Answers Should Be:

A73. Numbers 2 and 5 are improperly connected.

A74. The negative test lead must be connected to the **negative** (minus) side of the circuit.

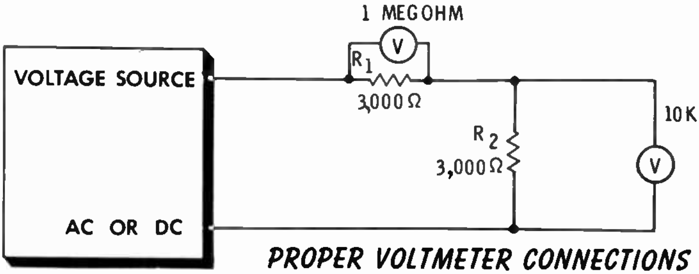
A75. This means that circuit current must enter the **negative** terminal of the meter and leave by the **positive** terminal.

A76. The **left** side of ammeter 3 is negative.

A77. Current to be measured should not exceed the **highest range** of the meter.

Voltmeters

Voltmeters are always connected in **parallel** with the component across which voltage is to be measured. As a result, the same voltage appears across the component and the meter. The illustration shows the proper connections.



PROPER VOLTMETER CONNECTIONS

The internal resistance of a voltmeter is normally very high. The higher it is, the greater the meter accuracy.

In the illustration, the voltmeter across R_1 has an internal resistance of 1,000,000 ohms. It will change the current flowing in the circuit very little, probably not enough to vary the true reading. As an example, assume that 0.1 amp is flowing before the voltmeter is connected. 300 volts (IR) should be read across R_1. The voltmeter adds 1,000,000 ohms in parallel, however. A little figuring shows that the equivalent resistance is now 2,991 ohms, which will increase the current to 0.1001 amp, lowering the voltage reading to a little over 299.5 volts. This is usually close enough for most purposes.

A voltmeter with an internal resistance of 10,000 ohms presents a different result. Using similar arithmetic, you find the new current to be 0.113 ampere and a voltage reading of 260.7 volts, almost 40 volts less than it should read.

Voltmeter Sensitivity—Internal resistance of a voltmeter is given in terms of meter **sensitivity** (ohms per volt). Resistance varies with the range settings. To find the internal resistance, multiply the ohms/volt rating by the maximum number of volts in a range. With a 20,000 ohms/volt meter, the following resistances are obtained:

10-volt range: 10V $\times$ 20,000 Ω/V = 200,000 ohms

50-volt range: 50V $\times$ 20,000 Ω/V = 1,000,000 ohms

250-volt range: 250V $\times$ 20,000 Ω/V = 5,000,000 ohms

Corresponding resistances of a 5,000 ohms/volt meter are:

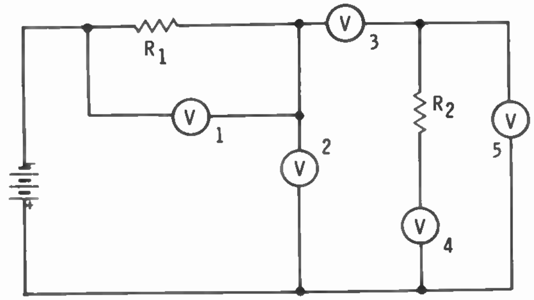
10-volt range: 50,000 ohms

50-volt range: 250,000 ohms

250-volt range: 1,250,000 ohms

The 20,000 ohms/volt meter is undoubtedly the more accurate meter. It will cost a few dollars more to attain this accuracy, but there will be times when you will be glad you paid extra for it.

FIND THE ERRORS IN THIS CIRCUIT



Q78. In the circuit above, which voltmeters are improperly connected in the circuit?

Q79. The internal resistance of a voltmeter is (higher, lower) than that of an ammeter.

Q80. What will happen to a circuit if a voltmeter is connected in series with it?

Your Answers Should Be:

A78. Voltmeter numbers 3 and 4 are improperly connected in the circuit.

A79. The internal resistance of a voltmeter is **higher** than that of an ammeter.

A80. The high resistance of the voltmeter will **decrease** the circuit current by a large amount.

WHAT YOU HAVE LEARNED

1. Resistance is a property of all materials which limits the flow of current.
2. Conductors have a low resistance; insulators have a high resistance.
3. Since voltage causes a certain amount of current to flow and resistance limits the amount that will flow, there is a special relationship between current, voltage, and resistance. This relationship is expressed by the following:

$$I = \frac{E}{R}, \text{ or current} = \frac{\text{voltage}}{\text{resistance}}$$

$$R = \frac{E}{I}, \text{ or resistance} = \frac{\text{voltage}}{\text{current}}$$

$$E = IR, \text{ or voltage} = \text{current} \times \text{resistance}$$

4. The unit of resistance is the ohm. The value of resistance in ohms can be measured with an ohmmeter.
5. Current flowing through a resistance generates heat. If temperature rises greatly, electrical resistance of the material increases.
6. Resistors are designated by construction (wirewound or composition) and by intended use (fixed, adjustable, or variable).
7. Resistances are rated by their heat-dissipating capability in terms of watts.
8. Resistor tolerance is given as a percentage value which indicates the amount a resistor may vary above or below the labeled value.

9. Four characteristics of a resistor must be known when purchasing a resistor. These are: type, value, tolerance, and power rating.
10. Wirewound resistors have their value and tolerance stamped on the body. Composition resistors are read by decoding colored bands painted around the body of the resistors.
11. Resistors, or any other electrical/electronic component, have only three possible ways in which they can be connected—series, parallel, and series-parallel. These terms are also the names of the circuits in which they appear.
12. Algebraic and arithmetic statements of Ohm's law are used to determine I, E, or R in a circuit or a portion of a circuit.
13. In a series circuit:
    a. Total voltage is divided among the load resistances.
    b. Current is the same through all the resistances.
    c. Total resistance is the sum of all the resistances.
14. In a parallel circuit:
    a. Source voltage appears across all the resistances.
    b. Total current divides among the resistances.
    c. Total resistance is less than the smallest resistance.
15. Never connect an ammeter in parallel with a circuit.
16. Never connect a voltmeter in series with a circuit.
17. Never connect an ohmmeter to a circuit in which current is flowing.

7

Understanding Transistors

What You Will Learn

Transistors were invented just a few years ago. Since that time millions have been used in a great variety of electronic devices. In this chapter you will learn something of what a transistor is and what it can do. You will also be given details about a few interesting transistor circuits that you may want to build.

WHAT IS A TRANSISTOR?

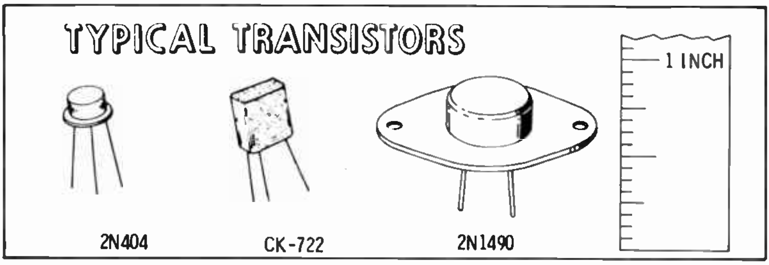
The term **transistor** comes from the combination of two words—"transfer resistor." A transistor **transfers** small values of electrical energy into larger values. Weak voltages (such as those representing sound) can be made strong enough by transistor circuits to operate a speaker.

A transistor is actually a variable **resistor**, but not of the ordinary type you have just studied. It is unique because its **resistance can be varied electrically.** Small incoming voltages cause small currents to flow through the transistor. The small currents make corresponding but large changes in the transistor resistance, causing other transistor currents to make equally large changes in value. The output signals are therefore similar to, but stronger than, the input signals.

Transistors are constructed from materials classified as **semiconductors.** Germanium and silicon are examples.

HOW TRANSISTORS ARE USED

Transistors come in several shapes and sizes. There are now hundreds of varieties, each one having special characteristics that makes it different than the others for specific applications. The three types shown in the diagram are representative of the shape and size of most transistors. An **alpha-numeric** (letter and number) code is assigned to each type of transistor. This designation, with the aid of a handbook, identifies the operating characteristics of each particular transistor.



Amplifiers

Transistors, as well as several other devices, are capable of converting small voltages or currents into larger ones. The process is called **amplification** (to enlarge). Electronic circuits that accomplish this function are known as **amplifiers.** Most of the circuits used in electronic equipment of all types are designed as amplifiers.

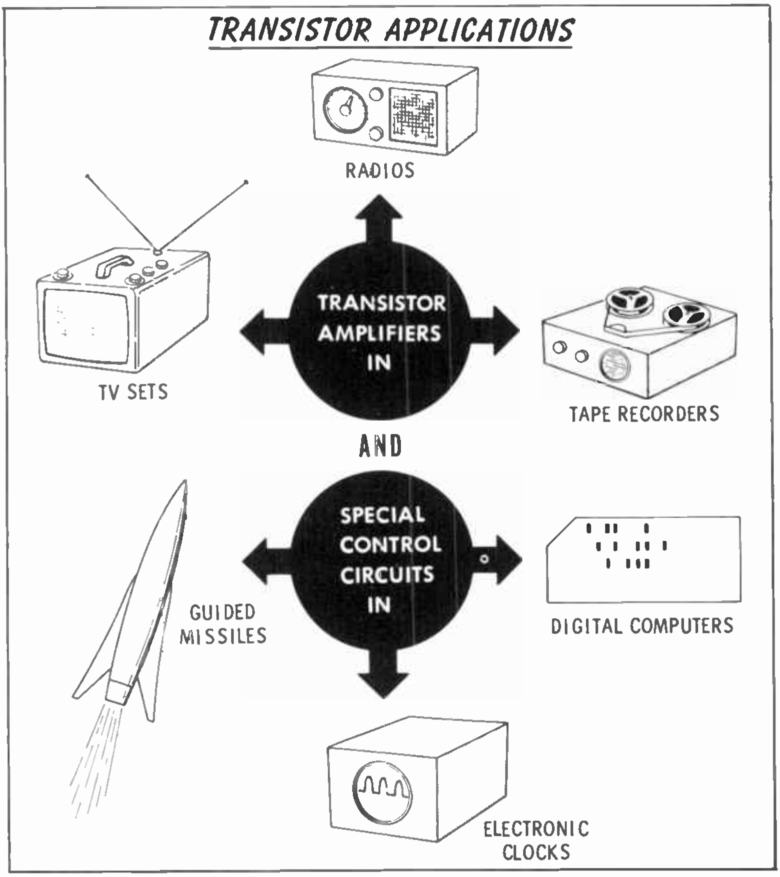
Vacuum tubes, for example, were used in amplifier circuits long before transistors were developed. Transistors are beginning to replace the tube as an amplifying device in many applications for several reasons. These include:

1. Small size and weight, allowing equipment to be made smaller and lighter.
2. Low operating voltages, decreasing the need for heavy and expensive power supplies.
3. Relatively noise free, permitting signals to be amplified without certain types of distortion.

Transistor amplifiers are used in radios, television receivers, tape recorders, phonographs, and a host of military, commercial, and industrial electronic equipment.

Control Circuits

In control circuits, a transistor acts as an electrically operated switch. Such circuits are built into electronic clocks, testing devices, digital computers, etc.



Q1. A transistor is a device that can convert (small, large) signals into (small, large) signals.

Q2. This conversion process is called ______________.

Q3. A transistor can amplify because its internal __________ can be electrically varied.

Q4. A transistor is _____ in size, _____ in weight, and can use ___ voltages for operation.

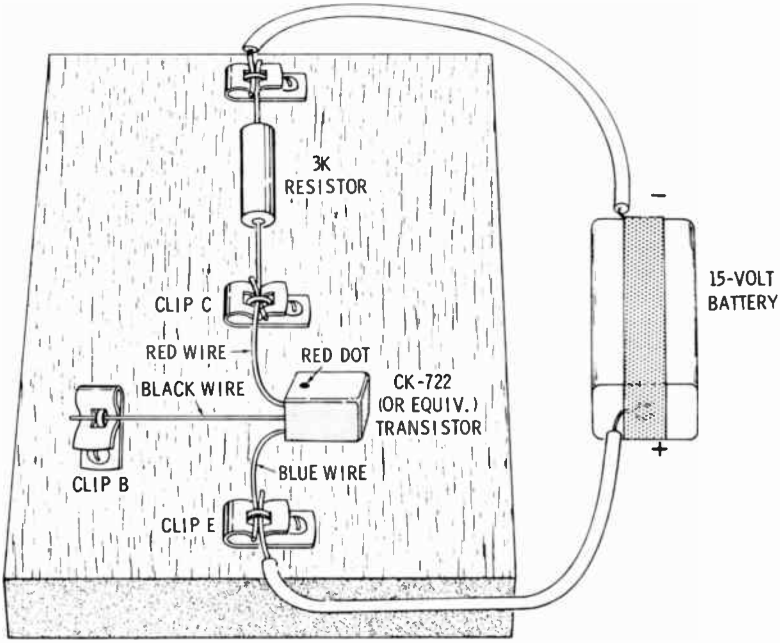
> **Your Answers Should Be:**
>
> A1. A transistor is a device that can convert **small** signals into **large** signals.
>
> A2. This conversion process is called **amplification.**
>
> A3. A transistor can amplify because its internal **resistance** can be varied electrically.
>
> A4. A transistor is **small** in size, **light** in weight, and can use **low** voltages for operation.

TYPICAL TRANSISTOR CIRCUITS

One type of transistor circuit will be explained to give you an understanding of transistor operation. The circuit can be constructed as an experiment if you desire.

A Transistor Voltage Divider

A transistor can be used with resistances in series to form a voltage divider. Construction details are shown below.

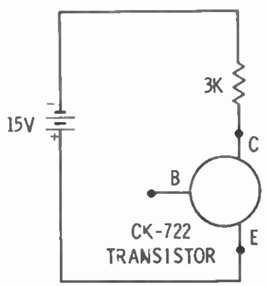


A TRANSISTOR VOLTAGE DIVIDER

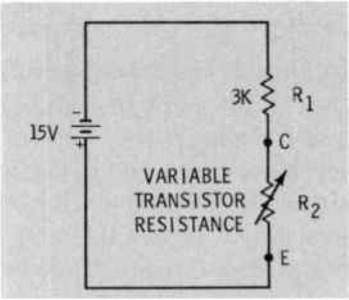
Be careful when handling the transistor because the fragile wires break very easily.

Two schematics of the circuit are shown below. One shows an incomplete symbol for the transistor—the correct version will be given and described later. The other schematic shows the transistor as a variable resistance. The slanted arrow indicates the resistance is variable.

SCHEMATIC DIAGRAMS OF THE ACTUAL AND EQUIVALENT CIRCUITS OF THE TRANSISTOR VOLTAGE DIVIDER



ACTUAL CIRCUIT



EQUIVALENT CIRCUIT

NOTE: Until you have more experience, do not connect any ohmmeter directly across the transistor leads. Certain ranges of some ohmmeters develop enough current to destroy small transistors. The 3,000-ohm resistor in the above circuit acts as a current-limiting resistance to prevent the 15-volt battery from doing the same thing.

Based on your knowledge of resistances in series, what value must R_2 be in order to obtain a voltage reading of 7.5 volts at terminal C? Yes, it must be the same value as R_1 (3,000 ohms) to divide the value of source voltage equally between them.

Q5. What approximate value must R_2 have if nearly all the source voltage is measured across R_1?

Q6. To have most of the source voltage dropped across R_2, R_2 must be (more, less) than 10 times the value of R_1.

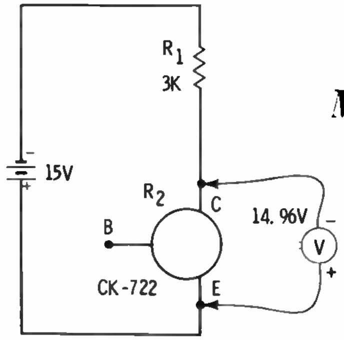
Your Answers Should Be:

A5. For 15 volts to appear across R_1, R_2 must be very close to zero ohms. **A very few ohms** would be a good answer. Remember, voltage (IR drop) is distributed among series resistors in accordance with their value in ohms. A resistor which is 10 times as large as another has 10 times as much voltage across it as the other.

A6. To have most of the source voltage dropped across R_2, R_2 must be **more** than 10 times the value of R_1.

The Circuit Operating as a Switch

If you measure the voltage across the transistor with the circuit connected as shown, you will find that it will be very close to 15 volts. An extremely accurate meter might measure it as 14.96 volts. This leaves 0.04 volt for R_1. If the voltage across R_2 is 374 (14.96 divided by 0.04) times greater than the voltage across R_1, the resistance of R_2 must be the same number of times larger. This works out to be a value of over 1,000,000 ohms. The illustration shows how the voltmeter is connected across the transistor.



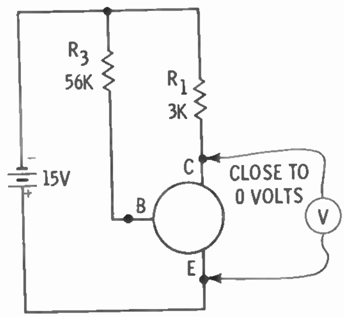
Measuring the Voltage Across the Transistor

Under these conditions, current in the circuit would be very small, about 15 millionths of an amp. In effect, the high resistance of the transistor is very close to being an open circuit—no current flowing.

The structure of the transistor material will cause this resistance to change when current flows from B to E.

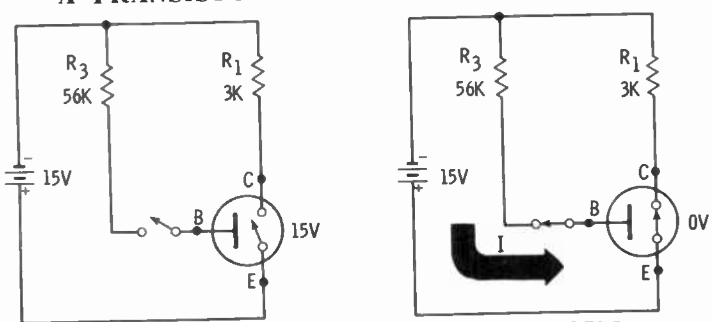
By adding a large resistor (56,000 ohms) from the negative side of the battery to the B terminal of the transistor, approximately 250 microamps will flow through the transistor. The meter reading, as shown below, is near 0 volts.

VOLTAGE ACROSS THE TRANSISTOR WITH A NEGATIVE VOLTAGE APPLIED TO TERMINAL B



In effect, the path through the transistor from C to E has decreased from a very high resistance to a very low resistance. The transistor is operating as if it were a switch. The pair of diagrams below show the transistor acting as a switch. With no current through B, the transistor acts as an open switch; with current it acts as a closed switch.

A TRANSISTOR CAN ACT LIKE A SWITCH



HIGH R FROM C TO E

LOW R FROM C TO E

Q7. **When a small amount of current enters the B terminal, the transistor acts as a(an) ______ switch and almost (all, none) of the source voltage appears across it.**

Q8. **With no current through B, the C to E switch is (open, closed) and almost (all, none) of the source voltage can be measured across the terminals.**

Your Answers Should Be:

A7. When a small amount of current enters the B terminal, the transistor acts as a **closed** switch and almost **none** of the source voltage appears across it.

A8. With no current through B, the C to E switch is **open** and almost **all** of the source voltage can be measured across the terminals.

In practice, the transistor switch is opened and closed by electrical signals applied to the B terminal. These will be discussed later in the chapter.

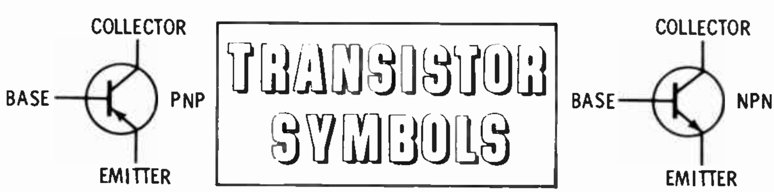
TRANSISTOR SYMBOLS AND CONNECTIONS

Transistors have their own symbols and methods of being connected within a circuit, the same as other electrical and electronic components.

Symbols

There are two types of transistors—NPN and PNP. The difference between the two is the type of materials used in their construction and, as a result, the direction that current flows between terminals.

Symbols for both types are shown below. The CK-722 (used in the experiment) is a PNP transistor.

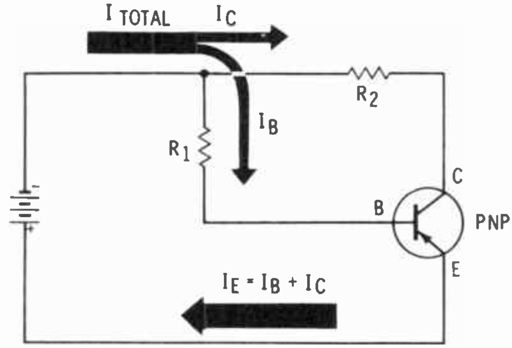


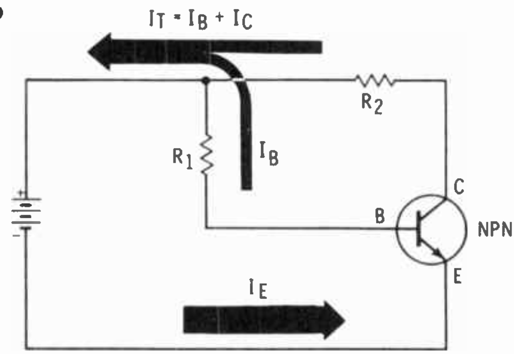
The only difference in the two symbols is the direction of the arrowhead. Be able to recognize either one. Current not only flows through the two types in different directions, but they are connected into a circuit differently.

Also note the names for the B, C, and E terminals. **Base, collector,** and **emitter** identify the significant parts of a transistor. B, C, and E are the notations often used in schematics.

Shown below are the basic circuits for NPN and PNP transistors and the flow directions for base, collector, and emitter currents. Study them carefully.

BASIC TRANSISTOR CIRCUITS





Q9. The symbol I_B stands for ____ current.

Q10. The symbol I_C stands for __________ current.

Q11. The symbol I_E stands for ________ current.

Q12. The symbol I_T stands for _____ current.

Q13. In both circuits, emitter current is equal to ____ current plus __________ current.

Q14. In both circuits, total current is equal to ____ current plus __________ current.

Q15. In either circuit, _____ current and ________ current are the same value.

Q16. The terminals of R_1 and R_2 nearest the transistor are negative in the (NPN, PNP) circuit.

Q17. Emitter current is (greater, less) than the base current.

Your Answers Should Be:

A9. The symbol I_B stands for **base** current.

A10. The symbol I_C stands for **collector** current.

A11. The symbol I_E stands for **emitter** current.

A12. The symbol I_T stands for **total** current. (Total current refers to the current that flows through the voltage source.)

A13. In both circuits, emitter current is equal to **base** current plus **collector** current.

A14. In both circuits, total current is equal to **base** current plus **collector** current.

A15. In either circuit, **total** current and **emitter** current are the same value.

A16. The terminals of R_1 and R_2 nearest the transistor are negative in the **NPN** circuit. (The terminal of any resistor through which current enters has negative polarity.)

A17. Emitter current is **greater** than the base current.

A SIMPLE CONTROL CIRCUIT

A control circuit can be made from the transistor voltage divider used in the first part of this chapter. The control circuit will be used as a means of applying the principles you have learned about transistors. Enough details are furnished so you can construct and use the circuit if you desire.

Circuit Construction

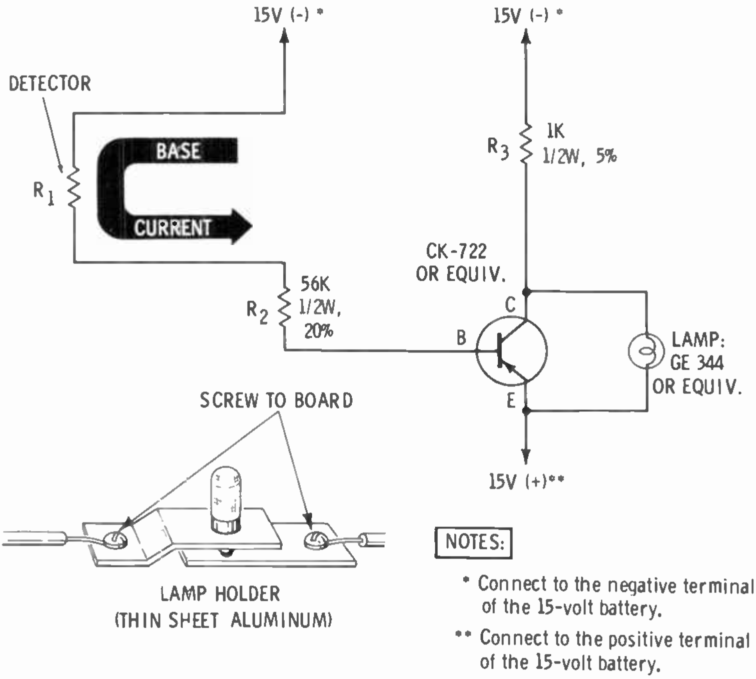
The control circuit is very similar to the other transistor circuits that have been discussed. A schematic diagram (including parts detail) is shown on the next page.

R_1 and R_2 connect the transistor base to the negative terminal of the 15-volt battery. R_1 can be any low resistance material or device. Its purpose is to interrupt the base circuit when the event to be detected takes place.

R_3 connects the collector to the negative terminal of the battery. The positive battery terminal is connected to the emitter. A lamp is connected in parallel with the transistor and will light when the event is detected.

The battery is not shown as a symbol in the schematic. Arrowheads, however, point to the proper terminal connections. This technique is used to save space and reduce clutter in the schematic diagram.

A SIMPLE ALARM CIRCUIT AND DETECTOR



Q18. When base current flows through the transistor, a very (high, low) resistance appears between collector and base.

Q19. When resistance between C and E is high, (fifteen, zero) volts will be developed between collector and base.

Q20. The voltage polarity of R_3 is negative on the (collector, battery) side.

Q21. The voltage polarity of R_2 is positive on the (base, detector) side.

Q22. The lamp (will, will not) light as long as base current is flowing.

Your Answers Should Be:

A18. When base current flows through the transistor, a very **low** resistance appears between collector and base.

A19. When resistance between C and E is high, **fifteen** volts will be developed between collector and base. (By comparison, R_3 will be a very low resistance. Therefore, most of the voltage source will be developed across the transistor.)

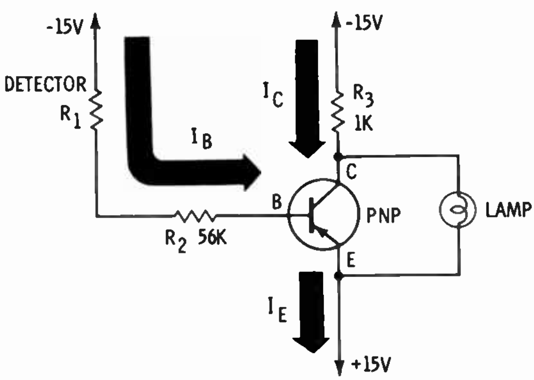
A20. The voltage polarity of R_3 is negative on the **battery** side. (Remember that collector current in a PNP circuit flows toward the collector. The polarity of R_3, then, must be minus to plus, top to bottom.)

A21. The voltage polarity of R_2 is positive on the **base** side.

A22. The lamp **will not** light as long as base current is flowing. (When base current flows, C-to-E resistance is almost zero. Not enough voltage is developed across the transistor to light the lamp.)

How the Circuit Operates

The preceding questions established the fundamental principles of transistor operation. Now these principles will be used to explain how the circuit operates.



Current Flow in the Transistor Alarm Circuit

When detector R_1 remains unbroken, the following conditions exist:

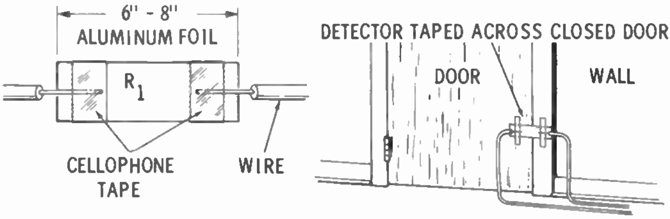
1. Base current flows through the transistor.
2. The transistor acts as a closed switch.
3. Zero voltage appears between C and E.
4. The lamp does not light.

When the detector is broken (opened):

1. Base current stops flowing.
2. The transistor acts as an open switch (from C to E).
3. Voltage appears between C and E.
4. Voltage is applied across the lamp, causing it to light.

The Detector—A simple detector can be made from a strip of aluminum foil. Taped to a door or a window, it will break when either is opened, thus lighting the alarm. Construction details are shown below.

ALARM DETECTOR CONSTRUCTION



Q23. The lamp is out when ---- current is flowing.

Q24. The lamp is on when C-to-E resistance is (high, low).

Q25. When the lamp is lit, there is (zero, maximum) voltage across R_3.

Q26. When the detector breaks, there is (zero, maximum) voltage across R_2.

Q27. The value of base current is equal to ------- current minus ---------- current.

Q28. In a circuit using an NPN transistor, base current flows (toward, away from) the source, and emitter currents flows (toward, away from) the transistor.

Q29. (Collector, emitter, base) current is equal to the total current flowing through the source.

Your Answers Should Be:

A23. The lamp is out when **base** current is flowing.

A24. The lamp is on when C-to-E resistance is **high.**

A25. When the lamp is lit, there is **zero** voltage across R_3.

A26. When the detector breaks, there is **zero** voltage across R_2.

A27. The value of base current is equal to **emitter** current **minus** collector current.

A28. In a circuit using an NPN transistor, base current flows **toward** the source, and emitter current flows **toward** the transistor.

A29. **Emitter** current is equal to the total current flowing through the source.

A TRANSISTOR AMPLIFIER

A transistor can be used to amplify voltages. As you recall, amplify means to increase amplitude or value. In other words, a weak signal (radio wave or audio voltage, for example) can be made stronger by passing it through an amplifying circuit.

Alternating Current or Voltage

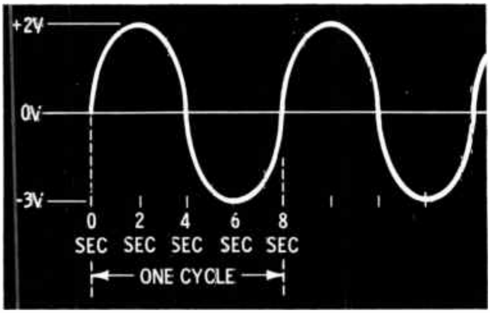
Before you begin thinking about amplifiers you should become more familiar with alternating voltage. You know that an alternating current reverses itself periodically. During one period of time, current flows in one direction. During the next period, current flows in the opposite direction. The flow of current does not make the change instantaneously; it does not move in one direction, then pause before it moves in the other. The changes occur over a period of time, regardless of how short the time may be.

The illustration on the next page shows a graph of how an AC voltage (or current) changes direction. The same picture can be seen on an electronic test instrument, called an **oscilloscope.**

The dimensions of the graph show voltage values vertically and time in seconds horizontally.

You will note that this AC **sine wave** (as it is called) takes 2 seconds to change from zero volts to its maximum of 2 volts. It rises rapidly during the first second (to approximately 0.7 of its maximum value). It then rises less and less rapidly until its full value is finally reached at the end of the remaining second.

AN AC SINE WAVE



From zero to 2 seconds the voltage is rising in the positive direction. It decreases to zero volts, following the same shape curve, in the next 2 seconds. At this point it has completed one half of its full cycle. This portion of the **waveform** is called the **positive half cycle.**

During the **negative half cycle,** it repeats the first half, except that now it moves in the negative (or opposite) direction. From zero volts, it **increases** in value until it reaches the maximum—minus 2 volts. This takes 2 seconds. In the next 2 seconds, the voltage **decreases** from its maximum negative voltage back to zero.

The rise and fall of the positive and negative half cycles are identical. The only difference is the direction—one is from zero to a maximum positive voltage and back to zero, while the other is from zero to a maximum negative voltage and back to zero. AC voltage in your home follows the same pattern. It completes 60 full cycles every second (60 positive half cycles and 60 negative half cycles).

Q30. A weak signal can be increased in amplitude by passing it through a(an) ---------- circuit.

Q31. An AC cycle consists of two half cycles; one is -------- and the other is --------.

Your Answers Should Be:

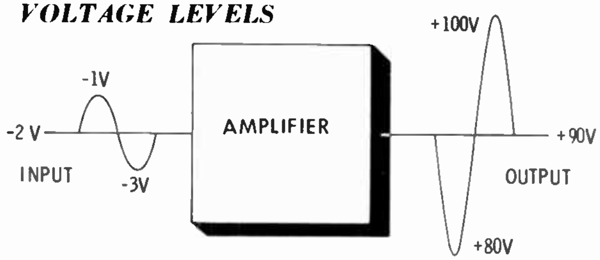
A30. A weak signal can be increased in amplitude by passing it through an **amplifying** circuit.

A31. An AC cycle consists of two half cycles, one is **negative** and the other is **positive.**

Gain

The behavior of an amplifier is described in terms of **gain.** Without going into lengthy detail, amplifiers are designed to operate at some definite voltage level during periods when no signals are applied. In the illustration below, the voltage level of the input side is —2 volts. The output side operates at +90 volts.

AN AMPLIFIER OPERATES AT CERTAIN VOLTAGE LEVELS



If an AC signal that is changing from +1 volt to —1 volt during a full cycle is applied to the input, the signal voltage will add to the DC voltage already present at the input. For example, when the signal is maximum positive, the +1 volt is added to the —2 volt DC level to produce a —1-volt input to the amplifier at that time. When the signal swings in the negative direction, —1 volt and —2 volts become —3 volts. In other words, the swing of the input is from —1 to —3 volts, or a **change in voltage** of 2 volts.

Assume that the characteristics of the amplifier are capable of making the corresponding output voltage changes shown in the diagram with such an input signal. The operating level of the amplifier output is +90 volts. During the first half cycle of the input, the output changes from +90 volts to +80 volts. During the second half cycle, the swing is from +90 volts to +100 volts.

This means that an **input voltage change** of 2 volts caused an **output voltage change** of 20 volts (from +80 to +100). The output change was ten times that of the input, so the **gain** of this amplifier is 10.

How would you express this in arithmetic form? Like this:

$$\text{Gain} = \frac{\text{change in output voltage}}{\text{change in input voltage}}$$

Or, if you want to find the change in output for a given amplifier with a particular input signal:

$$\text{Change in output E} = \text{gain} \times \text{change in input E}$$

Problem—If a certain signal causes a change of three volts on the input side of an amplifier and a corresponding change of 48 volts at the output, what is the gain?

$$\text{Gain} = \frac{\text{output change (volts)}}{\text{input change (volts)}} = \frac{48}{3} = 16$$

Problem—Input voltage of an amplifier changes from —1.5 volts to —4.5 volts. The amplifier gain is 12.3. What is the voltage change in the output?

$$\begin{aligned}\text{Output change (E)} &= \text{gain} \times \text{input change (E)}\\ &= 12.3 \times 3 \text{ volts}\\ &= 36.9 \text{ volts}\end{aligned}$$

Amplifiers can be designated with gains ranging from very small to very large. The amount of gain desired is first determined and then an amplifier is selected that has such a gain.

Q32. An alternating voltage appears at the input of an amplifier. It causes the input voltage to vary from —2 volts to —1.2 volts. What is the change in input voltage?

Q33. The same change in input voltage produces an output waveform that swings from +12 volts to +42.6 volts. What is the gain of the amplifier?

Q34. An amplifier has a gain of 39; the input voltage swings from —5.25 to —5.05 volts. What will be the change in the output voltage?

Q35. Would a steady DC voltage applied to the input of an amplifier cause the circuit to amplify?

Your Answers Should Be:

A32. Change in input voltage is **0.8 volt.**

A33. The gain of the ampliler is **38.25.**

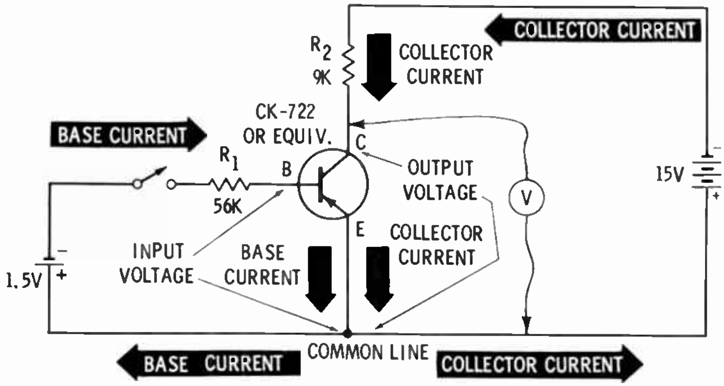
A34. Output voltage change would be **7.8 volts.**

A35. The answer is **no.** (After the initial rise of the DC voltage at the instant it is applied, there would be no further change in the input voltage and consequently no change in the output voltage. Hence, there would be no amplification.)

A Simple Transistor Amplifier

You may wish to construct the transistor amplifier shown in the schematic diagram below. R_2 is shown as 9,000 ohms. If you discover you do not have a 9K resistor, but you do have an assortment of 3K resistors, what would you do? Yes, you could connect three 3,000-ohm resistors in series and have the equivalent of 9,000 ohms.

A SIMPLE TRANSISTOR AMPLIFIER CIRCUIT



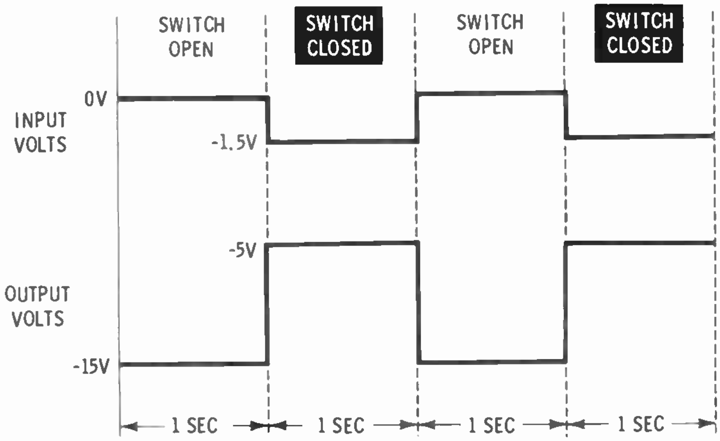
The input to this amplifier is maintained at 1.5 volts by the dry cell shown. An AC signal applied to the base will rise above and below this reference voltage.

The output voltage can be measured from the collector to the common line. Since the common line is connected to the emitter, the output voltage will be that appearing across the transistor from C to E. In all other respects the amplifier circuit is similar to the transistor control circuit.

A change in input voltage will occur if the switch in the line connected to the base is opened and closed. The change can be observed on a voltmeter with its leads connected to the base and the common line. Output voltage changes can also be read with a voltmeter connected as shown.

The graph shows the voltage changes that will occur.

VOLTAGE CHANGES IN THE TRANSISTOR AMPLIFIER



With the switch open, the input registers 0 volts and the output —15 volts. With the switch closed, the input changes to —1.5 volts and the output to —5 volts. The same readings occur each time the switch is opened and closed.

If the switch were opened and closed at one second intervals, as shown in the graph, the cycles would repeat themselves at a steady rate. The **frequency** would be one cycle every two seconds as opposed to the household electrical AC frequency of 60 cycles per second. Because they have straight sides and flat tops, the waveforms in the graph are called square waves.

Q36. What is the gain of the transistor amplifier circuit just described?

Q37. The output waveform rises rapidly, remains at a steady value, and then decreases rapidly to its original level. What type of waveform is it?

Q38. What type of voltmeter would you use to measure the output when the switch is closed?

Your Answers Should Be:

A36. **The gain is 6.7** (a change of 10 output volts divided by a change of 1.5 input volts).

A37. The waveform is a **square wave.**

A38. **A DC voltmeter.** (The same voltmeter would also be used for measurements while the switch is open.)

WHAT YOU HAVE LEARNED

1. A transistor is a variable resistor that can be controlled electrically.
2. Transistors use small input voltage changes to produce larger output voltage changes.
3. A transistor may be used as a resistor in a voltage divider.
4. A transistor may be used as an electrical switch. It will react as an open switch when no base current flows and as a closed switch when base current does flow.
5. There are two types of transistors, NPN and PNP. In an NPN, base and collector currents flow away from the transistor. Emitter current flows toward the transistor. These currents flow in opposite directions in a PNP transistor.
6. AC voltage rises to, and falls from, its maximum voltage periodically. The polarity alternates between positive and negative directions.
7. The gain of an amplifier is determined by dividing the change in input voltage into the corresponding change in output voltage.

8

How To Solder

What You Will Learn

You will now learn how to make permanent electrical connections using a procedure called soldering. You will be shown how to work with the necessary tools and hardware. The fundamentals are easily learned. Skill in soldering requires careful practice. When you complete this chapter you will be able to apply the fundamentals of soldering, select and use the proper tools, properly prepare an iron for soldering, make proper mechanical and electrical connections, and make and disconnect soldered joints.

THE PURPOSE OF SOLDERING

Solder is a special metal mixture applied to electrical connections to prevent **oxidation. Soldering** is the process of applying the right amount of the mixture to join two or more pieces of metal.

Oxidation is the result of a chemical reaction between air and certain metals. When iron oxidizes, rust forms on its surface. When copper oxidizes, a dull, insulating film forms on its surface. The film has a high resistance to current flow. In order to retain a good electrical connection, the film must be removed and prevented from forming again.

To protect iron from rusting, it is painted. To protect copper and similar metals from oxidation, they are coated with solder. In addition to providing a good electrical path, the solder also adds to the mechanical strength of the joint when two wires are joined.

THE PROCESS OF SOLDERING

Solder is applied to a connection with heat. A tool that supplies this heat is a **soldering iron** or a **soldering gun.**

Solder

Solder is a metal alloy (mixture) containing tin and lead. The alloy most usually used in electronic work is 60/40 solder—60% tin and 40% lead.

Other tin/lead ratios are available but are not recommended for use in electronic equipment or small electrical appliances. 50/50, 40/60, and 30/70 are all solders that have less tin content than the 60% desired. Tin is the metal in the alloy that leaves the bright, tightly bound, conductive coating produced by soldering.

Lead permits the alloy to have a reasonable melting point. If solder were 100% tin, it could not be melted and applied with an ordinary soldering iron. 70/30, 80/20 and other tin-heavy ratios are available and probably would permit a better soldering job. But, as the tin content of the alloy increases, so does its melting point. Higher heat is required for application. High temperatures damage or destroy components—resistors, coils, and transistors, for example—and excessive heat chars, burns, or melts insulation on wires and components. 60/40 solder seems to be the best balance between the need for a properly soldered joint and the maximum heat that can be tolerated.

Solder comes wrapped on spools or supplied in coil form. its shape is usually round and wire-like. However, it also can be procured in flat, ribbon-like lengths.

An oxidation dissolver called **rosin** must be used when soldering in electrical or electronic work. Although a connection may be cleaned until it is bright and shiny (as it should be), application of heat during the soldering process causes the connection to rapidly oxidize again. Rosin melts at low temperatures and forms a coating to protect the metal from air while heat builds up to melt the solder.

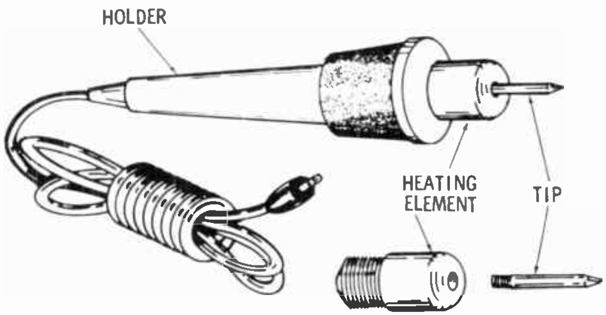
Rosin can be purchased separately in a tube or a can, but solder that contains a core of rosin can be purchased. Such a combination is called **rosin-core solder** and is recommended for all soldering in electrical circuits.

Some solders contain an **acid paste** in the core. **Do not use acid-core solder.** It corrodes metals used in electrical and electronic equipment. The corrosive effect eats away metal and leaves a nonconducting layer having a very high insulation resistance.

Soldering Tools

A soldering iron or gun is used to melt solder. For most electrical work, either is usually suitable. However, each has certain advantages for specific jobs. The gun (pistol-shaped) provides heat within a few second at the touch of a trigger, but is usually heavier, larger, and more difficult to use in close quarters than an iron of the same rating. An iron reaches soldering temperature slowly and must be unplugged to cool, but is usually less expensive than a gun.

SOME SOLDERING IRONS HAVE REMOVABLE TIPS AND HEATING ELEMENTS



The heating power of an iron and gun is rated in watts. Irons are available with ratings from 6 watts or less to 500 watts and more. The larger irons are for heavy industrial use. Irons rated from 25 to 75 watts are best for most electronic work. Remember to use no more heat than necessary to obtain a properly soldered connection.

A variety of tips can be used with the iron pictured above. At least one should be a **spade tip** which is most useful for general-purpose soldering.

Q1. For electronic work, solder should be a(an) ____ alloy and have a _____ core. The iron should be __ __ __ watts.

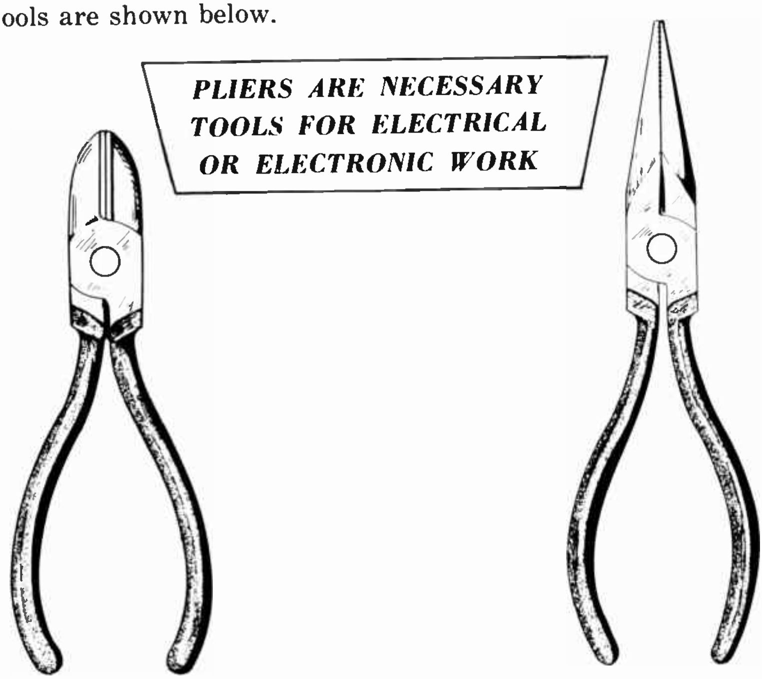
> **Your Answer Should Be:**
>
> **A1.** For electronic work, solder should be a **60/40** tin/lead **25 to 75** alloy and have a **rosin** core. The iron should be **30 to 40** watts.

SOLDERED CONNECTIONS

You will often hear that a good, tight **mechanical connection** is required before soldering. This means a connection that will remain tightly bound between wire and wire, or wire and terminal. It must not be movable during the soldering process and it must be strong enough to resist jarring loose under normal equipment operation.

Tools for Making Connections

In addition to an iron, other tools for soldering are needed. Although primarily used when making a mechanical connection, these tools have other useful purposes. Two such tools are shown below.



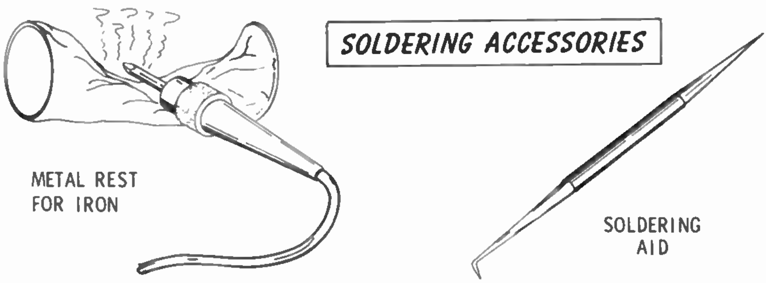
DIAGONAL CUTTERS

NEEDLE-NOSE PLIERS

Diagonal Cutters—Diagonal cutters, also called "dikes," are used for cutting wire, trimming leads and terminals to length, and stripping insulation from wire.

Long-nose, or needle-nose, pliers—Long-nose pliers are used to hold materials in place, form wire to the shape of terminal connections, make wire splices, and as a means of diverting soldering heat from delicate parts.

Metal Stand (Rest) for Iron—A soldering-iron stand is a useful accessory for soldering work. One can be purchased, but you can easily make one from a small tin can. Flatten one side of the can by bending a small area of the top and bottom rims outward. Just enough bending is needed to keep the can from rolling. A dent placed in the top forms a seat for the iron. Placed on the rest, the iron will not be free to burn other material on the bench, and contact with the can helps draw away excess heat.



Soldering Aids—Soldering aids come in several shapes. They are used primarily to remove excess solder during soldering and unsoldering. The one shown above has a sharp point and hook. An ice pick can also be used.

Q2. "Dikes" can be used to cut wire and remove ___________.

Q3. Long-nose pliers can be used as a means of bypassing ____ during a soldering job.

Q4. An ice pick can be used to remove excess ______ while unsoldering.

Q5. A wire splice must be mechanically tight so the wires will not ____ during soldering.

Q6. __________ must be removed from bare wires before they can be soldered.

Your Answers Should Be:

A2. "Dikes" can be used to cut wire and remove **insulation.**

A3. Long-nose pliers can be used as a means of bypassing **heat** during a soldering job.

A4. An ice pick can be used to remove excess **solder** while unsoldering.

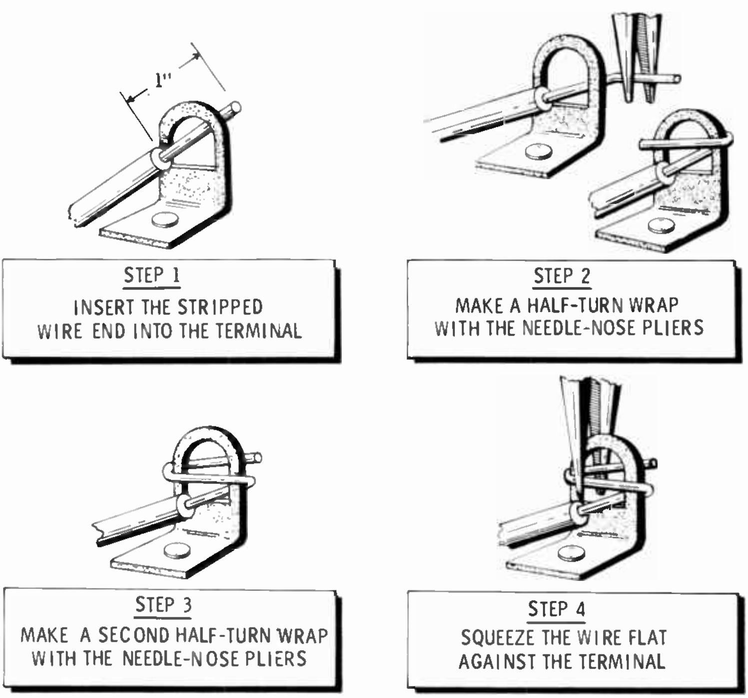
A5. A wire splice must be mechanically tight so the wires will not **move** during soldering.

A6. **Oxidation** must be removed from bare wires before they can be soldered.

Connections Between Terminals and Wires

Below is the proper way to splice a wire to a terminal.

CONNECTING TO A TERMINAL



Preparing the Wire—The insulation must first be removed from the end of the wire. From ⅜ to 1 inch or more of bare wire is needed, depending on the type of connection to be made. If the wire is not bright and shiny, it probably has an oxidized film on it. The film should be removed by scraping with a knife or rubbing with fine sandpaper.

Preparing the Terminal—A new terminal (one never used) will be ready for the splice. It has been coated with metal to which solder will readily adhere. If the terminal is not shiny and silvery color, it should be cleaned also. Sandpaper, with the help of a knife point, will do the trick. If the terminal has been previously used, remove all excess solder. This can be done by heating the terminal and wiping the melted solder away with a rag or a small wire brush. Care must be taken to prevent any of the molten solder from being splattered onto your skin or into your eyes.

Making the Connection—Follow the steps shown in the illustration on the opposite page to make a connection. If two or more wires are to be secured to a terminal, make the connection for each in the same manner. This can be done individually or by the wires together as a group.

After making the connection, test it carefully. Check the length of the bare wire left between terminal and insulation. Too much bare wire (over ⅜″) may be the cause of future shorts. Wiggle and tug on the connection. Make sure the wire does not move on the terminal.

Q7. From _ to _ inch or more of bare wire should be exposed for connection to a terminal.

Q8. The wire should be wrapped through and around the terminal with _________ pliers.

Q9. Wire should be squeezed tight on the terminal for a strong ___________ connection.

Q10. Wires and terminals must be clean. They can be cleaned with a knife or __________.

Q11. Exposed wire should be no longer than ____ inch from terminal to insulation.

Q12. If the connection moves while being wiggled or tugged, what should be done?

Your Answers Should Be:

A7. From ⅜ to 1 inch or more of bare wire should be exposed for connecting to a terminal.

A8. The wire should be wrapped through and around the terminal with **long-nose** pliers.

A9. Wire should be squeezed tight on the terminal for a strong **mechanical** connection.

A10. Wires and terminals must be clean. They can be cleaned with a knife or **sandpaper.**

A11. Exposed wire should be not longer than ⅜" from terminal to insulation.

A12. If the connection moves while wiggled or tugged, unsolder it and resolder it more carefully.

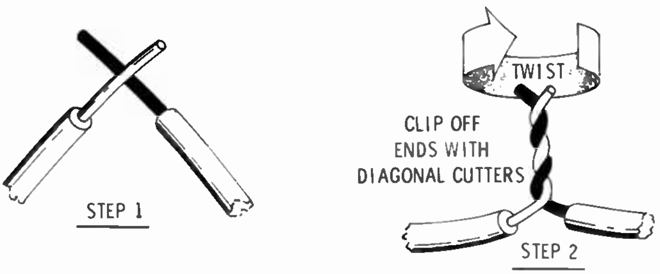
Wire-to-Wire Connections

Wire-to-wire connections are also made by splices that are mechanically strong. Three common splices are shown below.

Pigtail Splice—This splice is easily made. Cross the wires, as shown in the illustration, and begin twisting the wires together. The twist should be started by hand and completed with pliers to make sure the splice is tight. Do not exert too much pressure or the wires may break at the bottom of the splice.

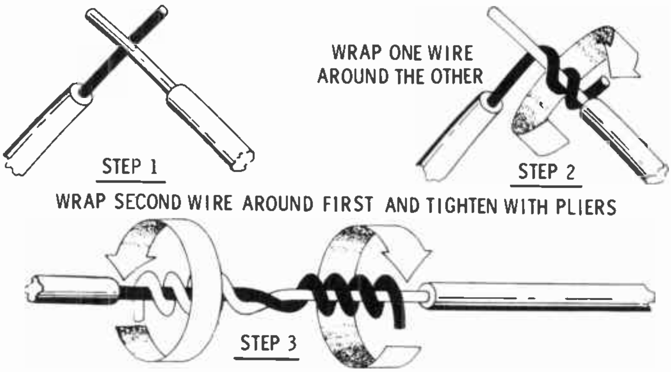
After the splice has been soldered, fold it back and alongside one of the wires. Wrap plastic insulating tape around the splice. The wrap should have two or three layers if the wire is used for 115-volt purposes.

THE PIGTAIL SPLICE



Western Union Splice—Developed in the early days of the telegraph, the Western Union splice is neat and mechanically tight if properly made. Starting from the crossed-wire position, wrap one wire neatly around the other. Keep the coils close together. Do the final tightening with a pair of pliers. Then straighten the wires as in Step 3. Wrap the second wire closely around the first and tighten. There should be at least four coils on each side of the junction. Solder, then wrap the splice with plastic tape.

THE WESTERN UNION SPLICE



Stranded-to-Solid Splice—Twist the stranded wire into a straight, tight spiral and wrap around the solid wire as in Step 2 of the Western Union splice. Make at least a half-dozen turns. Fold and tightly crimp the end of the solid wire over the turns. Solder and wrap the splice with tape.

Q13. A pigtail splice is made by _________ wires together.

Q14. A Western Union splice is made by _________ one wire around the other to form tight coils.

Q15. In a stranded-to-solid splice, the _________ wire should be wrapped around the _____ wire.

Q16. After a splice has been formed by hand it should be tightened with ______.

Q17. The splice should then be _________ and _____.

Q18. Before making any splice, the bare wires should be ________.

Your Answers Should Be:

A13. A pigtail splice is made by **twisting** wires together.

A14. A Western Union splice is made by **wrapping** one wire around the other to form tight coils.

A15. In a stranded-to-solid splice, the **stranded** wire should be wrapped around the solid wire.

A16. After a splice has been formed by hand it should be tightened with **pliers.**

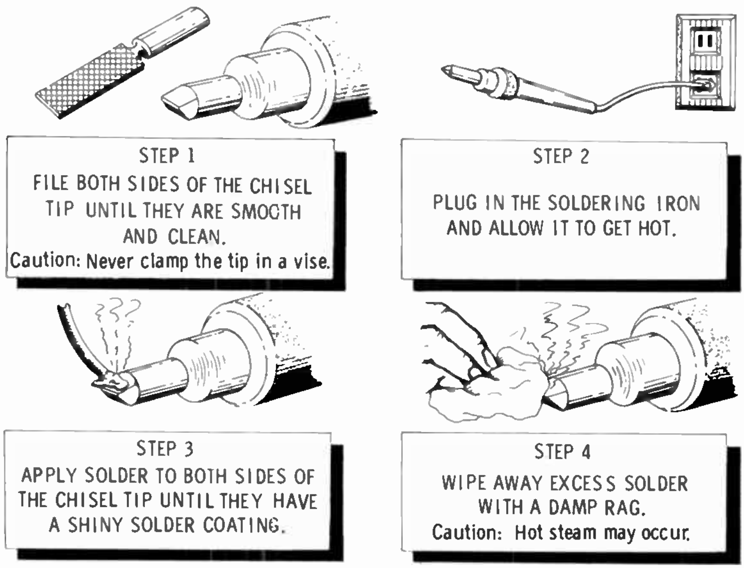
A17. The splice should then be **soldered** and **taped.**

A18. Before making any splice, the bare wires should be **cleaned.**

SOLDERING

The tips of some soldering irons need to be **tinned.** Any tip that is corroded needs to be retinned and, if dirty, needs to be wiped clean with a rag. Tinning (with solder) is the process of applying a protective coating of solder on the copper tip to prevent corrosion. The process is shown below.

TINNING A SOLDERING IRON

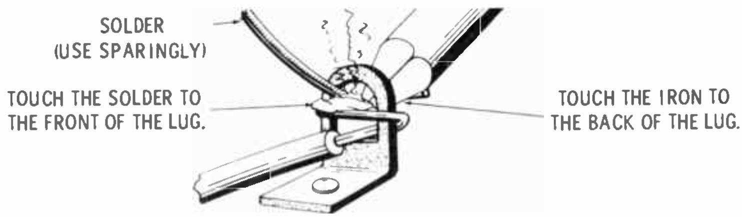


Soldering Wire to a Terminal

A good solder joint has just enough solder to bond the splice together; has a smooth, semishiny, unblemished appearance; and has edges that seem to blend cleanly and smoothly into the terminal and wire.

Any other appearance is a sign of improper soldering. A large glob on the terminal indicates too much solder was applied. The temperature of the metal was too low if the joint has a dull and pitted appearance, or a ball of solder that does not blend into the metal.

SOLDERING TO A TERMINAL



The iron should be applied to the back side of the terminal and held firmly against the wire. After a few seconds, touch the solder to the wire at the front of the terminal. If the solder readily melts, the connection is sufficiently heated. If the connection is not hot enough, remove the solder and continue heating until it is. Do not touch the solder to the iron.

When the connection is hot enough, touch the solder to the wire in front of the terminal. Rosin will melt and coat the connection. Let the solder flow to the terminal and the iron. It will flow properly when the connection is the right temperature. When the connection has been coated (not just covered) with solder, remove the length of solder. Leave the iron on the connection to boil away the rosin. If any rosin remains under the solder, an insulation barrier will be formed. Now remove the iron and let the connection cool. **Do not move the joint while it is cooling.**

Q19. The copper tip of a soldering iron must be ______ to prevent corrosion.

Q20. Solder is applied to a connection (at the same time as, some time after) the iron is applied.

Q21. Solder is applied to the (connection, iron).

Your Answers Should Be:

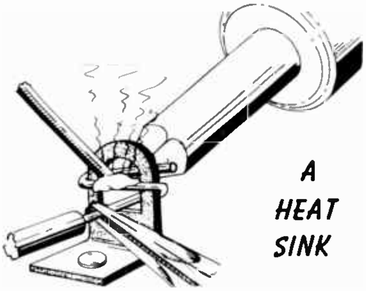
A19. The copper tip of a soldering iron must be **tinned** to prevent corrosion.

A20. Solder is applied to a connection **sometime after** the iron is applied.

A21. Solder is applied to the **connection.**

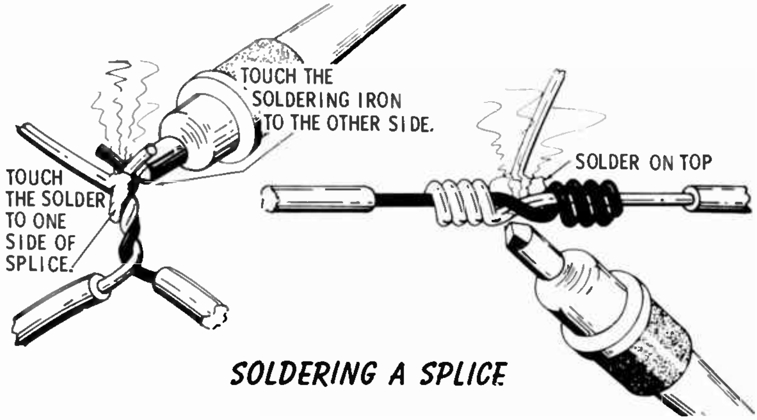
Soldering a Splice

Quite often heat from the soldering iron may melt or burn the insulation on a wire being soldered, or may damage a component (resistor, transistor, etc.). Heat from the iron travels rapidly down the wire.



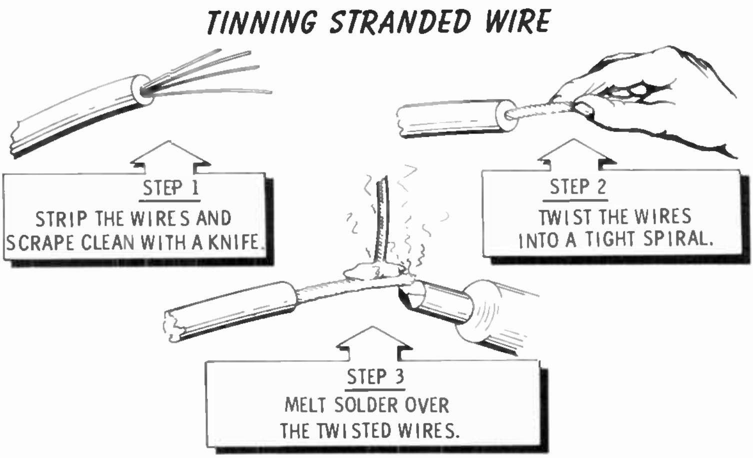
To prevent this, use the long-nose pliers as a **heat sink.** Grip the wire between the terminal and insulation, or the lead between the component and connection, as shown in the illustration. The iron in the pliers dissipates most of the heat before it can travel further down the wire.

The correct positions of iron, connection, and solder while soldering splices is shown below. **Let the solder flow to the iron through the connection.**



SOLDERING A SPLICE

Tinning Stranded Wires—Conductors made up of several small wires are called **stranded wires.** When the insulation is stripped back, the small wires tend to fan out. In fact, the wires are very difficult to keep together, especially when an attempt is made to fasten them under a screw-down terminal. Connecting stranded wire to a terminal often leaves an untidy job with one or more of the small wires pointing away from the connection. Many shorts have been caused by stray wires from a stranded conductor. This problem can be solved by tinning the strands.



After the tinned strands have cooled, shape the wire to fit the terminal to which it will be connected. If it is a screw-down terminal, place the end of the wire in the jaws of the long-nose pliers and bend the wire over the rounded back to form a loop. Slip this around the screw. If the wire is to go into a terminal or around a solid wire instead, use the pliers to form it to the object.

Q18. _________ ______ make a good heat sink.

Q19. A heat sink placed between the insulation and the ___________ will help keep the insulation from being melted or burned.

Q20. Wires of a stranded conductor can be kept together by ________.

Q21. Solder should flow to the ____ through the ___________.

Your Answers Should Be:

A18. **Long-nose pliers** make a good heat sink.

A19. A heat sink placed between the insulation and the **connection** will help keep the insulation from being melted or burned.

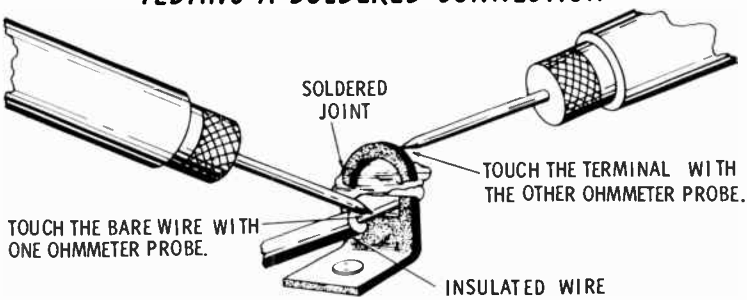
A20. Wires of a stranded conductor can be kept together by **tinning.**

A21. Solder should flow to the **iron** through the **connection.**

Checking a Soldered Connection

One way to test a solder job is with an ohmmeter. A good solder connection has zero resistance. The procedure is shown below. In making the test, touch the test probes to the metal of the pieces that are joined. Do not touch the probes to the solder itself.

TESTING A SOLDERED CONNECTION

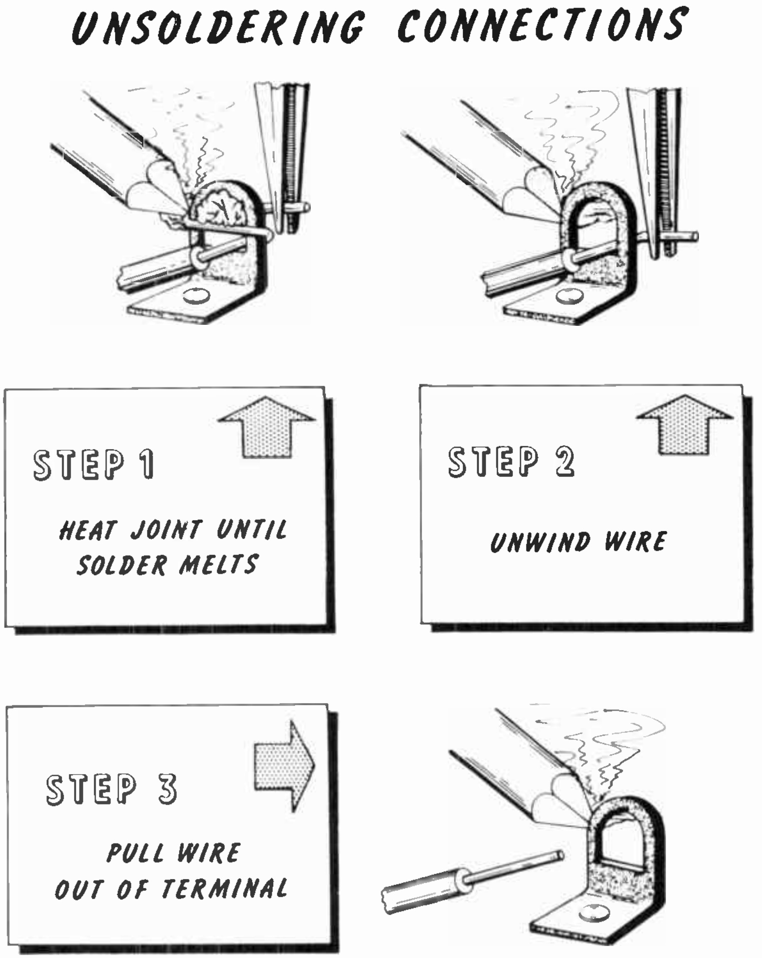


An ohmmeter test does not always reveal a poor soldering job. But if the meter reads zero; the solder looks neat, smooth, semishiny, and well blended into the metal; and you observed all the precautions, the connection should be electrically good. The precautions are restated below.

1. Never solder with a cold iron.
2. Never solder with an untinned or dirty iron tip.
3. Let the solder flow to the iron through the connection.
4. Let just enough solder flow to coat the connection.
5. Burn away all rosin. Any left beneath the solder will cause the insulating effect of a **rosin joint.**

Unsoldering Connections

It is quite often necessary to disconnect a component or a wire from a soldered terminal. The procedure is relatively simple if you take care to do it correctly and make sure that you do not burn or char any of the nearby parts. Follow the steps as outlined here.



Place an ice pick or soldering aid into the eye of the terminal by following Step 3. This will prevent the opening in the terminal from remaining filled with solder.

WHAT YOU HAVE LEARNED

1. Rosin-core, 60/40 solder should be used in electrical and electronic work.
2. A soldering iron for electrical work should have a rating of 25 to 75 watts.
3. Diagonal and long-nose pliers are required to make splices and as help in soldering. A soldering aid is also helpful.
4. If wires or terminals are not cleaned of oxidation prior to soldering, a high-resistance connection may result. Cleaning can be done with a knife and/or sandpaper.
5. Wires joined to terminals or wires must form a tight mechanical connection.
6. A pigtail splice is formed by twisting wires together; a Western Union splice is made by wrapping each wire in tight coils around the other.
7. Soldering irons are tinned by filing off the oxidation and coating the tip with solder.
8. When soldering, certain precautions must be followed to obtain a good electrical connection. These are:
   - a. Never solder with a cold iron.
   - b. Never solder with an untinned tip or one that is dirty.
   - c. Let the solder flow to the iron through the connection.
   - d. Let just enough solder flow to coat the connection.
   - e. Burn away all rosin.
   - f. Do not move the connection while it is cooling.

9

Understanding Transformers

What You Will Learn

Man has learned how to improve the usefulness of AC voltage by converting it to higher and lower values. In this chapter you will learn how a transformer can accomplish this. When you have finished, you will be able to explain what transformers are, how they are used, and how they are connected into circuits.

WHAT IS A TRANSFORMER?

A transformer is an electrical device which converts AC voltages and current from one value to another. Transformers are made in a number of varieties and sizes. Large transformers are used to furnish 115 volts AC for homes. The voltage at the generating plant may be several thousand volts, which is reduced to the 115-volt level by a series of transformers along the power line leading to the user. The final step-down in voltage is usually accomplished by a transformer on a utility pole near the user's home.

There are transformers in most homes also. Door bells or chimes usually operate on 12 or 16 volts AC. A transformer changes the house voltage of 115 volts to the bell-ringing voltage. Most radios, television receivers, record players, stereo systems, etc., contain one or more transformers. Some of these convert the 115 volts to lower or higher voltages to operate the sets; other transformers are used as connecting links between circuits.

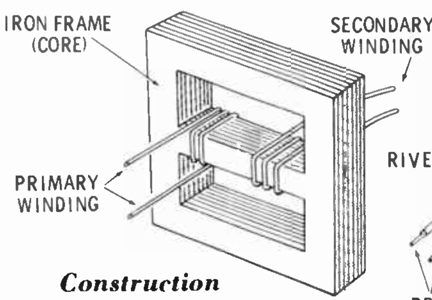
HOW DO TRANSFORMERS WORK?

Transformers contain coils of wire wound on an iron frame. As you learned in earlier chapters, AC flowing through a coil develops a magnetic field that expands and contracts in step with the changes in the current. The magnetic field of one coil **induces** current to flow in the other coil by cutting through the turns of wire.

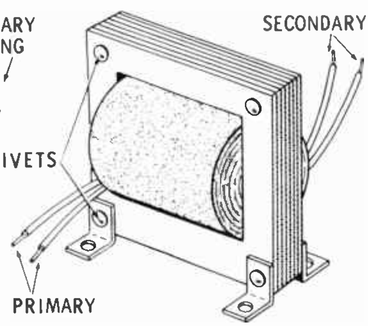
Transformer Windings

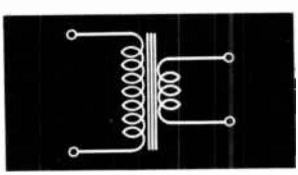
The basic transformer is constructed with two coils wound around a single **core** (iron frame). The coils are called **windings.** The input side is the **primary winding,** and the output side, the **secondary winding.**

A BELL TRANSFORMER

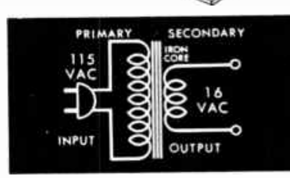


Construction





Schematic Symbol



Connections

The Primary Winding—The primary winding is the input to the transformer. It receives AC voltage and current from a source. The primary of the bell transformer, for example, is connected to a 115-volt line.

The Secondary Winding—The secondary winding is the output from the transformer. Its voltage and current values are different from those in the primary. In the bell transformer, the 115 volts applied to the primary is converted to a 16-volt AC output in the secondary.

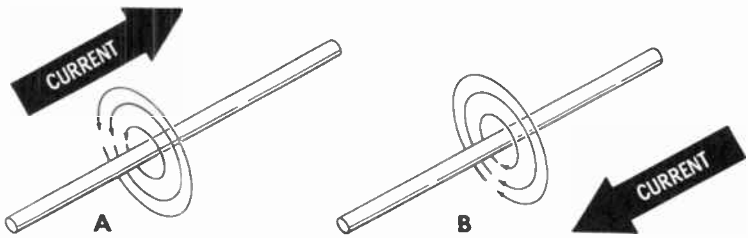
Fundamental Principle

The transfer of energy that takes place between the coils of a transformer is called **transformer action.** Transformer action is based on the fundamental electrical principle of a **moving** magnetic field being able to induce current in a conductor.

There are two facts regarding the relationship of current and a magnetic field:

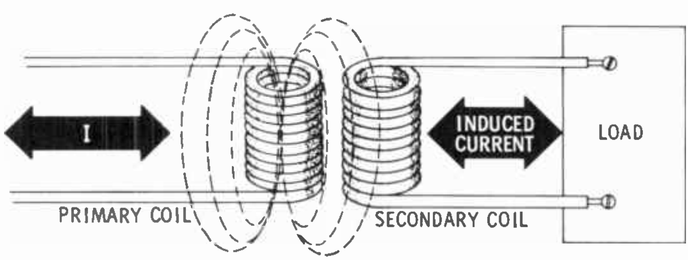
1. **A current flowing in a conductor develops a magnetic field about the conductor.** As shown in the illustration, the direction of the lines of force in the field depend on the direction of the current flow. In part A, the lines of force are counterclockwise—in part B, clockwise.

CURRENT FLOW CAUSES A MAGNETIC FIELD



2. **Magnetic lines of force cutting through a conductor cause current to flow in that conductor.** The field must be **moving.** In a single conductor, the current is very small. If the conductor is formed into a coil, many turns will be cut by the moving field, thus developing a larger current. An example is shown below.

A MOVING MAGNETIC FIELD CAUSES CURRENT FLOW



Q1. Magnetic lines must be (moving, stationary) to induce current in a conductor.

Your Answer Should Be:

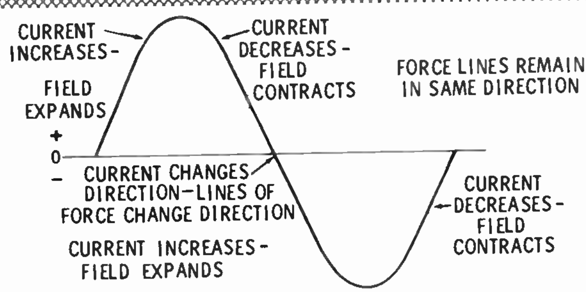
A1. Magnetic lines must be **moving** to induce current in a conductor.

Transformer Action

The requirements for induced current are that magnetic lines of force must cut through a conductor and the magnetic field must be moving (expanding outward or contracting inward).

DC Current—Direct current, as you know, maintains a steady level and always flows in the same direction. Does DC induce current to flow in another conductor? It produces a magnetic field whose strength (number of force lines) is proportional to the number of amperes flowing. But the magnetic field remains steady, neither expanding nor contracting. Therefore, DC does not induce current in another conductor.

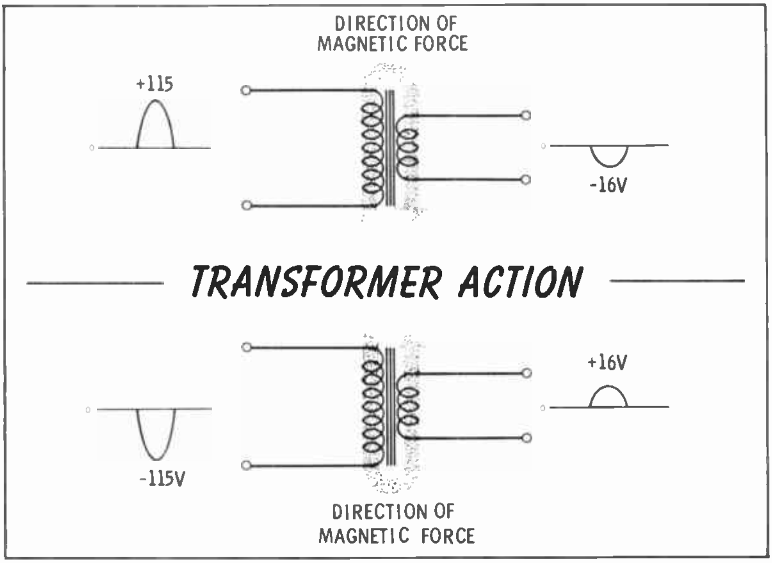
AC Current—Does alternating current induce electrons to flow in another conductor? Yes, because AC is constantly increasing and decreasing in value. The magnetic lines of force generated by the AC increase and decrease correspondingly. The magnetic field expands outward and contracts inward as the value of current changes. This means that the magnetic lines of force change direction as the current changes from the positive half cycle to the negative half cycle.



AN AC MAGNETIC FIELD IS CONSTANTLY EXPANDING AND CONTRACTING

The diagram on the opposite page demonstrates how the magnetic field expands and contracts with the rise and fall of current. The field is in constant motion. An alternating current, therefore, induces current to flow in another conductor or coil. In this case, the induced current will also be alternating.

Energy Transfer—An applied AC voltage causes current to flow in the primary winding of a transformer. This causes a changing magnetic field which induces a current to flow in the secondary. The induced current will develop an AC voltage across the secondary winding. Therefore, it is the nature of the voltage and current in the primary to transfer energy to the secondary in the form of a voltage and current. Transformer action for one full cycle of AC voltage is shown below.



Q2. AC current develops a changing ________ _____.

Q3. A changing magnetic field develops a(an) ___________ _______ in a conductor.

Q4. To induce current, a field must ____ through a conductor.

Q5. __ but not __ induces current in a conductor.

Your Answers Should Be:

A2. AC current develops a changing **magnetic field.**

A3. A changing magnetic field develops an **alternating current** in a conductor.

A4. To induce current, a field must **move** (or cut) through a conductor.

A5. AC but not DC induces current in a conductor.

TRANSFORMER CHARACTERISTICS

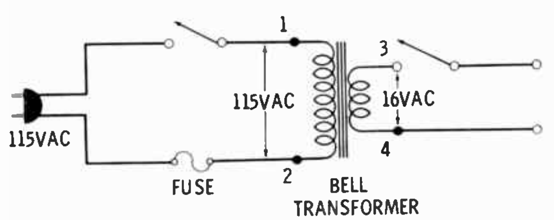
Now that you understand the fundamental principles of the transfer of energy (voltage and current) from primary to secondary, you are ready to learn how transformers are rated.

Basic Transformer Circuit

Below is a schematic diagram of a basic transformer circuit. This circuit demonstrates the principles and characteristics of nearly all transformers.

If you decide to build the circuit, a bell transformer can be purchased in most hardware stores. The circuit contains a fuse (note the symbol) to protect the transformer. If the secondary of the transformer should accidentally have a short placed across it, the short circuit will be reflected back into the primary, causing the primary current to increase to a large value. If this happens, the fuse will blow instead of the transformer windings burning out.

A Basic Transformer Circuit



The lines between the primary and secondary windings indicate an iron core which provides an easier path for the magnetic field through the coils.

Voltage Ratio

One of the specifications for rating transformers is stated in terms of **a voltage ratio.** This ratio is a comparison of primary voltage to secondary voltage, and is written as:

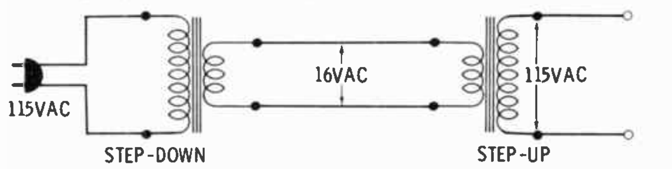
$$\text{Voltage ratio} = \frac{\text{primary voltage}}{\text{secondary voltage}}$$

Remember, the primary voltage is on the input side of the transformer and secondary voltage on the output side.

Step-Down Transformers—A **step-down transformer** is one having an input (primary) voltage larger than its output (secondary) voltage. The bell transformer is an example of a step-down transformer. Its voltage ratio is 115 to 16. It can be written as 115/16 or 115:16.

Step-Up Transformers—The input voltage of a **step-up transformer** is smaller than its output voltage. The transformer steps up the primary voltage to a higher value in the secondary. The distinction between step-up and step-down transformers is one of use only. As the following diagram shows, the same transformer can be used for either purpose.

STEP-DOWN AND STEP-UP CONNECTIONS



Q6. What is the voltage ratio of the step-up transformer in the diagram?

Q7. A(an) ____ ____ in a transformer helps direct the magnetic field through the coils.

Q8. For a given magnetic field, (more, less) current is induced in a straight wire than if it were wound into a coil.

Q9. A DC current does not induce current in a coil because its magnetic field is (moving, stationary).

Q10. Induced current flows in the (primary, secondary).

Your Answers Should Be:

A6. The voltage ratio of the step-up transformer is **16/115 (or 16:115).**

A7. An **iron core** in a transformer helps direct the magnetic field through the coils.

A8. For a given magnetic field, **less** current is induced in a straight wire than if wound into a coil.

A9. A DC current does not induce current in a coil because its magnetic field is **stationary.**

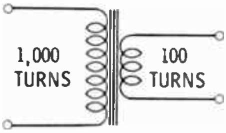
A10. Induced current flows in the **secondary.**

Turns Ratio

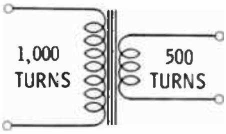
Since transformers must have a variety of different voltage ratios, what is there about transformer action that permits this to occur? Look at Answer 8 above and then answer the question. If one coil turn (loop) will induce a certain voltage, two turns will develop twice as much, and 100 turns 100 times as much.

Therefore, the voltage ratio between the primary and secondary windings depends on the turns ratio between the two windings. The diagram below shows an example.

VOLTAGE RATIO IS PROPORTIONAL TO TURNS RATIO



(A) 10 VOLTS/1 VOLT



(B) 10 VOLTS/5 VOLTS

Parts A and B both have 1,000 primary turns each. (This is an example only—a transformer might have many more.) The secondary winding of the transformer in Part A has 100 turns. The turns ratio is therefore 1000/100, or 10/1. If ten volts were placed across the primary, the turns ratio would produce 1 volt in the secondary. If 20 volts were applied to the primary (providing the wire could handle the increased current), the output would be 2 volts, etc.

In Part B, a turns ratio of 1000/500 (or 2/1) permits a voltage ratio of 10/5. If the primary voltage were reduced to 5 volts, there would be 2.5 volts on the secondary.

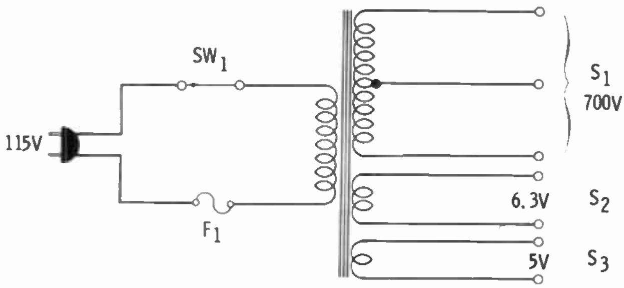
If current is doubled in the primary, the magnetic field strength will also double. Twice as many lines of force will cut the secondary and induce twice as much current. Secondary voltage will also be doubled.

But would the proportions of the voltage ratio be changed? No. To double the primary current, the primary voltage must be doubled. The voltage ratio would be increased in number but remain the same in proportion.

The reason voltage ratios are given in voltage figures instead of reduced fractions is to advise the user what the correct input voltage should be. Wire size of the windings is selected for the amount of current that will flow at that voltage. If voltage is increased beyond the rated figure, the increased current may burn the winding.

While the voltage ratio is usually given in voltage figures, the turns ratio is reduced to its lowest terms. For example, a turns ratio of 25,000/10,000 would be expressed as 5/2.

POWER TRANSFORMER



The diagram above shows a power transformer similar to those used in some radio receivers. It has three secondary windings—S_1, S_2, and S_3. Disregard the center tap on S_1.

Q11. The voltage ratio of the primary to S_1 is ______.

Q12. The turns ratio of the primary to S_3 is ______.

Q13. The transformer (does, does not) have an iron core.

Q14. The symbol designated by F_1 is a(an) ____.

Q15. Would S_1 increase to 1,400 volts if the primary were connected to a 230-volt source?

Your Answers Should Be:

A11. The voltage ratio of the primary to S_1 is **115/700.**

A12. The turns ratio of the primary to S_3 is **23/1.**

A13. The transformer **does** have an iron core.

A14. The symbol designated by F_1 is a **fuse.**

A15. S_1 would probably **not** increase to 1,400 volts. (Doubling the current in the primary would undoubtedly blow F_1, so there would be no voltage on either side of the transformer.)

Frequency Rating

Another transformer rating is the AC frequency for which the transformer is designed. Frequency, as you recall, is measured in cycles per second. DC has zero frequency because its voltage does not vary. AC voltage varies because its value rises and falls during its positive half cycle followed by a similar rise and fall in the negative direction. The frequency of the voltage is the number of times a complete cycle repeats in a second.

Transformers are designed to operate at one specific frequency. Wire, insulation, and core material are selected to operate efficiently at the number of times the voltage (current) values rise and fall and change direction.

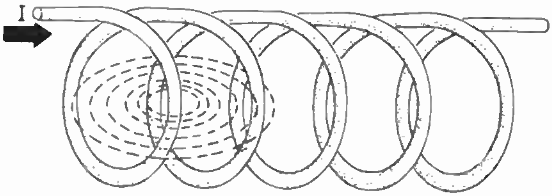
Reactance—You are aware that the atomic structure of a resistor or wire offers a resistance to the flow of electrons (current). Electrons find it twice as difficult to flow through a 2,000-ohm resistor as through one of 1,000 ohms.

Constantly changing AC current encounters a similar **reaction** when flowing in a coil. Expanding and contracting lines of force cut through the primary coil (the conductor in which they were developed) as well as the secondary winding.

As the illustration on the next page shows, the magnetic field induces a current in its own coil that tends to oppose the coil current. These two currents react against each other. This characteristic is called **inductive reactance.** It opposes or limits the flow of AC just as resistance limits AC or DC in a resistor.

For purposes or simplicity, only one segment of the total force lines is shown in the diagram. Keep in mind that the magnetic field actually surrounds the conductor at every point along its length.

MAGNETIC LINES CUTTING AN ADJACENT TURN



Reactance is directly related to frequency. The amount of reactance in a coil is determined by the frequency of the current and by the number of turns of wire in the coil. The greater the number of times the magnetic field changes direction in a second, the more times adjacent turns will be cut, and the greater will be the opposing current.

Coils and transformers are designed to operate at the reactance established by the designated frequency. For example, a coil may have a reactance of 30 ohms to a current whose frequency is 60 cycles per second. If the coil is connected to a 600-cycle source, its reactance will increase to 300 ohms. Since reactance is an opposition to AC, the current through the coil will be less with the 600-cycle source than with the 60-cycle source.

Suppose a 400-cycle transformer is connected to a 60-cycle 115-volt wall outlet. What will happen to the transformer? The reactance will be reduced by almost one fourth and almost four times as much current will flow. The excess current will probably burn the winding. Remember to check the frequency rating before connecting a transformer to a voltage source.

Q16. A full AC cycle contains _________ and _________ half cycles.

Q17. Transformers are designed to operate at one specific __________.

Q18. A transformer is designed to operate at 60 cycles per second. What will happen if it is connected to a DC source?

Your Answers Should Be:

A16. A full AC cycle contains **positive** and **negative** half cycles.

A17. Transformers are designed to operate at one specific **frequency**.

A18. A transformer designed for 60 cycles per second and connected to DC will have its winding burned. DC has a frequency of zero cycles per second and therefore a reactance of zero ohms. The only limit to the flow of current would be the low resistance of the wire.

WHAT YOU HAVE LEARNED

1. Transformers are electrical devices which convert AC voltage and current from one value to another.
2. Transformers contain at least one primary and one secondary winding. The windings are coils and are sometimes wound on iron cores.
3. Current flowing in a conductor develops a magnetic field about the conductor. Magnetic lines of force cutting through a conductor cause current to flow.
4. Transformers can be designed for AC but not for DC.
5. Transformer action is a transfer of energy. AC in the primary generates a magnetic field which induces current in the secondary.
6. Transformers are rated as follows:
   a. Voltage ratio. The voltage ratio specifies the number of volts transferred between the two windings. The transformer can be used as either a step-up or a step-down unit, depending on which winding is used as the input.
   b. Turns ratio. A ratio of primary turns to secondary turns.
   c. Frequency. Because of AC reactance, transformers are designed for use at a specific frequency. Use at any other frequency may damage the windings.

10

Understanding Capacitors

What You Will Learn

A capacitor is another very basic but highly useful circuit component. Since it can regulate current, as do resistors and coils, the capacitor is used for this purpose in most electronic and many electrical circuits. Upon completing this chapter, you will understand what capacitors are, how they are used and connected in circuits.

WHAT IS A CAPACITOR?

A capacitor has the ability to store electrical energy. Because it can do this, it is able to control the amount and the manner in which current will flow in a circuit.

Most electronic circuits consist of a combination of only three components—resistors, inductors, and capacitors. Each reacts in a different way to AC and DC voltage and current.

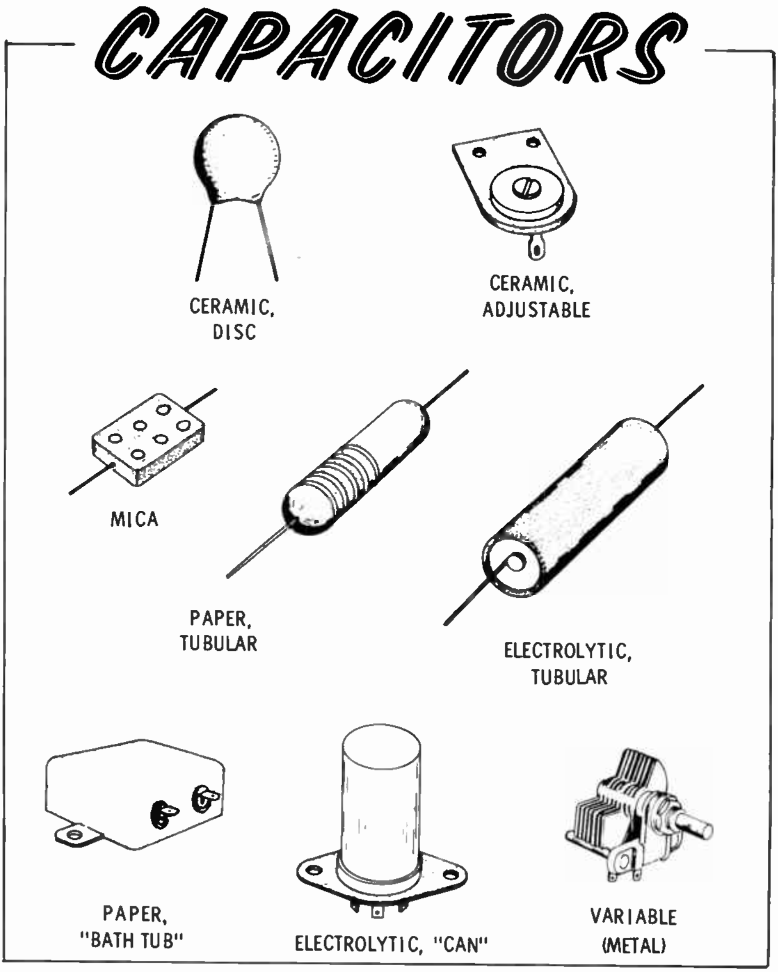
A **resistor**, as you recall, **controls** electricity by limiting the flow of current. This reaction is called **resistance.** It affects the flow of either AC or DC current.

An **inductor** controls electricity by regulating the flow of AC current. The magnetic field in an inductor cuts its own coils, developing a voltage that opposes a change in current. This is called **inductance.**

A **capacitor** controls electricity by also regulating the flow of AC current. It stores an electrical **charge** which opposes any change in current. This property is called **capacitance.**

HOW DOES A CAPACITOR WORK?

A capacitor, sometimes called a **condenser**, is manufactured in several shapes and sizes. A number of capacitors are shown below. You may recognize a few.

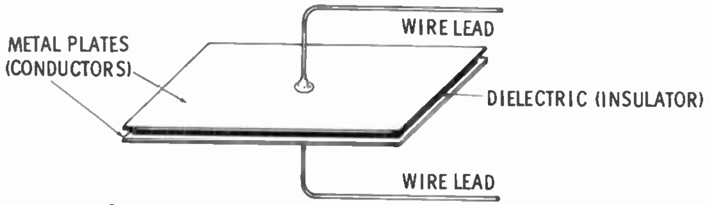


Several of each kind of capacitor are probably in your home. They can be found in radios, television receivers, intercoms, audio systems, and other electronic equipment. A capacitor is used with some electrical motors and even in the ignition systems of automobiles.

Basic Construction

Every capacitor is constructed in the same basic manner. An insulating material, called a **dielectric,** is sandwiched between two conductors (usually a pair of metal plates). A wire is connected to each plate to form the leads or terminals of the capacitor. Details are shown below.

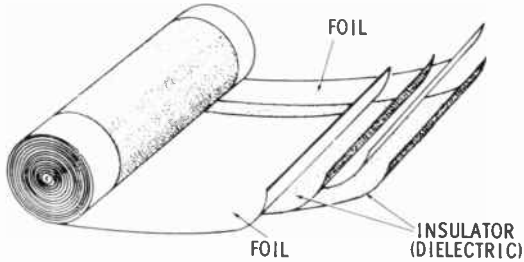
BASIC CAPACITOR CONSTRUCTION



This basic principle is elaborated upon to produce the shapes shown on the opposite page. For example, the plates of the variable capacitor are curved and exposed. Since air is an insulator, it forms the dielectric.

The tubular capacitor, as shown below, uses lengths of metal foil as the plates, which are separated by strips of treated paper to form a dielectric. Wire leads are connected to the exposed ends of the foil and the assembly is rolled into a tight spiral and placed in a case.

TUBULAR CAPACITOR



Q1. The opposition to current flowing through the atomic structure of material is called ___________.

Q2. The reaction of a changing magnetic field to current is called ___________.

Q3. The reaction of a stored electrical charge to current is called ____________.

Your Answers Should Be:

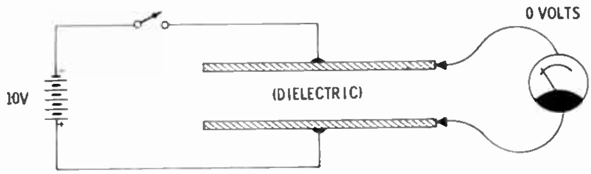
A1. The opposition to current flowing through the atomic structure of material is called **resistance.**

A2. The reaction of a changing magnetic field to current is called **inductance.**

A3. The reaction of a stored electrical charge to current is called **capacitance.**

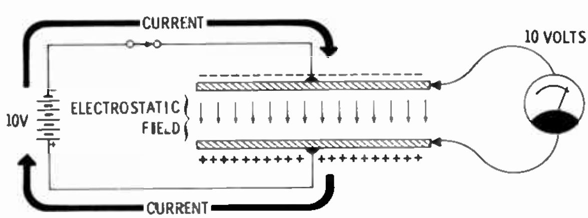
Electrical Principle

The structure of a capacitor obeys the fundamental principles of voltage and current as applied to conductors and insulators. Assume, as shown in the following diagram, that the plates of a capacitor are connected to a battery through a switch. An edge view of the plates is illustrated.



The open switch prevents the battery voltage from being applied across the capacitor. A voltmeter will show a zero voltage between the plates. This is normal, since all matter tends to seek a natural balance when no forces are applied.

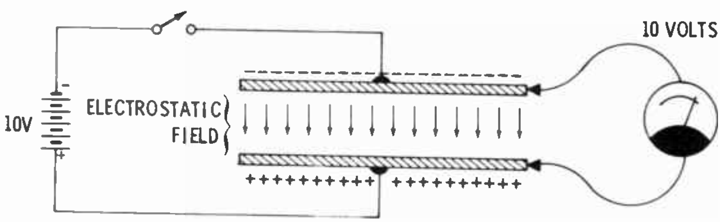
Suppose the switch is now closed. A first thought might be that no current would flow. Current does not flow through an insulator, and the dielectric is an insulator. Current in the circuit will flow, however.



Current will flow until a charge (voltage) of ten volts appears across the plates. The plates are conductors and therefore have electrons free to flow as current. Electrons have a negative charge. They are repelled (caused to move) by the negative pole of the battery and attracted by the positive pole. The positive terminal pulls electrons away from the bottom plate of the capacitor and the negative terminal forces them to accumulate on the top plate.

A deficiency of electrons results in a positive **potential** (voltage) on the bottom plate and an excess of electrons makes the upper plate negative. Current flows, rapidly at first, but more slowly as the voltage across the capacitor builds up to the same potential as the battery. When current ceases to flow, 10 volts will be across the capacitor.

A field of force, equal to ten volts, now exists between the two plates. This field is called an **electrostatic** force and has a direction as shown by the arrows—from negative to positive. The excess electrons are attracted to the positive plate (whence they came). It is this attraction that develops the force. Suppose the switch is now opened. Will the electrostatic force of 10 volts disappear?



The voltage across the capacitor is still 10 volts, just as it was before the switch was opened. The excess electrons remain where they are because there is no path for them to return to the positive plate (assuming the voltmeter has no internal resistance through which electrons can travel).

Q4. Electrons leave the capacitor plate connected to the _________ battery terminal.

Q5. Electrons are repelled by a _________ voltage.

Q6. The plate that has a(an) (excess, deficiency) of electrons has a negative charge.

Q7. A(an) ______________ force is set up between the plates of a charged capacitor.

Q8. The insulating material through which the force lines extend is called a(an) ___________.

Your Answers Should Be:

A4. Electrons leave the capacitor plate connected to the **positive** battery terminal.

A5. Electrons are repelled by a **negative** voltage.

A6. The plate that has an **excess** of electrons has a negative charge.

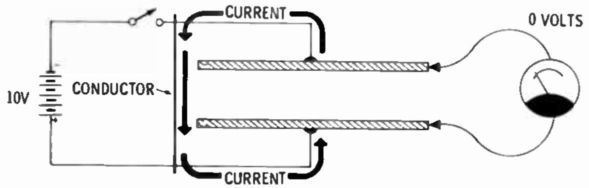
A7. An **electrostatic** force is set up between the plates of a charged capacitor.

A8. The insulating material through which the force lines extend is called a **dielectric**.

Capacitor Charge and Discharge

"**Charging**" is the term used when a capacitor is acquiring a potential. In the example on the preceding page, the capacitor was charged to 10 volts.

Some capacitors can be charged to extremely high voltages and will retain this charge for long periods. The capacitor in the high-voltage section of a TV receiver builds up to ten thousand volts or more. So be careful when working around capacitors. A capacitor can be discharged either through normal operation of a circuit or by shorting the capacitor leads.



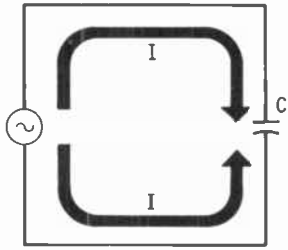
When the capacitor discharges, the excess electrons return to the positive plate, the difference in potential (voltage) between the two plates becomes zero, and the electrostatic force disappears. As a matter of fact, the voltmeter constitutes a circuit between the plates of the capacitor, thus forming a path for the electrons to return to the positive plate. The high resistance of the meter, however, limits the current, resulting in a long discharge time. This can be seen by watching the meter pointer.

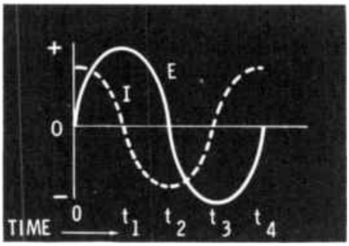
Effect on DC Current—As you have seen, a capacitor blocks the passage of DC current. Current flows only long enough to build up a charge equal to the source potential.

Effect on AC Current—You will often hear or read that AC flows **through** a capacitor. This is not true. As long as the dielectric retains its insulating quality (the applied voltage does not become great enough to puncture a path through the dielectric) very few electrons will pass through.

With AC voltage applied, electrons accumulate first on one plate and then the other, as the voltage changes polarity. But this electron current does not change in phase (in step) with the voltage. The diagram shows the schematic symbol and letter designation for a capacitor, and a graph of the current and voltage relationships.

Voltage and Current in a Capacitor





At time zero, the applied voltage starts to go positive. At that instant, current flow from one capacitor plate to the other is maximum. As the source voltage increases, 1 decreases because the charge on the capacitor is getting closer and closer to the applied E. When E reaches maximum positive (at time 1), the capacitor is charged to the same value. Current is zero. When source E decreases toward zero volts, capacitor E is greater and causes current to flow in the opposite direction. At zero source volts, current has become maximum negative (time 3). The difference and equality of the source voltage and the capacitor charge continue in the same time sequence for the next half cycle. As the graph shows, current is always a quarter of a cycle ahead of the source voltage.

Q9. Current leads AC voltage by a(an) _______ cycle in a capacitor circuit.

Your Answer Should Be:

A9. Current leads AC voltage by a **quarter** cycle in a capacitor circuit.

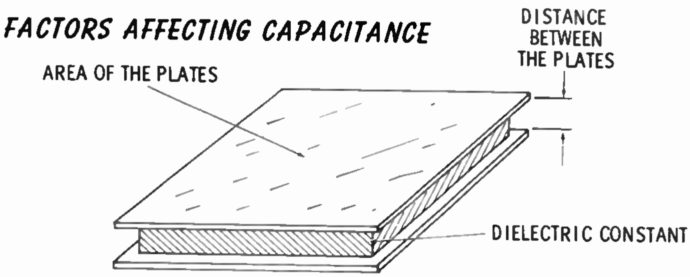
CAPACITOR CHARACTERISTICS

Before circuits are shown that prove the effects of a capacitor on AC and DC current, you must learn a little more about capacitor characteristics.

Units of Measurement

A capacitor is measured in terms of its capacitance, which is a definition of how many excess electrons it can store on one plate to develop a specific charge. A **farad** is the unit of capacitance just as ohm is the unit of resistance.

However, when a farad was first defined it was too large a unit for any practical purpose. Capacitors are either measured in microfarads (one-millionth of a farad), abbreviated μ(mu) or mfd, or in micromicrofarads, (one-millionth of a millionth of a farad), abbreviated $\mu\mu$f or mmf.



Capacitance (farads) is determined by three factors:

1. Area of the plates. Larger area, greater capacitance.
2. Distance between the plates. The closer the plates, the greater the capacitance.
3. Dielectric constant (type of material). A higher constant, a larger capacitance. The constant for air is given as 1. Paraffin paper is 3.5; mica, 6; flint glass, 9.9. For example, a mica capacitor would have 6 times as much capacitance as a capacitor with air as a dielectric, all other things being equal.

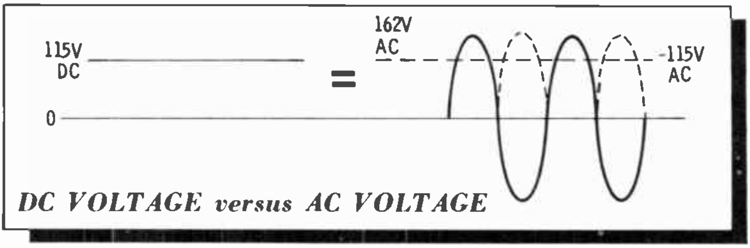
Voltage Rating

If the voltage applied across a capacitor is too large, the dielectric fails to maintain its insulating qualities. It breaks down under the stress of the electrostatic force and allows current to flow from one plate to the other.

Capacitors are given a **working-voltage** rating. This rating is the highest voltage that a capacitor can withstand without the possibility of creating a short-circuit through the dielectric. The type of material and thickness of the dielectric determines what the working voltage will be.

Since the distance between plates is one of the factors which determines the capacitance and working voltage, a capacitor having both a large capacitance and a high voltage rating will also have a large plate area.

A working-voltage rating pertains to a DC voltage or the **effective** value of AC. The peaks of an AC voltage wave are about 1.41 times its effective or working voltage. 115 volts DC and 115 volts AC are compared below.



DC VOLTAGE versus AC VOLTAGE

The peaks of 115 volts AC are actually 162 volts. A capacitor with a 150-volt rating will work well on 115 volts DC but not 115 volts AC. Standard practice is to use a capacitor with a working voltage about 50% higher than any voltage expected in the circuit.

Q10. A (thick, thin) dielectric gives more capacitance.

Q11. A small plate area develops (greater, less) capacitance than a larger area.

Q12. Glass is a (better, poorer) insulator than mica.

Q13. Working voltage is equal to the DC value or to the ---------- value of AC.

Q14. A higher working voltage will be possible with a (thicker, thinner) dielectric.

Your Answers Should Be:

A10. A **thin** dielectric gives more capacitance.

A11. A small plate area will develop **less** capacitance than a larger area.

A12. Glass is a **better** insulator than mica.

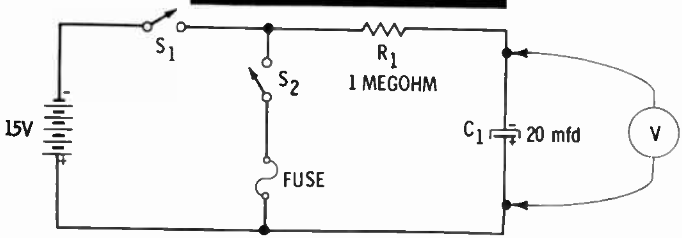
A13. Working voltage is equal to the DC value or to the **effective** value of AC.

A14. A higher working voltage will be possible with a **thicker** dielectric.

A TIMING CIRCUIT

A capacitor and a resistor can be placed in a circuit to operate as a timing device. If the values of R and C are carefully selected, the circuit can determine when an exact number of seconds has elapsed. This circuit contains components from previous circuits—a 15-volt battery, a 1-megohm resistor, and two switches, plus a 20-mfd electrolytic capacitor (connected as shown).

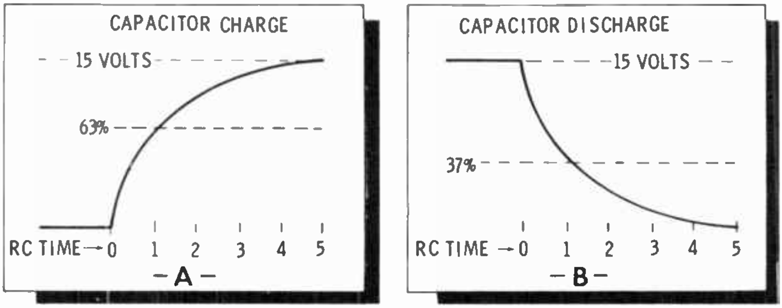
A TIMING CIRCUIT



The resistor limits the amount of current flow which charges C_1. The values of R_1 and C_1 determine the charge time.

If you have constructed the circuit, you can see the build-up of the capacitor charge (voltage) by watching the voltmeter. At the instant S_1 is closed, the meter pointer begins to move quickly across the scale. As the capacitor increases its charge (in opposition to battery voltage), current starts to decrease. The pointer moves slower and slower. Before it reaches 15 volts (full charge), its movement is almost impossible to see.

In an RC (resistance-capacitance) circuit, charge and discharge times are measured in RC seconds. Part A in the illustration below shows the rise of voltage across a capacitor during charge.



RC is a quantity obtained by multiplying R (ohms) by C (farads). Any capacitor in an RC circuit (such as this one) charges to 63% (actually 63.2%) of its final value (battery voltage) in one RC second. In 5 RC seconds it reaches full value. The arithmetic statements are:

$$\text{R(ohms)} \times \text{C(farads)} = \text{time(seconds)}; \text{ or}$$
$$\text{R(megohms)} \times \text{C(microfarads)} = \text{time(seconds)}$$

Since R is one megohm and C is 20 microfarads in the circuit on the opposite page, the capacitor charges to 63% of its full charge in 20 seconds. 63% of 15 volts is 9.45 volts. When the meter pointer reaches this value you know that 20 seconds have passed since closing S_1.

If you open S_1 and close S_2, the capacitor discharges at the rate shown in Part B (the exact reverse of Part A). The capacitor discharges to 37% of its full charge in one RC second, a value of 5.55 volts. The **RC time constant,** as it is called, holds true for any voltage.

Q15. How long does it take the capacitor in the circuit on the opposite page to charge to 15 volts?

Q16. If R_1 were 10 megohms and C_1 were 16 microfarads, how long would it take C_1 to charge to 9.45 volts?

Q17. If a 50-volt battery were used, how many seconds would it take the capacitor to reach 63% of full charge. What would the voltage be at that time?

Your Answers Should Be:

A15. **100 seconds.** (If one RC time is 20 seconds, 5 RC time constants equal 100 seconds.)

A16. **160 seconds.** (9.45 volts is the 63% level with a 15-volt source. 10(megohms) × 16(microfarads) is equal to 160 seconds.

A17. **160 seconds.** Regardless of the voltage, it will still take one RC time to reach 63% of full charge. 31.5 volts is the 63% level.

DC BLOCKING

By alternately manipulating the two switches in the preceding circuit, you can simulate what the capacitor will do if AC voltage is applied. Closing one switch charges (increasing AC voltage) the capacitor, and closing the other switch (and opening the first switch at the same time) discharges (decreasing AC) the capacitor.

Whether DC or AC, current in the circuit did not pass through the capacitor. Instead, it flowed back and forth through the circuit, collecting first on one plate and then on the other. The effect is that of AC being passed through the capacitor. This characteristic of a capacitor is used in most electronic circuits where it is necessary to control alternating current, but yet allow it to flow through the circuit.

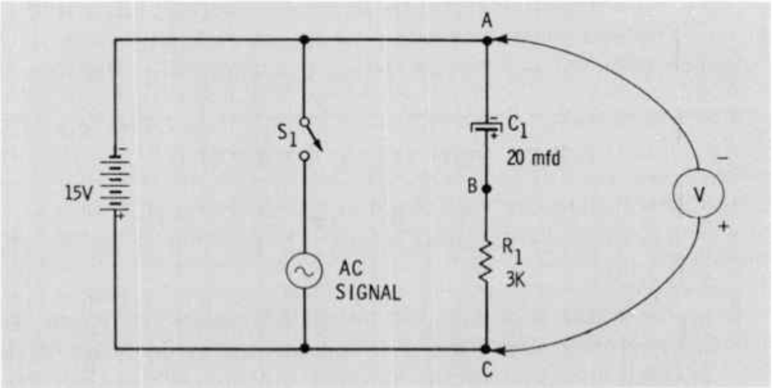
Transistors and vacuum tubes operate in electronic circuits with DC voltage applied to their elements. In nearly all such circuits, an AC signal is applied to the input of the circuit (to be amplified, for example). The AC must be allowed to pass through the amplifier, but the DC voltage must not. A capacitor can be used for this purpose—**blocking DC.** The circuit on the next page demonstrates how this is accomplished.

DC Blocking Circuit

The circuit which follows uses a 15-volt battery, a 3,000-ohm resistor, and a 20-mfd electrolytic capacitor.

How many volts would you expect to read with the meter probes connected to points A and C? Fifteen volts, the full battery voltage, is correct. Points A and C are directly connected to the battery. How many volts will appear between points B and C?

DC BLOCKING



To develop a voltage across R_1, current must flow through it. At the instant the circuit is connected, current flows from the lower plate of the capacitor through R_1 and the battery to the upper plate. In 5 RC times, the capacitor is fully charged and current stops flowing.

Applying the voltmeter across R_1 after this time gives a reading of zero volts. When current is not flowing through a resistor, a voltage drop is not present.

Applying an AC Signal—Closing S_1 applies an AC signal (voltage and current) across the same load. AC current flows back and forth from one plate of the capacitor to the other through the signal source. It also develops a voltage across R_1 that corresponds to the changes of the AC signal. Connections from B and C to another circuit would apply the changing voltage to the input of the second circuit. And no DC would interfere with its proper operation.

Q18. In the above circuit (without AC applied), how long does it take C_1 to charge to 63% of 15 volts?

Q19. The ________ terminal of an electrolytic capacitor must be connected to a negative voltage source.

Q20. After C_1 is charged, __ will not flow through R_1.

Your Answers Should Be:

A18. **0.06 second.** R_1 is 0.003 megohm and when it is multiplied by 20 microfarads, one RC time is 0.06 second, or 60 milliseconds.

A19. The **negative** terminal of an electrolytic capacitor must be connected to a negative voltage source.

A20. After C_1 is charged, DC will not flow through R_1.

WHAT YOU HAVE LEARNED

1. Capacitance controls the flow of AC current.
2. Capacitors are used in many electrical and electronic circuits.
3. A capacitor is a pair (or pairs) of plates separated by a dielectric. The dielectric, an insulator, does not pass current as long as the applied voltage is kept within the capacitor rating.
4. When a capacitor is connected to a voltage source, electrons move from one plate through the circuit and accumulate on the other plate. This charges the capacitor electrically and develops an electrostatic field between the plates. A capacitor discharges when the excess electrons on one plate return to the other plate.
5. DC current is blocked by a capacitor. AC "passes through" by alternately charging and discharging the capacitor.
6. The effect of an electrostatic charge on AC is to cause current in a circuit to follow the AC wave pattern a quarter of a cycle in advance of the voltage.
7. A capacitor is measured in farads, microfarads (mfd), and micromicrofarads (mmf). It has a working-voltage rating that should not be exceeded.
8. Capacitors can be used in a timing circuit where charge and discharge time is measured in terms of an RC time constant. Another use for a capacitor is to block DC from those parts of a circuit where it is not desired.

11

Understanding Diodes

What You Will Learn

In the early days of electricity, a terminal for an electrical device was called an electrode—a battery electrode, for example. When a device having two electrically active terminals was developed, it was termed a di(two) -ode(electrode). A diode is a device through which current passes readily in one direction but with great difficulty in the other. In this chapter you will learn of the two different families of diodes, what they are, how they work, and what useful purposes they serve in a circuit.

WHAT IS A DIODE?

A **diode** is an electrically operated device which has two elements (or terminals). If a voltage source is applied to these elements in the correct polarity, current flows through the diode. However, if the polarity is reversed, very little (if any) current passes through.

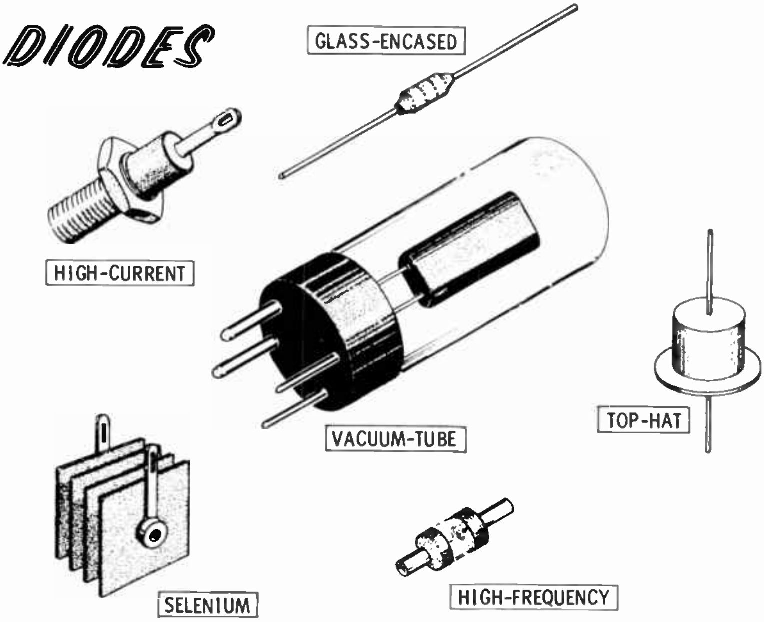
There are two general families of diodes—**vacuum tube** and **solid state.** A **vacuum-tube diode** is constructed with the two elements enclosed in a glass or metal envelope. Current flows from one element to the other through a vacuum or, in some units, through a special type of gas.

A **solid-state diode** contains two dissimilar metals or two different types of semiconductor materials. Current flows between the junction formed by the metals or materials.

HOW DO DIODES WORK?

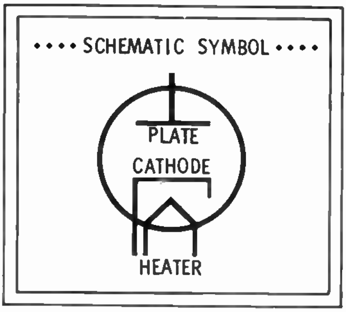
Although both types of diodes conduct current in one direction only, the electrical principles which permit them to do this are different.

Their appearances are different also. The largest of the devices is the vacuum-tube diode; the others shown below are representative shapes of the solid-state variety.



Vacuum-Tube Diodes

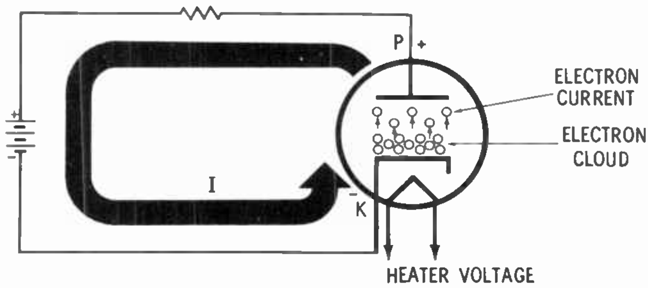
The exterior of a vacuum-tube diode is usually a glass tube (sometimes metal) fitted into an insulated base. The interior is a vacuum (to permit ease of a electron flow). Suspended in the vacuum are two elements, as shown in the schematic symbol, called a **cathode** and a **plate.** A third element, a **heater,** is mounted close to the cathode.



Each element is connected to a **pin** (two are for the heater) on the base of the tube. The pins fit into a tube **socket** having terminals to which connections can be readily made.

The Cathode—The cathode is normally a small metal cylinder sitting upright in the tube. It is coated with a certain type of material which emits electrons when heated. A voltage (the amount depends on the tube design) applied to the filament wires of the heater raises the temperature of the cathode high enough to cause the coating to "boil off" a cloud of electrons. The electron cloud surrounds the cathode as long as the heater gives off heat.

ELECTRON FLOW IN A VACUUM-TUBE DIODE



The Plate—The plate (sometimes called an **anode**) is a metal cylinder mounted around the cathode. With a battery connected to the diode as shown in the diagram, current flows through the tube. Negative voltage on the cathode (symbol K) repels the negative electrons from the cloud toward the plate (symbol P). Positive voltage on the plate attracts the electrons. Current flows from the plate through the external load, through the battery, and back to the tube via the cathode.

If the voltage polarity is reversed, current does not flow. A negative plate repels electrons back toward the cloud, and a positive cathode attracts them in the same direction.

Q1. Electrons flow from the -------- to the ----- in a vacuum-tube diode.

Q2. When heated, a(an) --------- ----- forms around the cathode.

Your Answers Should Be:

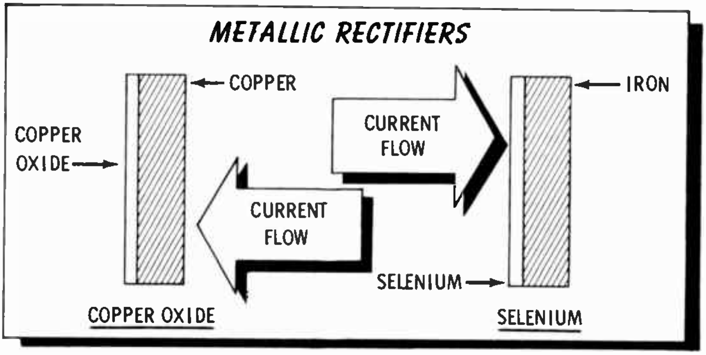
A1. Electrons flow from the **cathode** to the **plate** in a vacuum-tube diode.

A2. When heated, an **electron cloud** forms around the cathode.

Solid-State Diodes

In a solid-state diode, current flows through a material rather than a vacuum. There are two general types—one is a **metallic rectifier** and the other a **semiconductor diode.**

Metallic Rectifiers—These are constructed of two different metals tightly pressed together.



A **copper-oxide rectifier** is made of a thick disc or square of copper upon which a thin layer of copper oxide is deposited. As the illustration shows, current flows from the copper to the copper oxide if a negative voltage is applied to the copper and a positive voltage to the oxide. If the polarity of the voltage is reversed, a very small amount of current flows in the opposite direction. It is small compared to the amount that flows in the normal direction. In other words, the rectifier has a very low resistance in the direction from the copper to the copper oxide and a very high resistance in the opposite direction.

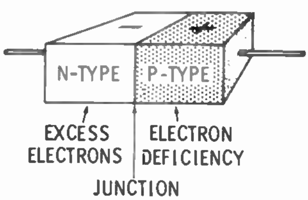
A **selenium rectifier** has a thick base of iron on which is deposited a thin layer of selenium. Current passes very easily from the selenium to the iron, but a very high resistance path exists in the opposite direction.

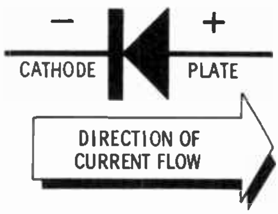
Semiconductor Diodes—A semiconductor diode is made of the same materials as those used in transistors, usually **germanium** or **silicon.** The silicon diode is more expensive than the germanium diode, but is able to handle a greater amount of current.

During manufacture, a tiny block, identified as **P-type,** is treated in such a way as to have a deficiency of electrons. Another block is identified as **N-type,** and is treated to have an excess of electrons. Such a diode is often called a **PN junction.**

When joined, a voltage barrier forms at the junction, preventing the electrons in the N material from moving over to the P material. However, when a voltage is applied (as shown in the drawing) the barrier is overcome and electrons flow from N to P. The schematic symbol used for all solid-state diodes is also shown.

SEMICONDUCTOR DIODE AND SYMBOL





Voltage polarities necessary for current to flow are labeled on the symbol. Current flows through the diode toward the arrowhead.

Q3. The arrowhead of a semiconductor symbol corresponds to the _____ of a vacuum-tube diode.

Q4. For current to flow in a diode, the cathode must have a _________ voltage with respect to a _________ voltage on the plate.

Q5. N-type germanium has an (excess, deficiency) of electrons.

Q6. From plate to cathode in a diode is a direction of ____ resistance.

Q7. In one type of metallic rectifier, current flows best from _________ to iron.

Q8. The letter symbol for a cathode is ____, and for a plate it is ____.

Your Answers Should Be:

A3. The arrowhead of a semiconductor schematic symbol corresponds to the **plate** of a vacuum-tube diode.

A4. For current to flow in a diode, the cathode must have a **negative** voltage with respect to a **positive** voltage on the plate.

A5. N-type germanium has an **excess** of electrons.

A6. From plate to cathode in a diode is a direction of **high** resistance.

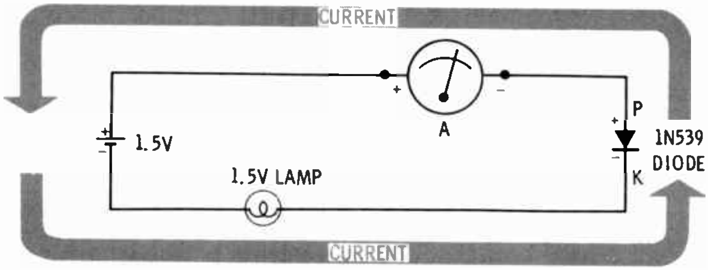
A7. In one type of metallic rectifier, current flows best from **selenium** to iron.

A8. The letter symbol for a cathode is **K**, and for a plate it is **P**.

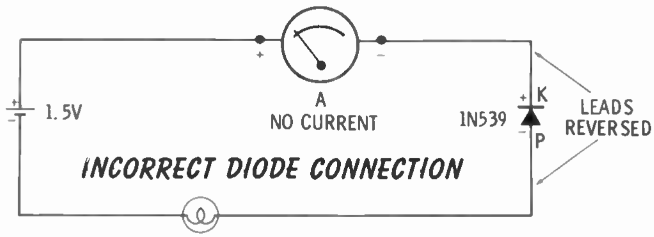
DIODE REACTION TO AC AND DC

It can be easily proved that a diode allows current to flow in one direction and not in the other by constructing the circuit below. A 1.5-volt lamp, an ammeter, and a diode are connected in series across a 1.5-volt cell. (Semiconductor diodes are distinguished from each other by a number-letter designation. The diode recommended for this circuit is a 1N539.)

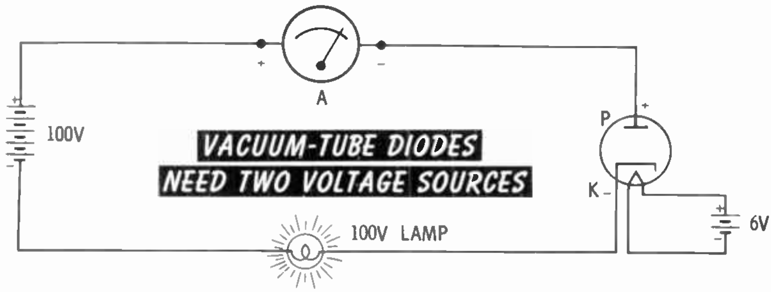
CORRECT DIODE CONNECTION



With the connections made as shown, current will flow and the lamp will light. The ammeter will record very close to 200 milliamps. Now reverse the connections of the diode. Will the lamp light? No. And, as indicated in the next drawing, the meter pointer will remain on zero. The plate-to-cathode resistance of the diode is sufficiently high to prevent a flow of current. A small amount may leak through, but it is not enough to record on the meter.



A vacuum-tube diode is shown in a similar circuit below.



Current flows. Note that this particular diode requires a 6-volt source to heat the filament and 100 volts across the cathode and plate. Other vacuum-tube diodes operate with higher or lower voltages, but all require two sources.

Q9. In the last circuit above, current travels through the lamp from (left, right) to (left, right).

Q10. If the vacuum tube and meter have zero resistances and the lamp has a resistance of 150 ohms, how much current will flow?

Q11. If the 6-volt battery is disconnected, how much current will flow?

Q12. How much current will flow if the 100-volt battery leads are reversed?

Q13. With the leads reversed, how much voltage will exist between K and P of the diode?

Q14. The plate of a semiconductor diode is designated by the (bar, arrowhead) symbol.

Your Answers Should Be:

A9. Current travels through the lamp from **left** to **right.**

A10. **0.67 amp.** (Because there is zero resistance in the rest of the circuit, 100 volts is applied across the 150-ohm lamp resistance.)

A11. **Zero current.** (Without heat the cathode does not emit electrons.)

A12. **Zero current.** (A negative plate repels and a positive cathode attracts electrons.)

A13. **100 volts.** (Although current is not flowing, the battery is still connected to the tube.)

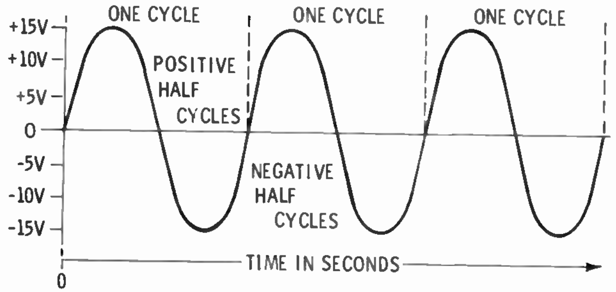
A14. The plate of a semiconductor diode is designated by the **arrowhead** symbol.

RECTIFYING AC

To **rectify** means to convert AC to DC. A **rectifier** is a device that accomplishes this, and a **rectifying** circuit is one in which it is done. A diode is a **rectifier.**

You know that an alternating voltage increases and decreases in positive voltage during a half cycle and in the next half cycle makes the same changes in negative voltage.

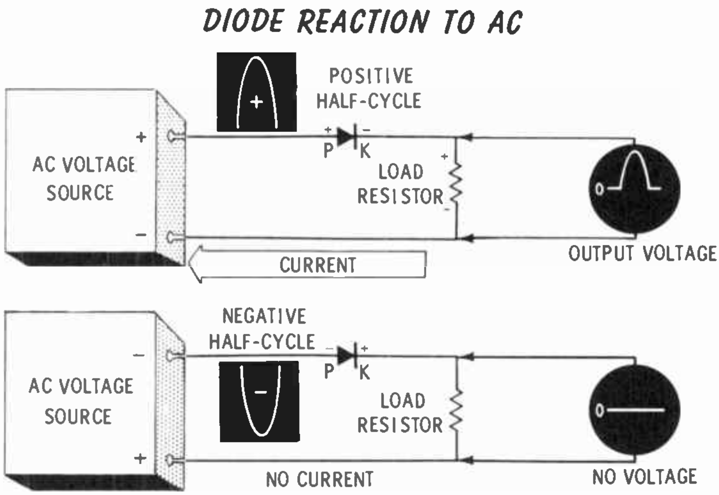
— AN ALTERNATING VOLTAGE —



As long as the voltage is generated, the positive and negative half cycles repeat themselves alternately.

Diode Reaction to AC

How does current flow in a diode circuit with AC voltage applied? Remember, current flows in one direction through a diode only when the plate is more positive than the cathode.



During a positive half cycle, the upper terminal of the source is positive with respect to the lower terminal. This means the lower terminal may be at zero volts, but it is negative when compared to the positive upper terminal. Therefore, the plate of the diode is positive with respect to the cathode. A changing half cycle of current flows.

If a device called an **oscilloscope** is connected across the load resistor, an exact picture of the changing voltage drop will be shown. This changing voltage will look exactly like the waveform at the voltage source.

During the next half cycle, the upper terminal voltage becomes negative with respect to the lower, and the diode plate is negative with respect to the cathode. As you know, current will not flow under these conditions. Since the diode presents a very high resistance in the circuit, all of the source voltage will be dropped across it. No voltage will be displayed across the load resistor.

Q15. As the circuit is connected above, only the ________ half cycles of the AC voltage will appear across the load resistor.

Q16. A rectifier converts __ to __.

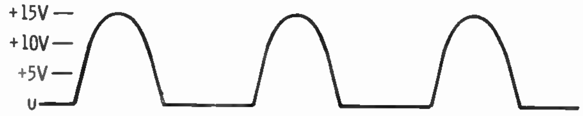
Q17. Draw a diagram showing the waveforms that will appear across R in the above circuit.

Your Answers Should Be:

A15. As the circuit is connected, only the **positive** half cycles of the AC voltage will appear across the load resistor.

A16. A rectifier converts **AC** to **DC.**

A17.



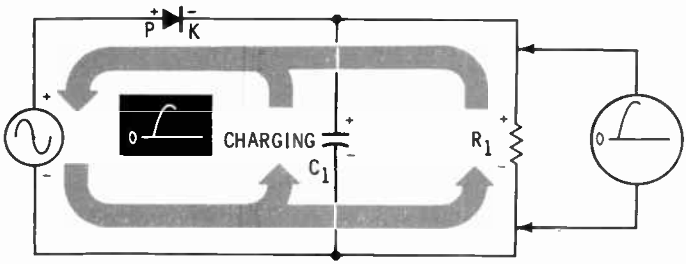
A DC POWER SUPPLY

Most electronic equipment requires two or more values of DC voltage to operate its circuits. Since alternating current is the normal supply, a **power-supply** circuit is used to provide the required DC voltages. Either a solid-state or a vacuum-tube diode is used for the initial conversion.

Filter Circuit

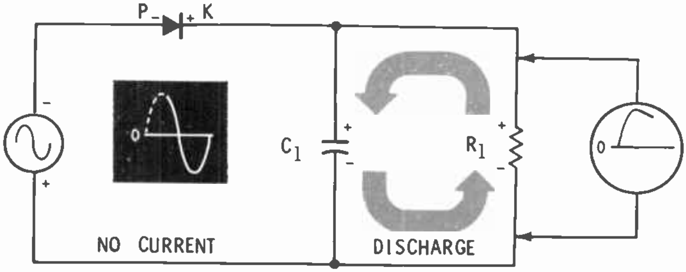
Your diagram shows the output voltage obtained from the diode circuit is DC—current flows in only one direction—but it is not a smooth, nonvarying DC. In fact, it is called a **pulsating DC.** The waveform is a series of pulses.

Filtering Action—The peaks and valleys of the pulsating waveform can be smoothed out by a **filter circuit.** A capacitor can be used to filter (smooth) out some of the changes.

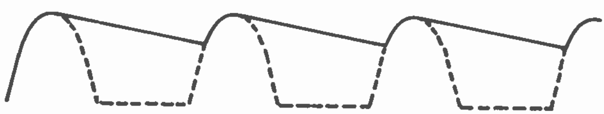


As the source voltage rises to maximum positive, current flows through R_1 and the diode. Some of the current also charges the capacitor to the value of the source voltage.

At the instant the applied voltage begins to decrease, C_1 starts discharging, trying to maintain the same voltage level. The discharge path of C_1, however is through R_1. The current from C_1 cannot flow backward through the diode. Since resistance regulates the time of discharge (5RC time constants to discharge completely), the discharge time is slow. As shown in the diagram below, the output waveform does not follow the descending curve of the input. It decreases at a much slower rate.



During the negative input half cycle, the diode does not allow current to flow, but the capacitor continues to discharge. The discharge current decreases as the capacitor charge grows less. On the next positive swing, the diode does not conduct current until after the input voltage has increased to an amount equal to the charge on C_1 at that instant. The plate must be more positive than the cathode for the diode to conduct. The sequence continues. The resulting output waveshape (in solid lines) is shown below. Such an output is called **DC ripple voltage.**



Q18. The pulse-like waveform developed by a diode circuit is called _________ __.

Q19. The changing voltage pattern made by these pulses can be smoothed out by a ______ circuit.

Q20. The filter capacitor begins to _________ as soon as the positive voltage input begins to decrease.

Q21. The filtered output is called a __ ______.

Your Answers Should Be:

A18. The pulse-like waveform developed by a diode circuit is called **pulsating DC.**

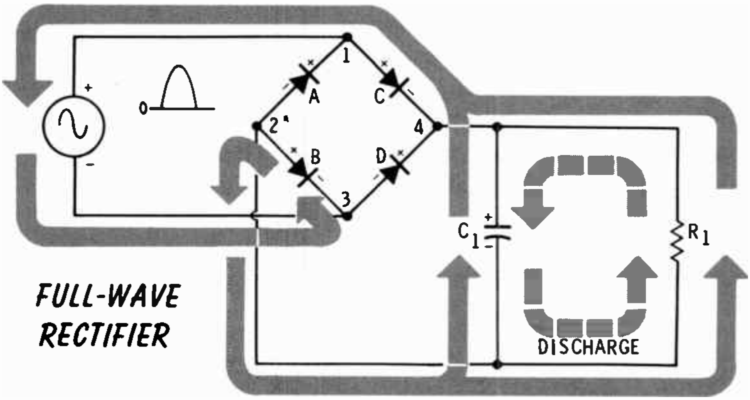
A19. The changing voltage pattern made by these pulses can be smoothed out by a **filter** circuit.

A20. The filter capacitor begins to **discharge** as soon as the positive voltage input begins to decrease.

A21. The filtered output is called a **DC ripple.**

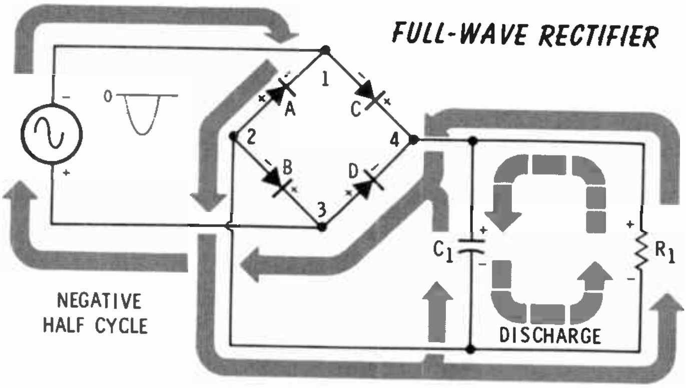
Full-Wave Power Supply

The preceding circuit is a **half-wave** rectifier. It allows only half the AC wave (positive half cycles) to appear across the load resistor. **Full-wave** (both positive and negative half cycles) rectification can be obtained with the switching action of the diodes in the circuit below.

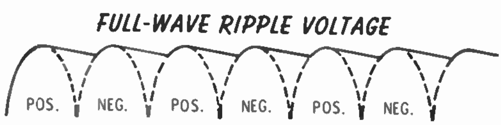


On the positive half cycle, current leaves the lower terminal of the AC voltage source and enters terminal 3 of the 4-diode network (called a **bridge**). The bridge is positive to negative from top to bottom because of the source polarity. Diode B has a negative cathode and a positive plate, but diode D has reverse polarity across it. Current must therefore flow through diode B to terminal 2. This current charges C_1 and flows through R_1 to terminal 4. Because of polarities, this current must flow through diode C. Diodes D and A are of the wrong polarity.

C_1 charges as the voltage increases and discharges during the voltage decrease, just as in the half-wave circuit.



During the negative half cycle, the polarities of the voltages on the four diodes are reversed. Current leaving the upper end of the source arrives at terminal 1. The voltage on diode C is of the wrong polarity, but diode A will conduct. Current leaves terminal 2, and then follows the same path as the positive half-cycle current. C_1 has just begun to discharge; the rising current restores the charge to full voltage. The remainder of the current flows through R_1 in the same direction as the positive half-cycle current did. At terminal 4, only diode D has the correct voltage polarity to conduct. Current flows through diode D to terminal 3 and the AC sources.



Q22. A(an) ---- ---- rectifier provides better filtering action than a (full-wave, half-wave).

Q23. In the diagram at the top of this page, current at terminal 1 will not flow through diode C because current will not pass from ----- to -------.

Q24. Current at terminal 4 will not go through diode C because its cathode is -------- and its plate is --------.

Your Answers Should Be:

A22. A **full-wave** rectifier provides better filtering than a **half-wave.**

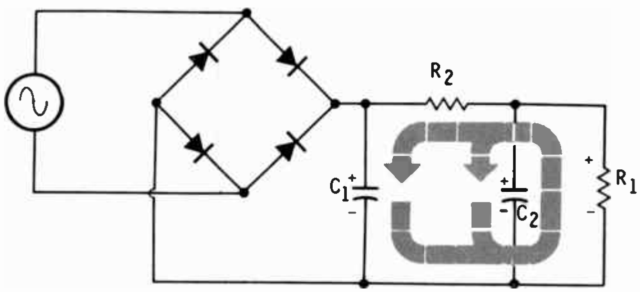
A23. Current at terminal 1 will not pass through diode C because current will not pass from **plate** to **cathode.**

A24. Current at terminal 4 will not go through diode C because its cathode is **positive** and its plate is **negative.**

Improving the Power Supply

The DC ripple remaining on the full-wave rectifier output may be satisfactory DC voltage for some equipment but not for others. The output can be made still smoother by improving the filtering action.

A CAPACITOR-RESISTOR-CAPACITOR FILTER



By adding another capacitor in parallel with the load resistor and another current-limiting resistor in series with the discharge path, the filter network can reduce more of the ripple.

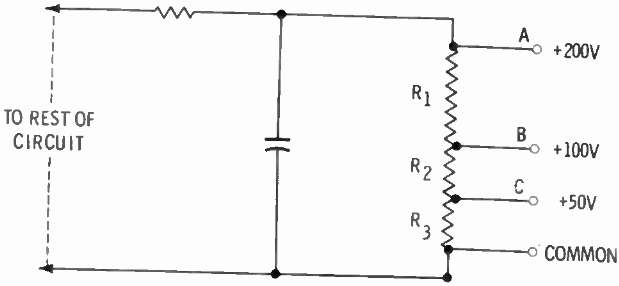
Both capacitors are charged and recharged by the positive and negative currents switched into the filter by the bridge. Both capacitors discharge together through R_1 as C_1 did previously. R_2 aids by limiting the flow of current through the filter.

Further improvement to the filtering action can be made by replacing R_2 with an **iron-core coil.** Such a coil is wound on a bar of iron. The reaction of a coil (inductor) to AC is, as you recall, one of resisting changes in current. Magnetic fields, reinforced by the iron core, smooth out the ripple by preventing the changes from occurring.

Load Resistors

Some electronic equipment requires two or more values of DC voltage for proper operation. These voltages can be selected from the load resistor.

THE LOAD RESISTOR CAN SUPPLY DIFFERENT VOLTAGES



Suppose that the DC requirements of the rest of the equipment were +200, +100, and +50 volts. A power supply can be selected or designed to produce a current large enough to cause a drop of at least 175 volts across R_1.

Either three series resistors of the correct values, or a bleeder resistor capable of being tapped at the desired values, can be used. The drawing above shows a bleeder resistor symbol.

By making connections to terminals A and Common, 200 volts will be available (for the plate of a vacuum tube, for example). To obtain 100 volts, the bleeder is tapped at the halfway point to obtain half the total voltage. For 50 volts, the resistance is tapped halfway between the 100-volt point and the common terminal.

Q25. A capacitor opposes changes in voltage by storing a ------- on its plates.

Q26. A coil opposes a change in current by developing a changing --------- ------.

Q27. Assume in the above figure that the bleeder must be replaced with three separate resistors. If you know that 0.1 amp flows through the bleeder to produce a total of 200 volts, what is the value of R_1, R_2, and R_3?

Your Answers Should Be:

A25. A capacitor opposes changes in voltage by storing a **charge** on its plates.

A26. A coil opposes a change in current by developing a changing **magnetic field.**

A27. **R_1 = 1,000 ohms; R_2 = 500 ohms; R_3 = 500 ohms.** If 0.1 amp developed 200 volts across the total resistance, the bleeder would have to be 2,000 ohms. ($R = E/I$). There would have to be 1,000 ohms on either side of the 100-volt tap, B. And the two resistors from B to Common must be 500 ohms each.

WHAT YOU HAVE LEARNED

1. Diodes are constructed in the form of vacuum-tube or solid-state devices.
2. All vacuum-tube diodes have a cathode and plate. The plate must be positive with respect to the cathode to permit current flow. Current will not flow in the reverse direction (plate to cathode) regardless of the polarity.
3. The plate and cathode in a vacuum-tube diode are housed in a vacuum. Heating the cathode causes it to emit electrons.
4. Solid-state diodes (metallic rectifiers and semiconductors) allow current to flow in one direction under conditions of proper polarity because of the materials from which they are made.
5. A diode converts AC to DC because it forms a one-way street for current. A circuit that does this is called a rectifier.
6. Output from a rectifier is pulsating DC. To smooth out the pulsations, a full-wave rectifier can be used. By adding a filter circuit—capacitors and resistors, or capacitors and a coil—the ripple can be made relatively smooth.
7. The smooth DC voltage can be taken from the power supply in desired values by tapping a bleeder resistor.

12

How Vacuum Tubes Work

What You Will Learn

You are now going to learn the basic principles about a device you have seen before—a vacuum tube. One member of the vacuum-tube family is a diode. The vacuum-tube group has several other members, many of which amplify and reshape the signals passing through your radio and television receivers. You will become familiar with the other types of tubes, learn how they work, and become acquainted with how some of them are used in circuits.

WHAT ARE VACUUM TUBES?

You should know at least part of the answer to this question. If a diode has two active elements (cathode and plate) suspended in an evacuated (vacuum) enclosure (tube), then all other vacuum tubes probably have the same number of elements or more.

That is exactly the situation. A **triode** is a vacuum tube with **three** active elements. A **tetrode** has **four,** and a **pentode** has **five.** There are other tubes with more elements, and still others with special elements. However, they all obey the same principles that will be discussed here.

Each vacuum tube has a filament to heat the cathode. Although the filament itself is not considered an active element, it performs a necessary function—it produces the heat to boil a cloud of electrons away from the cathode.

HOW DOES A VACUUM TUBE WORK?

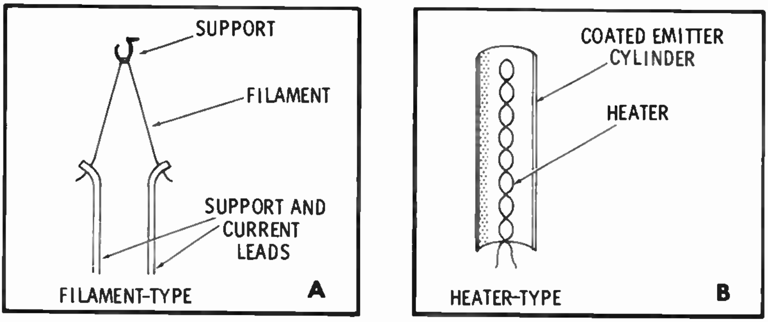
As you learned in the study of a diode, the cathode emits electrons and the plate receives electrons. Have you wondered how a diode is constructed to perform these functions?

Vacuum-Tube Fundamentals

Although the heaters, cathodes, and plates of the various kinds of vacuum tubes may be built to slightly different dimensions and shapes, the operating principles of all vacuum tubes are the same. The tube elements are placed in a vacuum to eliminate any air molecules that would retard the free flow of electrons to the plate.

Heater and Cathode—The heater (filament) is a fine wire which, when energized, raises the temperature of the cathode to the desired emitting level. Heater-cathode combinations are of two types.

TYPES OF CATHODES



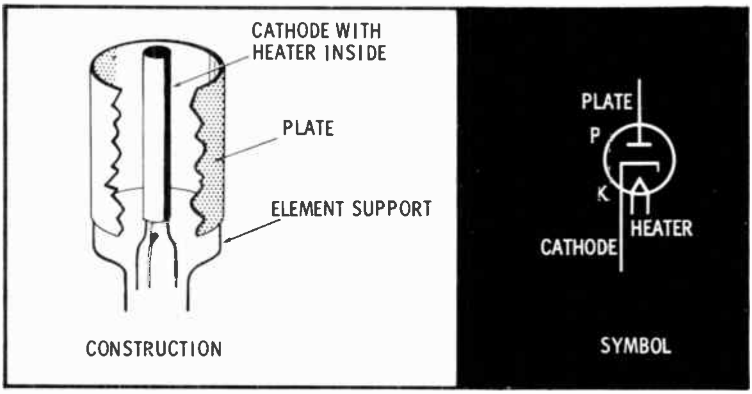
Part A shows a filament-cathode. The single wire serves as both the filament and cathode; it is made of a material (normally coated or uncoated tungsten) that emits electrons when hot.

Part B shows a heater-cathode combination in which there are two separate elements. The cathode, coated with an electron-active substance, fits like a sleeve over the filament.

The filament-cathode requires less current to heat it to an electron-emitting temperature. This type of cathode works best when connected to a DC voltage source. If energized by AC, tube current would vary with the AC alternations. But because AC current is more easily supplied, most of the tubes used in electronic equipment are of the heater-cathode type. The heater and the cathode are electrically insulated from each other so that the alternating current flowing through the heater does not affect the tube current.

Plate—The plate is usually a metal cylinder surrounding the cathode. Construction details and the accepted diode tube symbol are shown below.

DIODE CONSTRUCTION AND SYMBOL



Cathode Temperature—The number of electrons that form in a cloud around the cathode depends on the cathode temperature. The temperature of the cathode is controlled by the heat generated by the filament. There is an upper limit, however, beyond which a further increase in temperature will not cause an increase in electron emission. This is called **cathode-temperature saturation.**

Plate Voltage—The plate attracts electrons from the electron cloud when the plate voltage is positive with respect to the cathode. By raising and lowering the plate voltage, a greater or fewer number of electrons will be drawn from the cathode. This increases or decreases the value of plate current (tube current). The upper limitation, where a further increase in plate voltage will not attract any additional electrons, is called **plate-current saturation.**

Q1. A cathode emits __________.

Q2. Plate current flows when the plate is _________.

Q3. Plate current can be increased by increasing the _______ on the _____.

Your Answers Should Be:

A1. A cathode emits **electrons.**

A2. Plate current flows when the plate is **positive.**

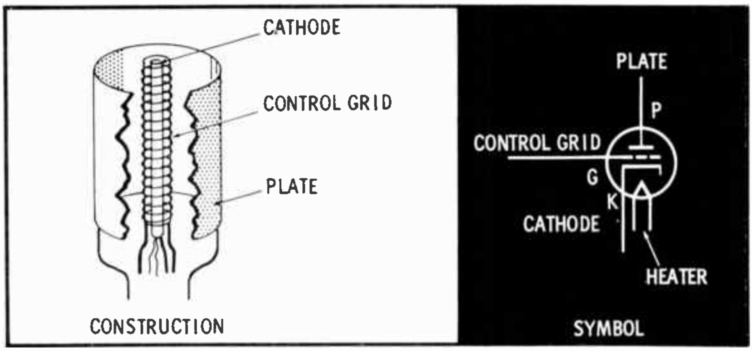
A3. Plate current can be increased by increasing the **voltage** on the **plate.**

The Triode

If a diode has two active elements, it is logical that a triode must have three. The cathode and plate are similar to those in the diode. The third element is a **control grid.**

Construction—The elements in a triode are supported in the same manner as they are in a diode. The control grid is a spiral of fine wire positioned between the plate and cathode. It is much closer to the cathode than to the plate.

Triode Construction and Symbol



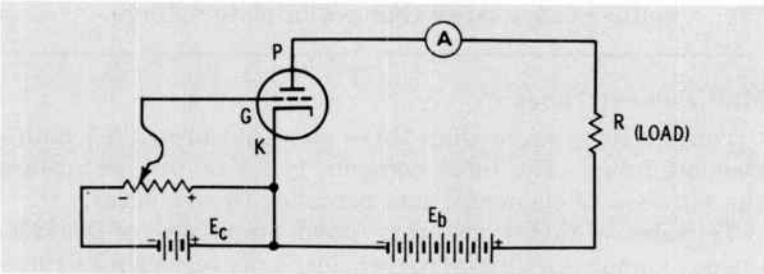
Operation—Plate current in a diode is determined by cathode temperature and plate voltage. In a triode, the voltage of the grid with respect to the cathode also controls the amount of plate current.

Because of its nearness to the cathode, the grid has greater control over the number of electrons reaching the plate than the plate does itself. Large changes in plate voltage cause only small changes in plate current. But small changes in grid voltage cause large changes in cathode-to-plate current.

In fact, if the grid is made sufficiently negative with respect to the cathode, the flow of current will be stopped or cut off. The lowest voltage at which this occurs is called the **cutoff bias.** Bias voltage is the normal voltage difference between cathode and control grid. The grid is usually more negative than the cathode.

A Triode Circuit—Below is a circuit which shows how a triode functions.

A TRIODE AMPLIFIER



Battery E_B is connected in such a way that the plate is positive with respect to the cathode. In an actual circuit the positive voltage for the plate is normally obtained from a power supply. Battery E_C places a negative voltage on the grid with respect to the cathode. A resistor takes the place of this battery in an actual circuit.

When the grid voltage is sufficiently negative to cut off the plate current, no current will flow through the load resistance. If made less negative, the grid will allow some current to flow and a voltage will be developed across R (load). If made even less negative, more plate current will flow and a greater voltage will be dropped across the resistor.

Assume that the change in grid voltage in the last two steps is 2 volts (from —6 to —4). Also assume that the change in the plate-resistor voltage is a total of 60 volts. This means that the grid-voltage change has been amplified 30 times (60/2). An AC signal on the grid would cause the same amount of amplification. This is how a triode amplifies.

Q4. The control grid is mounted closer to the (cathode, plate) than to the _____.

Q5. The voltage on the control grid that stops plate current is called ______ bias.

Q6. A triode amplifies because _____ changes in grid voltage cause _____ changes in plate voltage.

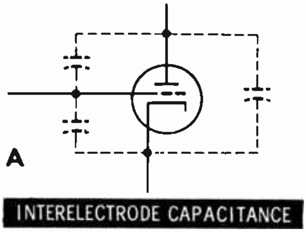
> **Your Answers Should Be:**
>
> A4. The control grid is mounted closer to the **cathode** than to the **plate.**
>
> A5. The voltage on the control grid that stops plate current is called **cutoff** bias.
>
> A6. A triode amplifies because **small** changes in grid voltage cause **large** changes in plate voltage.

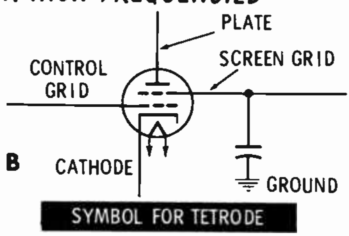
Multielement Tubes

Tubes having more than three elements are called **multielement** tubes. The most common types in this group are the tetrodes (4 elements) and pentodes (5 elements).

Tetrodes—Triodes are very good amplifiers of low-frequency signals. At high frequencies, however, such as those used in radio and television, a triode distorts (changes the form of) a signal during amplification. The distortion is caused by the capacitance that exists between the plate and grid. Since these two elements are conductors separated by an insulator (vacuum), a capacitor is formed. Capacitance also exists between the other elements, but has less effect on the signal.

A TETRODE IS BETTER FOR HIGH FREQUENCIES

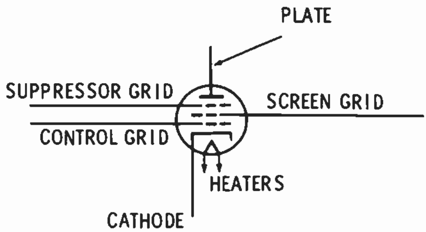




Part A in the above illustration shows the **interelectrode** (between elements) **capacitance** in a triode. Plate voltages are fed back to the control grid through this route, causing distortion. In a tetrode, the extra grid (called a **screen**) between the control grid and plate reduces the interelectrode capacitance and can be used to divert the feedback voltage to **ground** through a capacitor. Note the tetrode symbol in Part B. **Ground** is a wire (or the chassis) which serves as a common conductor for, or connection to, other components.

Pentodes—The fifth element in a pentode alleviates another problem encountered in vacuum tubes—the problem of **secondary emission.** Many of the electrons making up the plate current strike the plate with sufficient velocity to release other electrons from the plate material and bounce them back into the space between the screen grid and plate.

SYMBOL FOR A PENTODE



The fifth element of the pentode is called a **suppressor grid.** This element is usually connected internally to, and has the same potential as, the cathode. In other words, the suppressor grid is negative with respect to the plate. Spacing between the turns of wire of the suppressor grid is wide enough for plate current to pass through, but yet sufficiently close enough to repel the negative secondary electrons back to the plate.

Q7. _______________ ____________ between the plate and grid of a triode causes signal distortion.

Q8. The fourth element of a tetrode is called a ______ ____.

Q9. The screen grid bypasses the distorting feedback voltage to ______ through a capacitor.

Q10. The ______ symbol is an indication of a common connection to a wire or chassis for several components.

Q11. Electrons that bounce off the plate due to current flow are called __________ ________ electrons.

Q12. The ___________ grid of a pentode repels electrons back to the plate.

Q13. The ___________ grid is tied to the cathode.

Your Answers Should Be:

A7. **Interelectrode capacitance** between the plate and grid of a triode causes signal distortion.

A8. The fourth element of a tetrode is called a **screen grid.**

A9. The tetrode bypasses the distorting feedback voltage to **ground** through a capacitor.

A10. The **ground** symbol is an indication of a common connection to a wire or chassis for several components.

A11. Electrons that bounce off the plate due to current flow are called **secondary emission** electrons.

A12. The **suppressor** grid of a pentode repels electrons back to the plate.

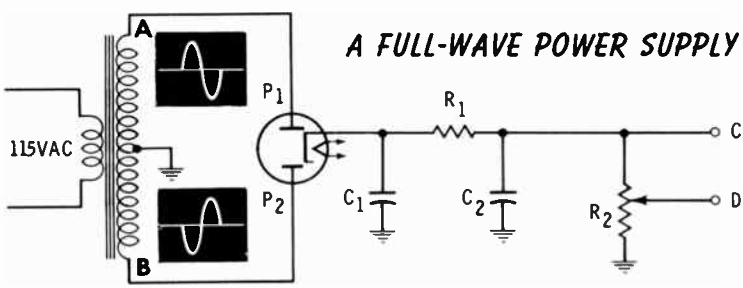
A13. The **suppressor** grid is tied to the cathode.

VACUUM-TUBE CIRCUITS

There are thousands of different vacuum-tube circuits. No one could hope to learn how each circuit works by memorizing their operating details. However, you can analyze how they work by applying the principles of electricity and electronics. You have already acquired most of the fundamental principles, but not at the depth required to be an expert. See if you can apply some of these principles to the circuits that follow.

Full-Wave Vacuum-Tube Power Supply

The circuit below performs the same rectification function as did the diode full-wave power supply in the last chapter.



The transformer steps 115 volts AC up to the value desired on the secondary. Each terminal of the secondary is connected to a separate plate of the **twin diode.** The secondary winding of the transformer is center-tapped to ground.

C_1, R_1, and C_2 form the filter network. By storing a charge during each AC half cycle, and discharging slowly through the resistors, the capacitors smooth out the ripple in the pulsating DC. R_2 is a bleeder resistor that provides selected DC voltages for other vacuum tubes.

Note that C_1, C_2, and R_2 each have one side connected to ground. The ground symbol indicates a common connection for all components terminated in this manner.

The principle of a center-tapped transformer winding is the manner in which AC voltages appear on either end of the winding. The first half cycle appearing at point A is positive with respect to ground. This makes the center tap more positive than point B, or point B is, in effect, swinging in a negative direction.

When point A is positive, point B is negative. Plate P_2 is cut off, but P_1 conducts. Current travels through the upper half of the secondary to ground, up through R_2 (charging the capacitors on the way) through R_1, and then to the cathode. The top of R_2 is positive with respect to ground.

When point A swings negative, point B swings positive.

Q14. When a negative half cycle is developed from point A to ground (P_1, P_2) conducts.

Q15. With current from cathode to P_2, current flows through R_2 from (top to bottom, bottom to top).

Q16. When current leaves P_1, it will enter R_2 at the (top, bottom) and leave at the (top, bottom).

Q17. When P_2 conducts, C_1 will charge by storing excess electrons on the (top, bottom) plate.

Q18. The vacuum tube in the circuit is a ---- -----.

Q19. The voltage at point A would be measured from point A to ------.

Q20. If the voltage output at the top of R_2 is 200 volts, what will be the voltage at point D if the top is 3/5 of the resistance above ground?

Your Answers Should Be:

A14. When a negative half cycle is developed from point A to ground, P_2 conducts.

A15. With current from cathode to P_2, current flows through R_2 from **bottom to top.**

A16. When current leaves P_1, it will enter R_2 at the **bottom** and leave at the **top.**

A17. When P_2 conducts, C_1 will charge by storing excess electrons on the **bottom** plate.

A18. The vacuum tube in the circuit is **a twin diode.**

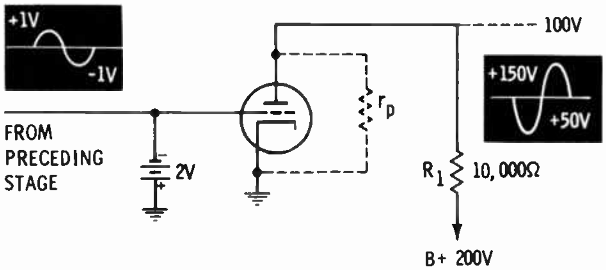
A19. The voltage at point A would be measured from point A to **ground.**

A20. 3/5 of 200 is **120 volts.**

Triode Amplifier

The circuit below is that of a triode amplifier. The B+ voltage of 200 volts is obtained from the load resistor (bleeder) of a power supply. The control grid has a fixed bias of —2 volts. Since there is a common connection through ground, the grid is two volts negative with respect to the cathode.

A TRIODE AMPLIFIER



With this bias, plate current is 0.01 amp (10 ma). The cathode-to-B+ path contains R_1 and r_p as resistances in series. R_1 is the load across which the voltage for the next circuit is developed; r_p is a variable resistance existing between cathode and plate. This variable resistance is known as the **plate resistance.** When plate current increases, r_p decreases; when plate current decreases, r_p increases.

With 0.01 amp flowing, there will be a 100-volt drop across R_1 (E = IR). Since B+ is 200 volts, there will be a 100-volt drop across r_p (200—100). This is the same as saying that the voltage from plate to cathode is 100 volts.

The AC signal on the grid swings one volt positive. Added to the —2-volt bias voltage, the grid is now at —1 volt with respect to the cathode. Plate current increases to 0.015 amp. The drop across R_1 is now 150 volts, leaving 50 volts across r_p. A change of 1 volt on the grid has changed the plate voltage from 100 volts to 50 volts.

When the AC signal swings one volt negative, grid bias becomes —3 volts. Plate current decreases to 0.005 amp. The voltage drop across R_1 is now 50 and across r_p, 150. Once again a change of 1 volt on the grid has caused a change of 50 volts on the plate. This means that the gain of the tube is 50.

Q21. When plate current increases, r_p __________.

Q22. Gain of an amplifier is determined by dividing the change in _____ _______ by the change in ____ ________.

WHAT YOU HAVE LEARNED

1. A diode has two active elements—a cathode and a plate. When heated, the cathode emits electrons. The plate draws current when it is more positive than the cathode.
2. A triode has a cathode, plate, and control grid. The control grid regulates the amount of plate current. A small change in grid voltage causes a large change in plate current and voltage.
3. The additional grid in a tetrode is called the screen. It eliminates the distortion effects of interelectrode capacitance.
4. A pentode has a suppressor grid that returns secondary electrons to the plate.
5. The ground symbol indicates a common wire or chassis for all components terminated to ground.
6. A full-wave vacuum-tube power supply uses a twin diode and a transformer center-tapped-to-ground secondary as input voltage.

Your Answers Should Be:

A21. When plate current increases, r_p, **decreases.**

A22. Gain of an amplifier is determined by dividing the change in **plate voltage** by the change in **grid voltage.**

7. Varying plate voltage varies plate current until the limit of plate-current saturation is reached.
8. Varying cathode temperature varies the supply of available electrons and therefore plate current. Maximum electrons will be available at cathode-temperature saturation.

TO THE READER

Thus far this volume has introduced you to many of the basic concepts of electricity and electronics. In fact, you should now be familiar with all of the basic principles upon which this science is based. Although you will need to learn more about these principles before you can become an accomplished technician, what you know now will make such study understandable and meaningful.

To insure that your grasp of these principles is sound, the remainder of this volume will be devoted to the application of these concepts to actual circuits in typical equipment. It will be more than just a review. The many components that you have studied will be tied together in describing how actual equipment works. In addition, you will become acquainted with the manner in which your radio and television receivers function.

13

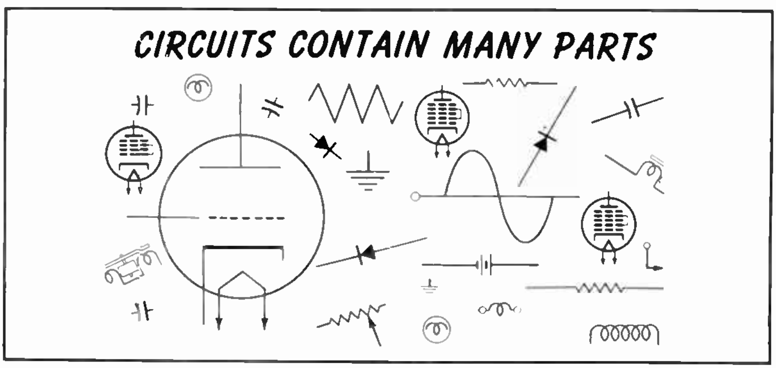
Basic Circuit Actions

What You Will Learn

It is important that you learn what an electrical or electronic circuit is. You will now learn to recognize the basic elements every circuit must have. When you complete this chapter you will be able to examine a circuit and determine how it works. In addition, you will learn the simple fundamentals used to determine how any circuit works.

INTRODUCTION

In the preceding chapters you have learned a great deal about electricity and electronics. If you have performed the experiments, you have learned even more.



The remaining chapters of this volume build upon what you have learned by showing you what electronic circuits are and how they are used in electronic equipment.

ELECTRICITY AND ELECTRONICS

You will read or hear many definitions for electricity and electronics which will seem to establish a difference between the two terms. Are they really different? The truth is, electricity and electronics are far more similar than they are different.

Electrical Circuits

In an electrical circuit, current from a voltage source flows through conductors to an electrical device. In passing through the device, current causes it to operate—a lamp lights, a motor rotates, a doorbell rings, an oven heats, etc. The electrical device, whatever it may be, must be part of a circuit connected to a voltage source. Compare this to an electronic circuit.

Electronic Circuits

In an electronic circuit, current from a voltage source flows through conductors and electronic components to perform a desired electronic function. For example, radio and television receivers contain many electronic circuits. In a radio, the functions of each circuit are such that the set reproduces a sound transmitted by a broadcast station many miles away. Circuits in a television set function in a similar manner and make it possible for you to see as well as hear a broadcast.

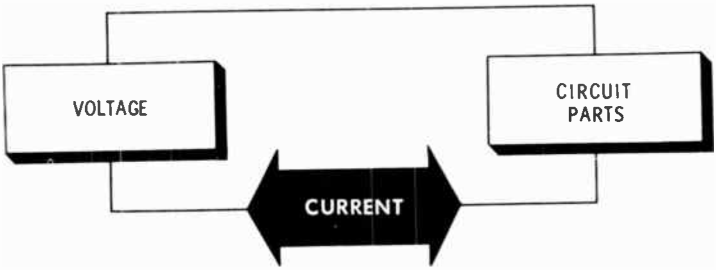
Basic Fundamentals

A radio or television set is plugged into the same voltage source as a lamp, motor, refrigerator, or any other electrical device. Current and voltage make no distinction between an electrical or electronic circuit. They react the same in either. The components that have been built into the circuit(s) determine how current and voltage will be used to make the electrical or electronic device operate.

The diagram on the next page expresses this concept by showing the relationship of the three elements contained in any circuit. If you accept the concept this illustration reveals and always remember it, you will have no difficulty in learning the electrical or electronic theory required to become a good technician.

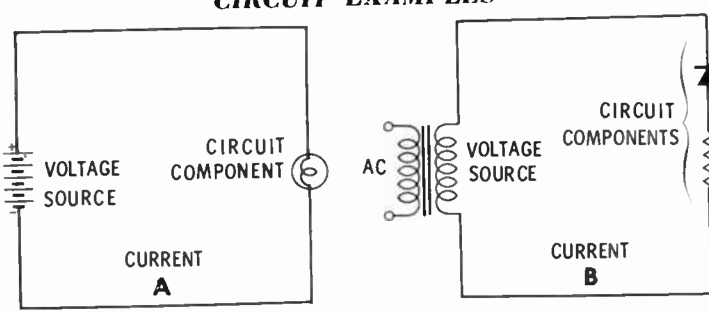
What does the illustration say? It states that any circuit contains only three factors—voltage, current, and circuit parts—which influence its operation.

The Electrical Elements in Any Circuit



Voltage, as you know, is an electrical pressure that causes current to flow under proper conditions. Current flows if there is a closed loop (complete path) from one side of the voltage source through the circuit components to the other side. The amount and type of voltage to be applied and how much current will flow is dependent on the type and value of components used in the circuit. As an example, you have seen circuits similar to those shown in the schematic diagrams below.

CIRCUIT EXAMPLES



Q1. What is the voltage source in Part A above? In part B?

Q2. What is the circuit component in part A? What are they in part B?

Q3. Which way will current flow (clockwise or counter-clockwise) in parts A and B?

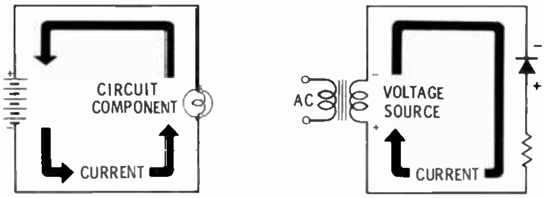
Q4. Which part (A or B) contains a circuit that is a closed loop?

Your Answers Should Be:

A1. The voltage source in part A is a **battery** and in part B it is a **transformer.** (You may have stated AC or electrical outlet for part B. However, you must get into the habit of looking at the voltage that is applied across a specific circuit shown in a diagram. The left side of the transformer may be plugged into a 120-volt AC outlet, but it is in another circuit consisting of the primary winding and the outlet. The circuit shown contains the voltage source and the circuit component. Remember to look for the specific voltage that is applied to an individual circuit.)

A2. The component in part A is a **lamp.** In part B the components are a **diode** (upper) and **resistor** (lower).

A3. Current will flow **counterclockwise in part A** and **clockwise in part B.**

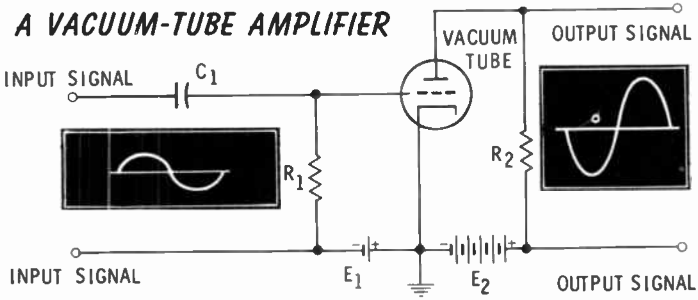


A4. Both circuits are closed loops.

You were not expected to give as long an answer as those shown above. If you arrived at the specific answers correctly, you have shown that you remember and can apply the information studied in other chapters of this volume.

The questions and explanations were included to underline a significant point—whatever happens in any circuit depends on the effect circuit components have on its voltage and current. This may sound like a very simple, easily understood statement, but those who do not study circuits with this simplicity in mind will find them difficult. Those who approach every circuit and resolve its complexities in terms of this simple, always reliable statement will have no trouble whatsoever.

Using the approach stated in the preceding paragraph, see if you can follow the analysis of a basic amplifier circuit. The circuit is similar to one of those used in preceding chapters.



Circuit Function

This circuit uses a vacuum tube. The function of the circuit is to amplify (increase) the voltage of the input signal, as shown in the difference between the input and output waveforms. Disregarding the input and output signals for a moment, you can find two voltage sources in this circuit—there are two battery symbols. The actual circuit will probably not have batteries; the symbols merely show that there is a DC voltage source across the points indicated.

Q5. The three basic factors of any circuit are ________, ________, and ____________.

Q6. The best method to use in analyzing any circuit is to determine the effect that circuit components have upon applied ________ and ________.

Q7. Redraw the vacuum-tube amplifier circuit and show the path and direction of current through the closed loop that includes E_2.

Q8. The three active elements in the vacuum tube above are ________ ____, ________, and _____.

Q9. The purpose of the circuit is to ________ the input signal.

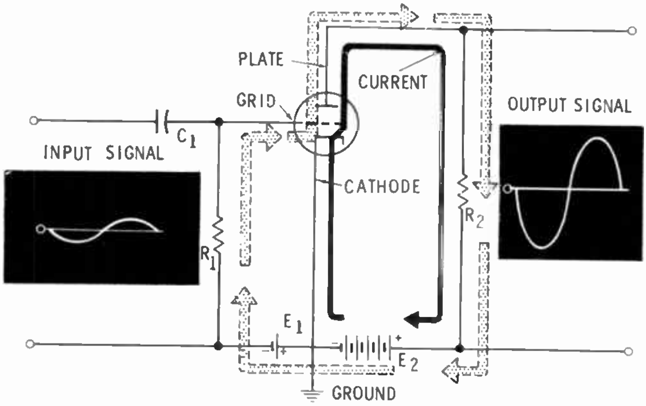
Q10. The two battery symbols are used to indicate __ ________ is being applied.

Your Answers Should Be:

A5. The three basic elements of any circuit are **voltage, current,** and **components.**

A6. The best method to use in analyzing any circuit is to determine the effect that circuit components have upon applied **voltage** and **current.**

A7.



You had two choices for the current path. They are represented as solid and dotted lines above. Although the solid line is correct, do not feel bad if you chose the other.

A8. The three active elements in the vacuum tube are **control grid, cathode,** and **plate.**

A9. The purpose of the circuit is to **amplify** the input signal.

A10. The two battery symbols are used to indicate **DC voltage** is being applied.

Control by the Grid

Current (the solid line) flows through the vacuum tube (a triode) if its plate is positive with respect to its cathode. This is the purpose of E_2. The amount of current that flows can be controlled by the voltage on the control grid with respect to the cathode. In fact, a small change in grid-to-cathode voltage causes a large change in plate current.

The grid-to-cathode voltage is negative and, if sufficiently high, will stop current flow altogether. As this voltage is made less negative, more and more current will flow.

The input to the triode amplifier circuit has the same shape as an AC-voltage waveform. It appears on the grid as a voltage also. Capacitor C_1 and resistor R_1 play a part in placing this signal voltage on the grid. The line through the center of the input waveform is called a **reference line.** (Voltage must always be thought of as being with reference to, or with respect to, some other point in the circuit.) In this case the reference line refers to the DC grid voltage (bias). The part of the waveform that is above the line is positive voltage, and the part below the line is negative. Since it is AC, the voltage of the signal is regularly changing from positive to negative.

The purpose of E_1 is to establish a uniform negative voltage between the grid and cathode. This makes the grid negative with respect to the cathode. In this circuit, current will not flow from the grid to the cathode. The changing voltage of the AC waveform is also on the grid, subtracting from or adding to the voltage of E_1. When the signal voltage is going positive, it subtracts from the voltage of E_1. For example if E_1 were —1.5 volts (negative from grid to cathode) and the signal were +0.5 volt at a given instant, voltage on the grid would be reduced to —1 volt (the grid still negative with respect to the cathode).

Q11. The control grid is (negative, positive) with respect to the cathode.

Q12. What will be the voltage on the grid when the signal voltage is —0.5 volt?

Q13. E_2 makes the plate --------- with respect to the cathode.

Q14. The amount of plate current that flows is controlled by the -------- on the ------------.

Q15. In a triode amplifier, a small change in grid voltage causes a (small, large) change in plate current.

Q16. The purpose of E_1 is to make the ---- negative with respect to the --------.

Your Answers Should Be:

A11. The control grid is **negative** with respect to the cathode.

A12. **2 volts.**

A13. E_2 makes the plate **positive** with respect to the cathode.

A14. The amount of plate current that flows is controlled by the **voltage** on the **control grid.**

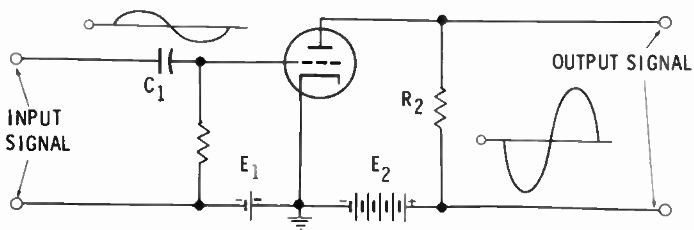
A15. In a triode amplifier, a small change in grid voltage causes a **large** change in plate current.

A16. The purpose of E_1 is to make the **grid** (control grid) negative with respect to the **cathode.**

Change in Plate Voltage

As you can see, the voltage on the grid changes in accordance with the changing voltage of the signal. Current through the tube changes in a like manner—it increases when the signal rises in the positive direction. This is because the negative repelling voltage of the grid is being decreased. When the signal increases in the negative direction, it adds to the negative voltage on the grid, causing plate current to decrease.

Amplifying a Signal



The changing current of the tube passes through R_2 on its return to voltage source E_2, causing the voltage across R_2 to change in the same manner as the changes of the signal voltage. Since a small change in grid voltage causes a large change in tube current, the changes in output voltage across R_2 are greater than the corresponding input changes on the grid. Thus, the signal has been **amplified.**

Circuit Analysis Summary

The entire explanation or understanding of this circuit is based on the effect the circuit components have on current and/or voltage. This is true of any circuit. You should have had very little difficulty in following the explanation even with your limited knowledge of electricity. The reason, of course, is that everything was explained in terms of changes in voltage or current with respect to the components of the circuit.

You may have been able to follow the explanation but you still may not fully understand exactly how the circuit works. To achieve this understanding and to become a good technician requires a knowledge of how the circuit components cause current and voltage changes to take place.

Many pages are devoted to this explanation in the remaining volumes in this set or in similar texts on electronics. The effect that vacuum tubes, resistors, capacitors, and even voltage sources have on a signal moving through a circuit requires a great deal of careful explanation. If you will remember to always relate the detailed descriptions to the effect they have on voltage and current changes, you will have no trouble.

Q17. In a triode amplifier, the (negative, positive) terminal of a DC voltage source is applied to the control grid.

Q18. The (input, output) signal causes grid voltage to vary.

Q19. Grid voltage regulates the amount of plate current by (attracting, repelling) electrons in the tube.

Q20. The circuit on the opposite page is called a(an) ---------- because it increases the voltage of the input signal.

Q21. The plate of the tube is kept at a (higher, lower) (negative, positive) voltage than the cathode.

Q22. The circuit amplifies the input signal because (small, large) changes in grid voltage cause (small, large) changes in plate current.

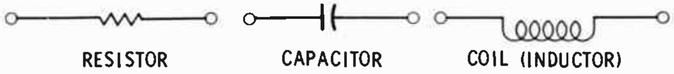
Q23. The changes in plate current cause (small, large) changes in plate voltage.

> **Your Answers Should Be:**
>
> **A17.** In a triode amplifier, the **negative** terminal of **a** DC voltage source is applied to the control grid.
>
> **A18.** The **input** signal causes grid voltage to vary.
>
> **A19.** Grid voltage regulates the amount of plate current by **repelling** electrons in the tube.
>
> **A20.** The circuit is called an **amplifier** because it increases the voltage of the input signal.
>
> **A21.** The plate of the tube is kept at a **higher positive** voltage than the cathode.
>
> **A22.** The circuit amplifies the input signal because **small** changes in grid voltage cause **large** changes in plate current.
>
> **A23.** The changes in plate current cause **large** changes in plate voltage.

CIRCUIT COMPONENTS

How many different circuit components are there? If this question is worrying you, you are worrying needlessly. There are only three major components (parts).

The Major Parts of Any Circuit



Resistors, Capacitors, and Coils

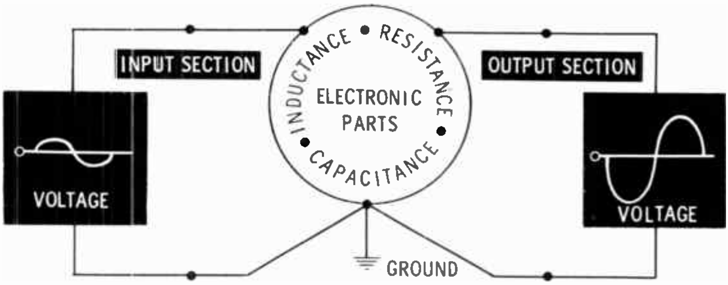
All circuits, regardless of their complexity, contain at the most only three different kinds of parts—**resistors, capacitors,** and **coils** (often called **inductors**).

The effect that a resistor has on current or voltage is measured in terms of its **resistance,** a term with which you are already familiar. The effect of a capacitor is measured in **capacitance.** The effect of a coil is called **inductance.** The effect each has on voltage or current depends on whether it is DC or AC, and, if AC, how rapidly the voltage or current is changing. But each effect—resistance, capacitance, or inductance—is based on a few easily learned principles.

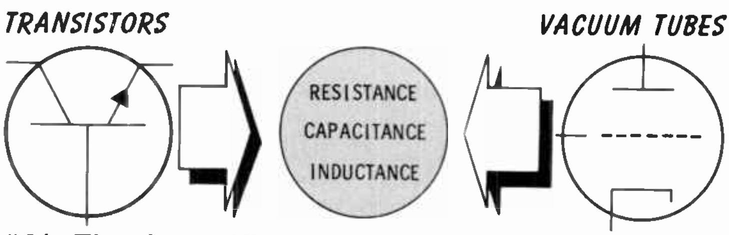
Circuit Applications

The illustration below shows that an input signal is converted to that shown at the output because of the effect of circuit resistance, capacitance, and inductance on the signal as it passes through the circuit. By this manner, the operation of any circuit can be explained. The **ground** symbol shown in the illustration is normally used as a reference point for zero voltage.

THE ELEMENTS OF ANY ELECTRONIC CIRCUIT



You might think that the symbol for a vacuum tube or transistor does not look like an inductance, capacitance, or resistance. You are correct. However, the way a vacuum tube or a transistor operates can be explained by how it reacts in terms of resistance, inductance, or capacitance when current is passing through it or when voltage is applied to it.



Q24. The three different electrical factors in a circuit are ________, ________, and circuit components.

Q25. The three different types of circuit components are __________, ___________, and coils.

Q26. Operation of a vacuum tube can be explained in terms of ___________, ____________, and ___________.

Your Answers Should Be:

A24. The three different electrical elements in a circuit are **voltage, current,** and circuit components.

A25. The three different types of circuit components are **resistors, capacitors,** and coils.

A26. Operation of a vacuum tube can be explained in terms of **resistance, capacitance,** and **inductance.**

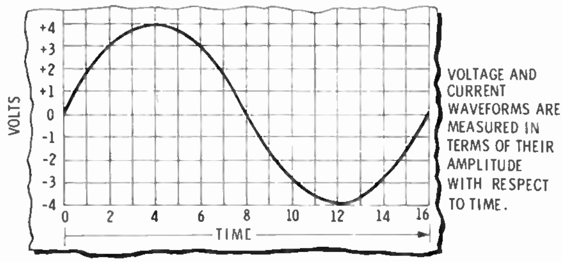
CHANGING VOLTAGE AND CURRENT

Circuits in electronic equipment are designed to obtain the performance desired of the equipment. A signal entering the first circuit is converted into an output signal that becomes the input to the next circuit where it is converted again. The input-conversion-output sequence continues through all the circuits until a waveform is obtained that will cause proper operation of the output device.

Voltage and Current Waveforms

Since the exchange between circuits is accomplished by voltage and/or current, a means of describing a waveform (signal) becomes very important. Like any other object, a waveform has dimensions. A sheet of paper, for example, is so many inches wide by so many inches long. A waveform has height and width dimensions also, but different units are used to describe them.

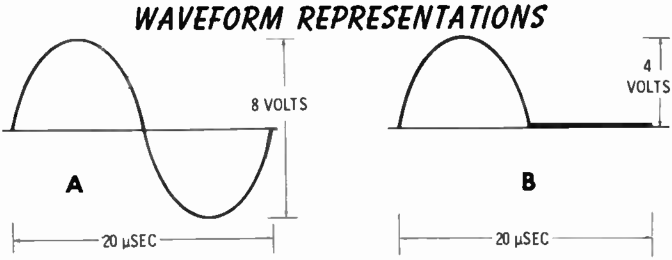
A Voltage Sine Wave



The illustration shows a single cycle of a voltage waveform. The AC **sine wave,** as this particular waveform is called, is continually changing at the rate indicated by its curvature.

Circuit Applications

Normal presentation in equipment diagrams indicates the amplitude of a waveform in terms of its maximum values.



Part A above shows the same sine wave as on the preceding page. The dimensions are 8 volts from its positive peak to its negative peak. The time duration of one cycle is 20 μsec (microseconds). A microsecond is one-millionth of a second.) Part B shows the same waveform after it has been rectified (using a diode circuit, for example). The single peak remaining is 4 volts from zero to maximum positive. The time duration of the cycle is still the same 20 μsec.

Understanding the dimensions of a waveform is very important. Waveform representations of signals are used constantly in electronics, since a vast amount of information about a signal can be put into this picture form. Amplitude and time values allow you to describe specifically what the voltage or current will do in a circuit.

Q27. In an equipment, the output signal of one circuit becomes the _____ ______ for the next circuit.

Q28. The exchange of signals between circuits is accomplished by _______ or _______ waveforms.

Q29. The dimensions of a waveform are _________ and ____.

Q30. A sine wave is a continuously (steady, changing) voltage or current.

Q31. In the diagram on the opposite page, what is the amplitude of voltage at time increment 4?

Q32. What is its value at time increment 8?

Q33. What is the amplitude at time increment 12?

Your Answers Should Be:

A27. In an equipment, the output signal of one circuit becomes the **input signal** for the next circuit.

A28. The exchange of signals between circuits is accomplished by **voltage** or **current** waveforms.

A29. The dimensions of a waveform are **amplitude** and **time.**

A30. A sine wave is a continuously **changing** voltage or current.

A31. At time increment 4, voltage has risen to **+4 volts.**

A32. At time 8, it is **zero volts.**

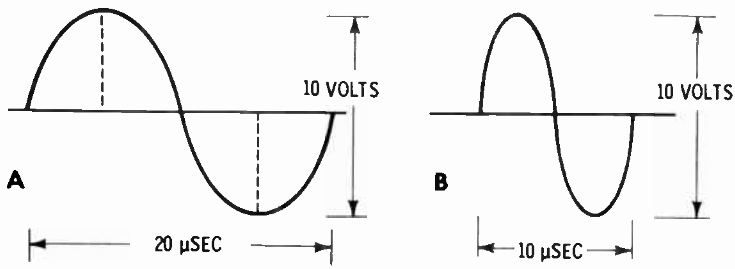
A33. At time 12, voltage has decreased to **—4 volts.**

Amplitude and Frequency

As you have learned, waveforms can be described by their time and amplitude dimensions. How is this done?

Time Dimension—Time is the horizontal dimension of a waveform. It is usually represented in terms of seconds, milliseconds (1/1,000 of a second), or microseconds (1/1,000,000 of a second).

TIME DURATION OF A CYCLE



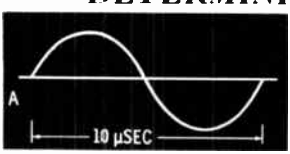
The time line for a waveform usually represents the duration of one cycle. In Part A above, it is 20 μsec and in part B it is 10 μsec. From this, the duration of a portion of a cycle can be determined. In part A, a half wave (half of a full cycle) is 10 μsec. A quarter wave (fourth of a full cycle) in part A is 5 μsec.

Frequency—Since a waveform cycle repeats itself continuously, its frequency can be determined. The frequency of a signal is the number of times that it repeats itself in a certain period of time, usually one second. If the time duration for one cycle is one second, the signal repeats itself once each second. Its frequency, then, would be one cycle per second. If one cycle is 1/10 of a second in duration, it repeats itself 10 times in one second, resulting in a frequency of 10 cycles per second. As you have already determined, the arithmetic expression to find frequency is:

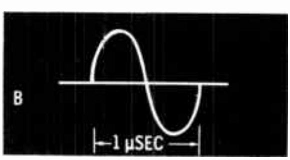
$$\text{Frequency} = \frac{\text{one second}}{\text{time duration of one cycle}}$$

If the time duration is expressed in milliseconds or microseconds, the top and bottom values of the right side of the expression must be expressed in the same units of time. In other words, both top and bottom values must be either in seconds, milliseconds, or microseconds. Failure to have these values in the same units of time is a common source of error when solving this type of problem.

DETERMINING FREQUENCY



$$\text{FREQUENCY} \begin{cases} = \dfrac{\text{1 SECOND}}{\text{10 MILLI SECONDS/CYCLE}} \\ = \dfrac{\text{1000 MILLISECONDS}}{\text{10 MILLISECONDS/ CYCLE}} \\ = \text{100 CYCLES PER SECOND} \end{cases}$$



$$\text{FREQUENCY} \begin{cases} = \dfrac{\text{1 SECOND}}{\text{1 MICROSECOND/CYCLE}} \\ = \dfrac{1,000,000\ \mu\text{SEC}}{1\ \mu\text{SEC/CYCLE}} \\ = \text{1,000,000 CYCLES PER SEC.} \end{cases}$$

Q34. The time dimension of a waveform is measured from (left to right, bottom to top).

Q35. There are _______ microseconds in a second.

Q36. There are ____ microseconds in a millisecond.

Q37. A full cycle is 60 milliseconds. What is the duration of a quarter cycle?

Q38. What is the frequency of a 100-millisecond cycle?

Q39. What is the frequency of a 0.001-second cycle?

Your Answers Should Be:

A34. The time dimension of a waveform is measured from **left to right.**

A35. There are 1,000,000 microseconds in a second.

A36. There are 1,000 microseconds in a millisecond.

A37. A full cycle is 60 milliseconds. A quarter cycle would be **15 milliseconds.**

A38. A 100-millisecond cycle has a frequency of 10 **cycles per second.**

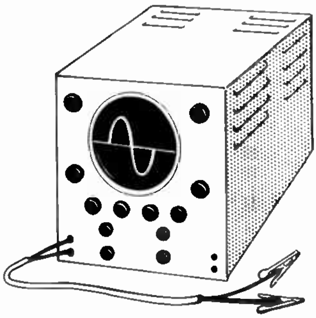
A39. A 0.001-second cycle has a frequency of 1,000 **cycles per second.**

WAVEFORM APPLICATIONS

The time and amplitude characteristics of a waveform allow it to be described in precise terms.

Oscilloscope

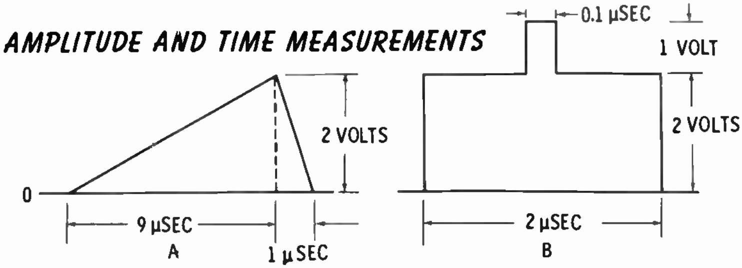
An **oscilloscope** is used to obtain a picture of a waveform at **test points** in a circuit. Even though the signal is constantly changing, controls on this instrument permit the waveform to be presented almost as if it were drawn on paper. From the presentation, the waveform can be evaluated in terms of its amplitude and time characteristics and it can be determined if the waveform is correct or not.



AN OSCILLOSCOPE

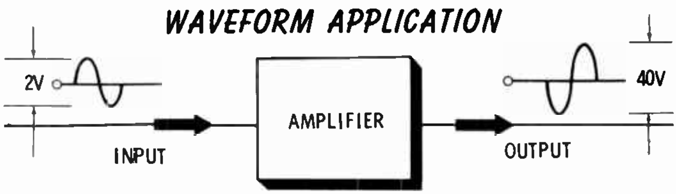
Nonsinusoidal Waveshapes

Waveforms which are not sine waves are called **nonsinusoidal.** Many are triangular, rectangular, or square in shape. Because of their nonsinusoidal shapes, two or more amplitude or time dimensions are required to describe them properly. Examples are shown below. With such information, it can be determined if the waveform going into or coming out of a circuit is correct.



Circuit Application

To show how waveform representations can be applied to the analysis of a circuit, a sample application is given below.



In the circuit above, the amplifier has a sine-wave input and output. Because of the characteristics of this amplifier, the output waveform is a reversal of the input. The output is also greater in amplitude: 40 volts output as compared to 2 volts at the input.

Q40. The test instrument which displays waveforms in a circuit is called a(an) ____________.

Q41. The areas of a circuit to which the test clips are applied are called ____ ______.

Q42. A nonsinusoidal waveform is one which is not a ____ ____.

Q43. A drawing which shows circuits represented in rectangular form is called a(an) _____ _______.

Q44. What is the frequency of the waveform in part A of the illustration at the top of the page?

Q45. What is the gain of the amplifier above?

Your Answers Should Be:

A40. The test instrument which displays waveforms in a circuit is called an **oscilloscope.**

A41. The areas of a circuit to which the test clips are applied are called **test points.**

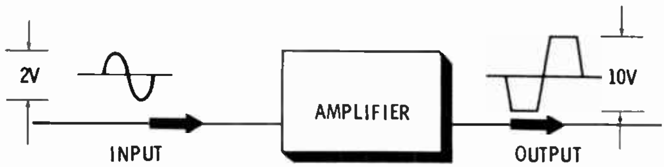
A42. A nonsinusoidal waveform is one which is not a **sine wave.**

A43. A drawing which shows circuits represented in rectangular form is called a **block diagram.**

A44. What is the frequency of the waveform in part A? **1,000,000** microseconds divided by **10** microseconds is **100,000 cycles per second.**

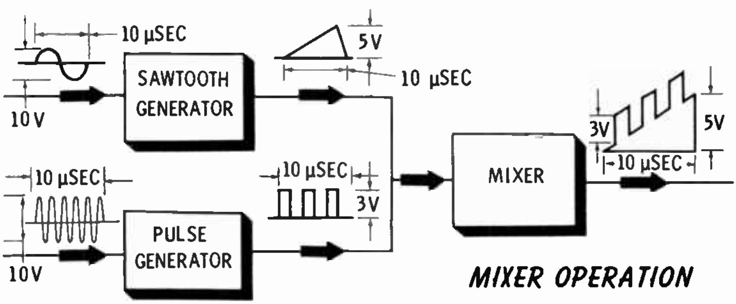
A45. **Gain is 20.** (40 volts divided by 2 volts.)

Try another circuit.



Instead of a sine-wave output, the tops of both peaks have been flattened. A section of circuit components (different from those in the preceding circuit) is responsible for the different outputs. The amount of gain is also different.

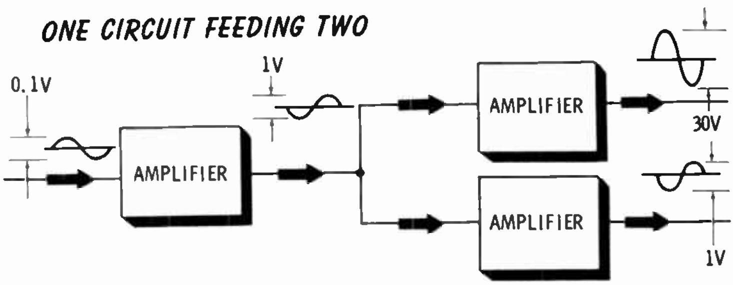
Outputs of two circuits are often fed into a single circuit.



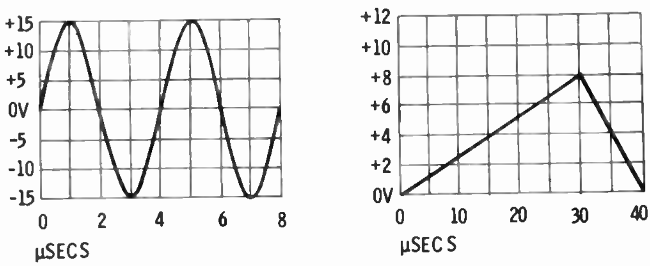
MIXER OPERATION

The sawtooth and pulse generators have sine-wave inputs of different frequencies. The input frequency of the pulse generator is six times the frequency of the sawtooth generator input. The sawtooth output (its name comes from its shape) has a time duration of 10 μsec during which three pulses are produced by the pulse generator. Both outputs are fed to the input of the mixer.

One circuit feeding into two circuits is the reverse of the preceding example. One combination might look like this.



A low-amplitude sine wave is amplified by the first amplifier and fed to two others. Their outputs are quite different.



Q46. What is the frequency of the sine wave in the illustration directly above?

Q47. What is the frequency of the sawtooth wave?

Q48. What is the peak-to-peak voltage of the sine wave?

Q49. How long does it take the sawtooth wave to rise to +8 volts?

Q50. How long does it take the sawtooth wave to decrease back to zero volts?

Q51. What is the time duration of a half cycle of the sine wave?

Q52. A(an) ______ circuit is capable of superimposing one waveform upon another.

Your Answers Should Be:

A46. The sine-wave frequency is **250,000 cycles per second.**

A47. The sawtooth frequency is **25,000 cycles per second.**

A48. The peak-to-peak sine-wave voltage is **30 volts.**

A49. The rise time is **30 microseconds.**

A50. The decay time is **10 microseconds.**

A51. The sine-wave half cycle is **2 microseconds** in duration.

A52. A **mixer** circuit is capable of superimposing one waveform upon another.

KEEP ELECTRONICS SIMPLE

In learning the electronic principles involved in a variety of circuits, a student technician often gets lost in the many details which are included. You have often heard the expression, "He can't see the forest because of the trees." A person so accused is so involved in examining the details of a single tree he loses sight of how it fits into the entire forest. This analogy aptly fits the study of electronics.

A circuit consists of components which have so many details it is easy for the student to get lost. The usual explanation of how a circuit works often causes a reader to look at a circuit as a group of isolated components.

The explanation must dwell on each of these components to define their place and purpose in the circuit. If the description continues for sentences or paragraphs, the reader has lost the important thread of information that runs through the circuit—how each of the individual components causes the input to be changed into the desired output. The solution to this problem is to keep the "big picture" of what the circuit is supposed to do as a mental image. Then, as each component is discussed, fit its function or action into the appropriate place in the picture. If you make this a habit, you will not get lost in details.

The next two chapters will explain how radio and television receivers operate. Each of the circuits will be described to show how they participate in fulfilling the electronic function of the equipment. Having a picture of how circuits work within familiar equipment will help you understand the details of electronic principles as you continue your study of this subject.

WHAT YOU HAVE LEARNED

1. There is little difference between electrical and electronic circuits. Both are based on identical principles. There is a difference, however, in the manner in which the circuits are applied.
2. Whether it be an application of electricity or one of electronics, circuits operate in a manner that is determined by the effect the components of the circuit have on current that is passing through the circuit or on the voltage that is applied to the circuit.
3. All electronic components, regardless of their name or description, are either resistors, capacitors, inductors, or a combination of these. The effect they have on voltage or current is called resistance, capacitance, and inductance. Since these are the only elements that constitute any circuit, learning their principles well and then applying their effect on current and voltage makes analysis of how a circuit works relatively easy.
4. The changing characteristics of voltage and current can be revealed in their waveforms. A waveform has two dimensions—amplitude (volts or amperes) for height, and time (seconds, milliseconds, or microseconds) for width.
5. Many students do poorly in learning electronics because they get lost in descriptive detail. To prevent this from happening to you, fit the function of each component into its place in the mental image you have retained of the entire circuit and what it is designed to do.

14

Radio Transmitters and Receivers

What You Will Learn

When you have finished this chapter you will have learned what the electromagnetic frequency spectrum is, what a radio transmitter is, how it develops a broadcast signal, and how radio signals are transmitted through the atmosphere. You will also learn how a broadcast signal is received, and how a radio receiver converts it into sound. In addition, you will become acquainted with the difference between amplitude and frequency modulation.

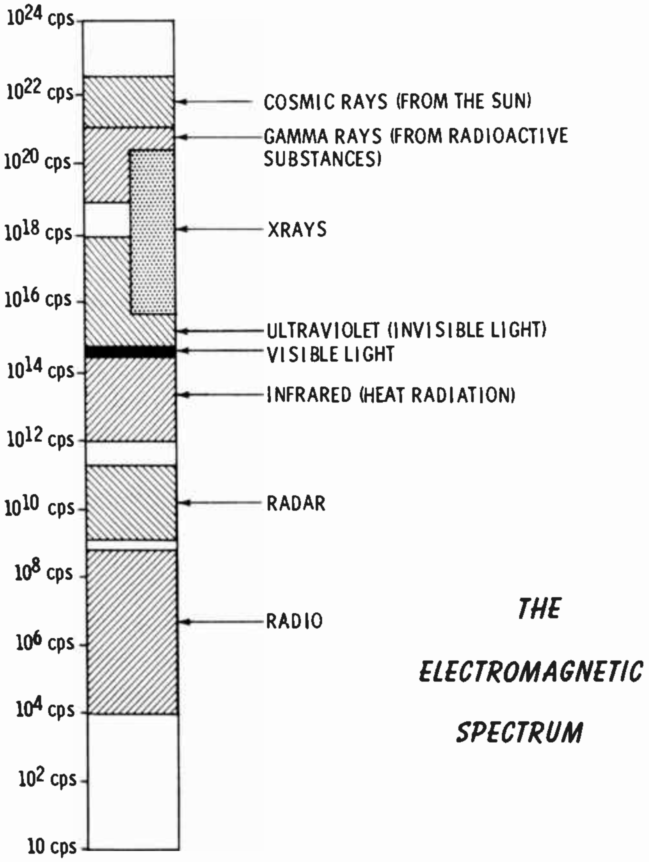
In this and the following chapter you will become familiar with the general principles of operation for certain equipment. As pointed out previously, an understanding of how electronic equipment works will help you put descriptions of components and circuits into proper frames of reference so their meaning is not lost.

ELECTROMAGNETIC RADIATIONS

Energy that radiates from a source is said to be an **electromagnetic wave.** Gamma rays, which are given off by radioactive particles such as radium, uranium, or atomic-bomb fragments, are electromagnetic waves. Cosmic rays from the sun travel extensive distances to the earth as electromagnetic waves. Electromagnetic waves, which include light, radiated heat, and radio signals, travel through space at the rate of 186,000 miles per second.

Electromagnetic Frequency Spectrum

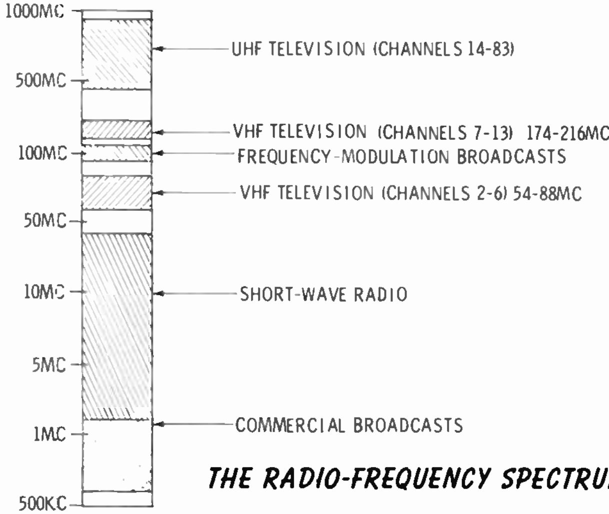
Electromagnetic radiations differ from each other in terms of their frequencies (cycles per second). As you recall from the last chapter, the frequency of one of these radiations is the number of times a single cycle repeats itself in 1 second. An **electromagnetic spectrum chart,** showing the relationship of these frequencies, is given below.



The chart shows that cosmic rays are radiated at a frequency of around 10^{22} cycles per second. (The number 10^{22} is 1 followed by 22 zeroes, or ten-thousand, million, million, million cycles per second.) At the lower end of the radio portion, radiation frequency is under 10^4, or ten thousand cycles per second.

Assigned Broadcast Frequencies

The Federal Communications Commission (FCC) has assigned specific groups of frequencies to different types of communications transmissions. This is shown in an expansion of the radio-frequency portion of the spectrum.



THE RADIO-FREQUENCY SPECTRUM

Commercial transmitters (radio and television, for example) are assigned a transmitting frequency in the appropriate part of the radio-frequency spectrum. Transmitters broadcasting in the home radio band, 535 kc to 1,605 kc (kilocycles), are required by law to be on their assigned frequency within plus or minus 20 cycles per second.

Q1. Cosmic rays and radio waves are examples of ________________ ___________.

Q2. Sound (is, is not) electromagnetic radiation.

Q3. Radio waves travel from the broadcast station to a receiving antenna at the rate of ______ miles per second.

Q4. __________ is the characteristic which distinguishes one electromagnetic wave from another.

Q5. Commercial radio transmissions are at a (higher, lower) number of cycles per second than television.

Q6. A frequency of 1,000 kilocycles would be assigned to (commercial, short-wave) radio.

Your Answers Should Be:

A1. Cosmic rays and radio waves are examples of **electromagnetic radiations** (waves).

A2. Sound **is not** electromagnetic radiation. Remember? It is changing air pressure.

A3. Radio waves travel from the broadcast station to a receiving antenna at the rate of **186,000 miles** per second.

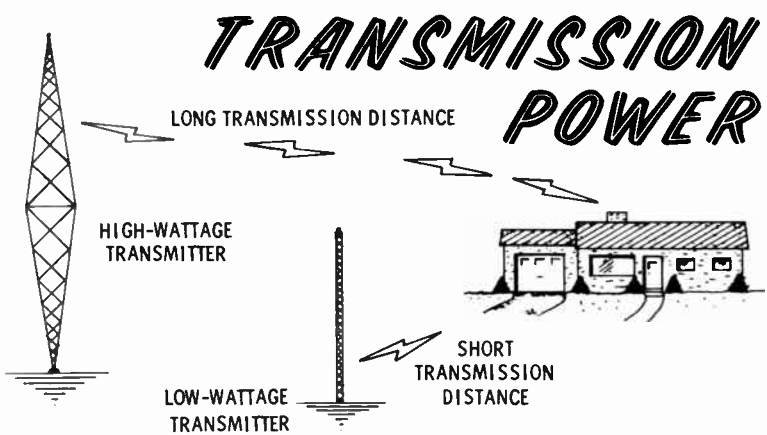
A4. **Frequency** is the characteristic which distinguishes one electromagnetic wave from another.

A5. Commercial radio transmissions are at a **lower** number of cycles per second than television.

A6. A frequency of 1,000 kilocycles would be assigned to **commercial** radio. (1,000 kilocycles is equal to 1 mc.)

RADIO TRANSMITTERS

The dial on your home radio receiver is marked off in numbers, probably from 550 to 1,600 kilocycles (or 55 to 160). By rotating the tuning dial, you select the desired station. Since each local station broadcasts at a different frequency, you are able to select the one you desire. The dial setting indicates the broadcast, or **carrier,** frequency of the station.



Transmitter Power

You have also noted that some stations come in stronger than others. The stronger stations broadcast at higher power (measured in **watts** or **kilowatts**) than the weaker. Or, if one of two stations broadcasting at equal power is stronger than the other, the stronger station is closer to your home.

The illustration on the opposite page shows two antennas transmitting at different frequencies in the broadcast band. The one farther away is broadcasting at many kilowatts of power and is able to reach the receiver. The low-wattage transmitter, although nearer, does not have enough power to span the distance. This may explain why you cannot pick up some stations that are located in your general area.

Carrier and Audio Frequency

The frequency assigned to a broadcast station is called its **carrier frequency.** The transmitter and its antenna are designed and tuned to that specific frequency. As its name implies, the carrier frequency carries the reproduction of the sound originating in the studio. Actually, there are two frequencies that leave the transmitter, a **radio frequency** (carrier) and an **audio frequency** (sound). Audio frequencies are classified as being between 20 and 20,000 cycles per second. The frequency range of most human ears, however, is usually no higher than 15,000 cps.

Q7. A home radio receiver (can, cannot) be tuned to 1 megacycle.

Q8. 900,000 cycles per second (could, could not) be a carrier frequency of a commercial broadcast station.

Q9. The power of Station A is one megawatt. Station B is broadcasting at 500 kilowatts. Which station will transmit the longer distance?

Q10. Two broadcast stations are equally distant from your home. Assuming your receiver is good, what would be the reason you could not receive one of them?

Q11. A human ear (can, cannot) hear a radio frequency.

Q12. A frequency of 600 kilocycles is classified as a(an) (audio, radio) frequency.

Your Answers Should Be:

A7. A home radio receiver **can** be tuned to 1 megacycle. One megacycle (1,000 kc) is within the broadcast band.

A8. 900,000 cycles per second **could** be a carrier frequency of a commercial broadcast station. It is the same as 900 kc.

A9. **Station A.** It has twice as much power.

A10. **One station** is so **weak in power** it cannot transmit the distance.

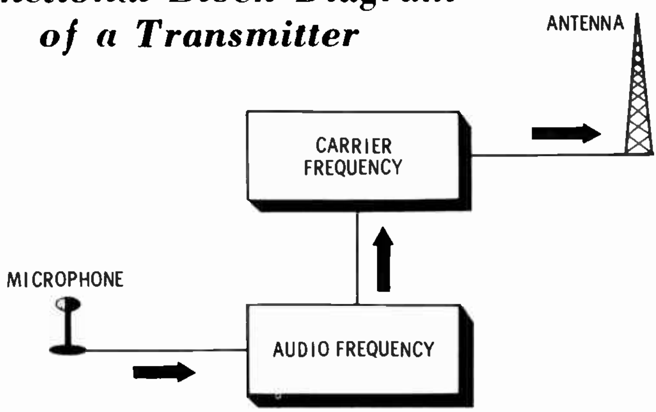
A11. The human ear **cannot** hear a radio frequency.

A12. A frequency of 600 kc is classified as a **radio** frequency.

A Basic Transmitter

The diagram below shows a **functional block diagram** of a typical broadcast transmitter. It is called a functional block diagram because each block is representative of a general electronic function and may include several circuits.

Functional Block Diagram of a Transmitter

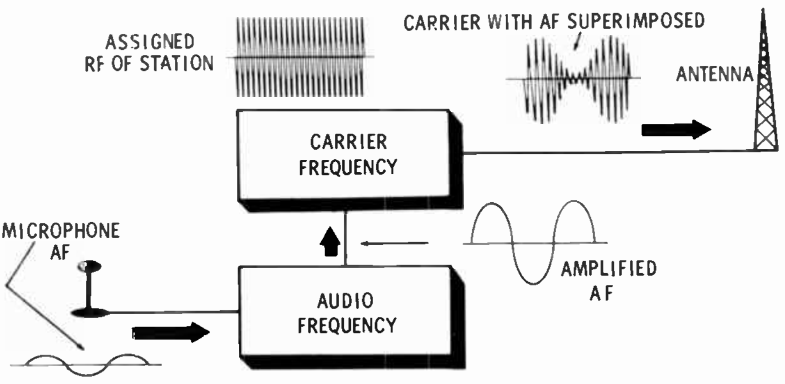


The arrowheads between blocks show the direction of signal flow. You can probably already read what the diagram reveals.

Sound enters the **microphone** and is fed to the audio-frequency (AF) section. The sound, because it is too weak for transmission purposes, is amplified (signal amplitude is increased) and then passed to the carrier-frequency section.

Carrier Frequency—The specific radio frequency (RF) assigned to the broadcast station is developed in the carrier-frequency block. Passing through several circuits, the RF signal is boosted in power (increased in amplitude) to the rated wattage output of the transmitter. Just before the RF carrier is fed to the antenna, the AF signal is superimposed on it. Waveforms developed in each block are shown below.

TRANSMITTER WAVEFORMS



Superimposing the Sound—The process of superimposing AF on the carrier, as shown in this particular example, is called **amplitude modulation** (AM). In amplitude modulation the audio frequency (varying at the changing rate of the original sound) is mixed with the carrier (a constant frequency) in a manner that causes that carrier **amplitude** to vary at the same rate as the audio. The carrier **frequency** remains unchanged.

Q13. The drawing on the opposite page is called a(an) ___________ _____ diagram.

Q14. Sound enters the AF section by way of a device called a(an) ___________.

Q15. ___________ on a block diagram show the signal direction between blocks.

Q16. Placing AF on a carrier without changing the carrier frequency is called __________ ___________.

Your Answers Should Be:

A13. The drawing on the opposite page is called a **functional block** diagram.

A14. Sound enters the AF section by way of a device called a **microphone.**

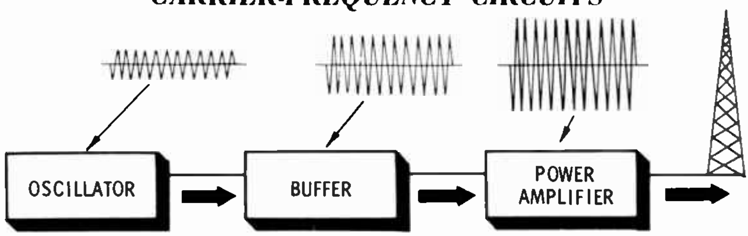
A15. **Arrowheads** on a block diagram show the signal direction between blocks.

A16. Placing AF on a carrier without changing the carrier frequency is called **amplitude modulation.**

Carrier-Frequency Circuits

A minimum number of carrier-frequency circuits are shown in the diagram below. An actual broadcast station has many more circuits to attain the frequency stability and power required of its transmitter. The additional circuits are similar to those shown, however.

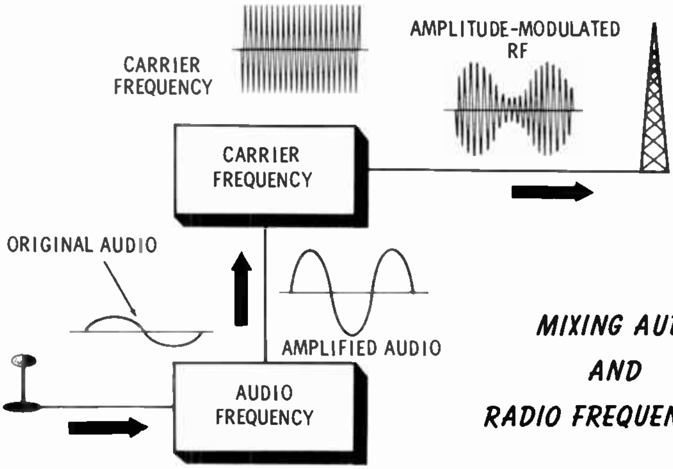
CARRIER-FREQUENCY CIRCUITS



The Oscillator—The purpose of the **oscillator** is to generate a stable RF signal. The resistance, inductance, and capacitance that make up its input circuit are such that they will not allow the vacuum tube in the oscillator to amplify any other signal but that of the desired frequency. The stable-frequency, low-amplitude output of the oscillator is shown above.

The Buffer—This stage (another name for circuit) is sometimes called an **intermediate power amplifier**, or **frequency multiplier.** In most transmitters it performs three functions. As a **buffer**, the stage isolates the oscillator from the effects of the other **circuits.** Without this isolation, stray signals may be fed back to the oscillator, causing it to operate at the wrong frequency. As an **amplifier,** the buffer increases the amplitude of the oscillator signal to a level that is between the desired transmitter output and the amplitude of the oscillator signal. In many transmitters the buffer circuit **doubles** (or even **triples**) the frequency of the oscillator output. The oscillator may not be capable of generating the station frequency by itself. In order to produce the assigned frequency, a transmitter may require several multiplier stages.

The Power Amplifier—The purpose of the **power amplifier** is to increase the amplitude of the RF signal to the power (wattage) requirements of the station. Several stages of power amplification may be required to achieve this. Normally, the audio signal from the AF circuitry is fed to the final power amplifier and used to modulate the carrier.



MIXING AUDIO AND RADIO FREQUENCIES

Q17. A transmitter circuit which amplifies a signal and increases its frequency is called a(an) ___________.

Q18. A(an) ___________ generates a signal which has a uniform frequency.

Q19. ______ amplifier output is measured in watts.

Q20. AF and RF are mixed in what stage?

Q21. The carrier arrives at the antenna with its waveform (amplitude, frequency) modulated.

Your Answers Should Be:

A17. A transmitter circuit which amplifies a signal and increases its frequency is called a **multiplier.**

A18. An **oscillator** generates a signal which has a uniform frequency.

A19. **Power** amplifier output is measured in watts.

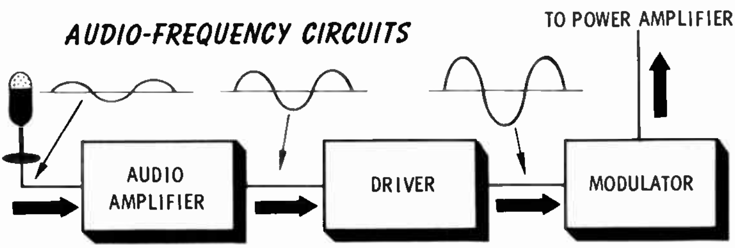
A20. AF and RF are mixed in **the final stage of the power amplifier.**

A21. The carrier arrives at the antenna with its waveform **amplitude** modulated.

Audio-Frequency Circuits

The Microphone—Regardless of the many different types of microphones that are available, even the best develop only a weak signal.

The Audio Amplifier—Although a single stage of audio amplification is sometimes all that is necessary, larger transmitters may have two, three, or more stages to obtain the desired undistorted level of amplitude.



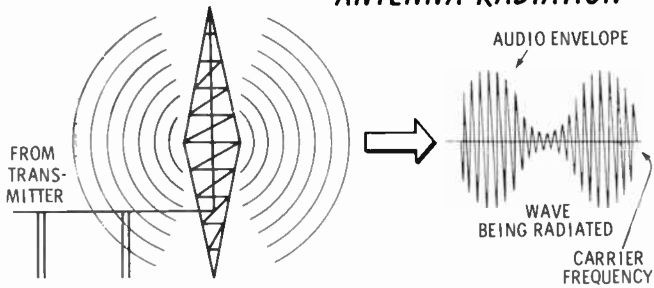
The Driver—Like most circuits, the **driver** obtains its name from its purpose. The driver amplifies the AF to the voltage level required to "drive" the tubes of the modulator. The modulator tubes require large changes in signal amplitude to operate properly.

The Modulator—The **modulator** is a power amplifier quite similar to the final circuit of the carrier-frequency block. It amplifies the audio signal to a power level suitable for modulating the carrier power in the final power amplifier. Power output of the modulator is fairly close to half the power of the final carrier amplifier.

Antennas

If all circuits are operating properly, an AM (amplitude-modulated) carrier is fed to the antenna and transmitted into the atmosphere.

ANTENNA RADIATION



Power is fed to the antenna in the form of both current and voltage. Voltage sets up an electric field along the length of the antenna. Current, in traveling through the antenna (a conductor), sets up a corresponding magnetic field. Both fields vary at the rate of the carrier frequency and at the amplitude and frequency of its audio envelope.

Both fields expand outward and collapse back to the antenna at the rate of the carrier frequency. The outermost waves continue through space and do not return to the antenna. This action is similar to dropping a pebble in a pool. The energy of the waves moves outward in ever-widening circles; the water, however, remains in place.

Q22. The weak output of a microphone is fed to one or more stages of ----- amplification.

Q23. The output of even the best microphones (can, cannot) be fed directly to the modulator.

Q24. The output of the ---------- is connected to the carrier power amplifier.

Q25. For proper modulation, the output of the modulator stage must be ---- that of the power amplifier.

Q26. Carrier voltage develops a(an) --------- field and carrier current develops a(an) -------- field on the antenna.

Q27. All of the energy in the antenna fields (does, does not) leave the antenna.

Your Answers Should Be:

A22. The weak output of a microphone is fed to one or more stages of **audio** amplification.

A23. The output of even the best microphones **cannot** be fed directly to the modulator. (Even the most powerful microphones develop a signal that is much too weak to drive the modulator.)

A24. The output of the **modulator** is connected to the carrier power amplifier.

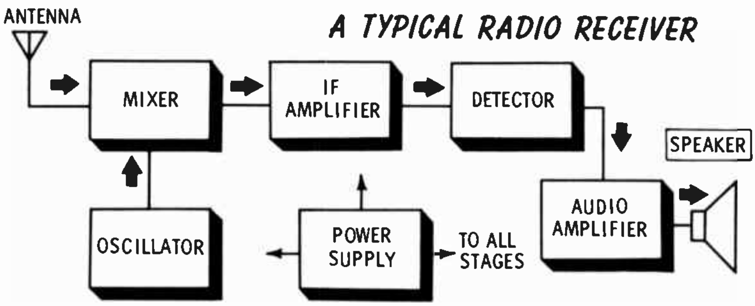
A25. For proper modulation, the output of the modulator stage must be **half** that of the power amplifier.

A26. Carrier voltage develops an **electric** field and carrier current develops a **magnetic** field on the antenna.

A27. All of the energy in the antenna fields **does not** leave the antenna. (Only the outermost waves.)

A RADIO RECEIVER

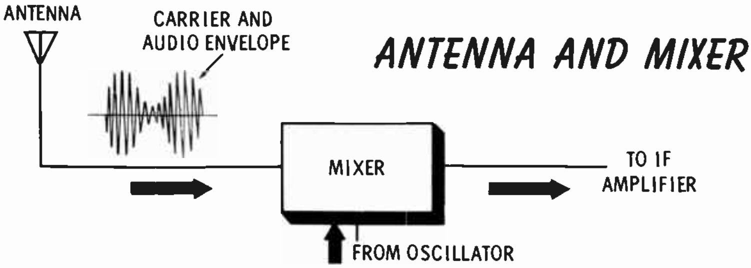
The block diagram for a radio receiver similar to the one in your home is shown below.



The purpose of the radio receiver is to convert the amplitude modulation on the carrier back to its original sound. As the carrier increases in ever-widening circles on leaving the transmitter antenna—like ripples in a pool—its energy decreases in amplitude. The increasing circumference of the circles causes power in the waveform to be distributed over an ever-increasing area. By the time the signal reaches the receiver antenna it is rather weak, usually around a few thousandths or millionths of a volt. The receiver, therefore, must amplify the received signal to a level that will operate the speaker within the hearing range of the human ear. The receiver must also extract the audio component (the **envelope**) from the carrier. The carrier brings the signal to the receiver, but has no value in the reproduction of the audio frequency in the receiver.

Receiver Circuits

The Power Supply—Each receiver has a power supply. Its purpose is to convert 115 volts AC from an electrical outlet (or to provide DC if the receiver is battery-operated) to voltages that will operate the receiver properly.



The Antenna and Mixer—Carrier frequencies from all stations within range of a receiver appear on the antenna of the receiver. When you turn the dial of your radio to a specific station, you adjust the electronic components of the **mixer** input so that the receiver will accept a particular carrier frequency and reject all others. The received carrier enters the mixer to be amplified. Some radios have, in addition, an **RF amplifier** between the mixer and antenna.

Q28. What part of the received radio wave does the receiver convert back into original sound?

Q29. A radio wave decreases in power as the circumference of its area increases. What is the approximate amount of voltage that enters the receiver antenna?

Q30. The _____ ______ converts AC to voltages required to operate the receiver circuits.

Q31. A single broadcast frequency appears at the input of the (antenna, mixer).

Your Answers Should Be:

A28. The **amplitude modulation** (or audio envelope).

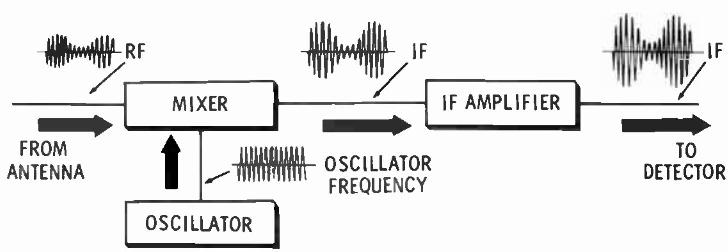
A29. A few thousandths or millionths of a volt.

A30. The **power supply** converts AC to voltages required to operate the receiver circuits.

A31. A single broadcast frequency appears at the input of the **mixer.**

The Oscillator—The receiver oscillator is similar to its counterpart in the transmitter. Both generate a signal of constant frequency and amplitude. The purpose of the receiver oscillator is slightly different, however. It is designed to generate a frequency that is a constant number of kilocycles above the carrier frequency, regardless of the station to which the receiver is tuned. The tuning dial changes the values of the electronic components in the frequency-generating circuit of the oscillator at the same time it is adjusting the frequency-reception components of the mixer. The arrangement of adjustable components is such that the oscillator will always be tuned 456 kilocycles (or a similar frequency) above the frequency of the carrier being accepted by the mixer. The output of the oscillator is fed to the mixer, as shown in the diagram below.

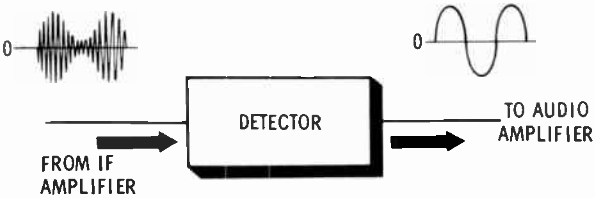
MIXER, OSCILLATOR, AND IF AMPLIFIER



The Mixer—The carrier and oscillator frequencies combine in the mixer tube and four different frequencies appear at the output. One of these four is the **difference** between the oscillator and the carrier frequencies, and is usually 456 kilocycles. The other three are rejected by the next stage.

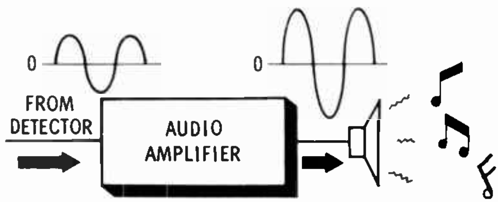
The IF Amplifier—The abbreviation for **intermediate frequency** is IF. In most home receivers the IF is 455 or 456 kc. Amplifying a single frequency in the IF circuit is much easier and causes less distortion than if it were necessary to tune this amplifier to each of the many station frequencies. The only purpose of this stage is to amplify the IF (which still retains the original audio frequency) and pass it on to the detector.

DETECTOR



The Detector—The purpose of the **detector** is to remove the audio component from the IF waveform. The audio envelope is the same (although reversed) at the top of the waveform as it is at the bottom. The detector circuit is so designed that it accepts only the audio frequency at the top and rejects the IF frequency in the waveform.

AUDIO AMPLIFIER AND SPEAKER



The Audio Amplifier—The final circuit in the receiver amplifies the AF fed to it by the detector. The amount of amplification can be varied by the volume-control knob on the front of the receiver. The output of the audio amplifier is applied to the speaker voice coil, causing the speaker cone to reproduce the sound that originated at the studio.

Q32. The _________ removes the AF from the IF waveform.

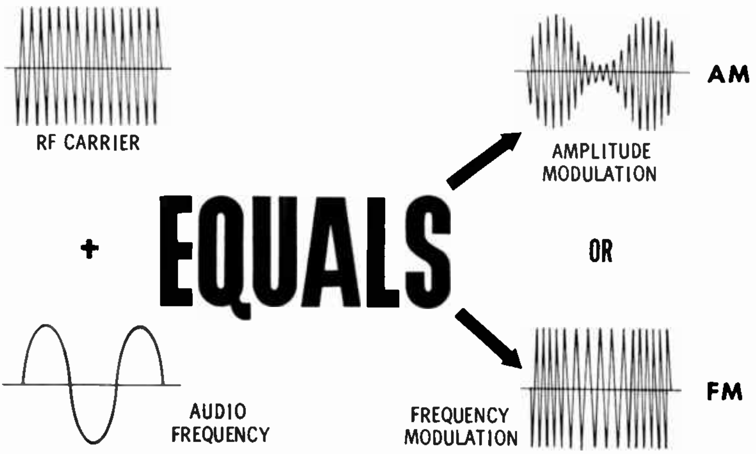
Q33. The oscillator develops a signal at a constant __________ and __________.

Q34. A converter combines the functions of _____ and ___________.

> **Your Answers Should Be:**
>
> A32. The **detector** removes the AF from the IF waveform.
>
> A33. The oscillator develops a signal at a constant **amplitude** and **frequency.**
>
> A34. A converter combines the functions of **mixer** and **oscillator.**

FREQUENCY MODULATION

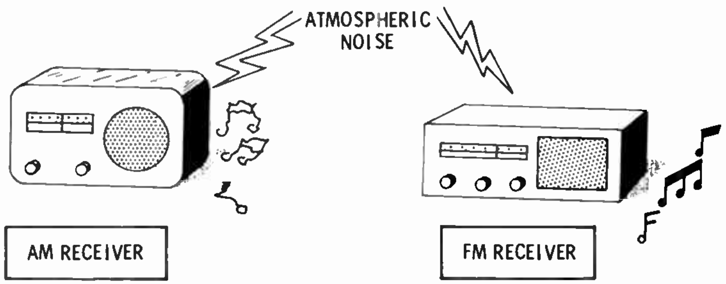
The transmitter and receiver with which you have just become familiar employs amplitude modulation (AM) to carry the audio. Another method of superimposing audio on a carrier is called **frequency modulation** (FM). Its process is quite different. The two are compared below.



Both AM and FM start out with a carrier frequency and an audio frequency (sound originating in the studio). In amplitude modulation, as you already know, the sound is superimposed on the carrier frequency (which is constant) by varying the carrier **amplitude** in conformance with the voltage and frequency of the audio.

In FM, however, the audio is mixed with the RF in such a way that the carrier **frequency** is varied in accordance with the amplitude of the sound. As the audio cycle goes positive, carrier frequency increases. When the audio cycle goes negative, carrier frequency decreases. The sum of the two changed frequencies in one audio cycle is still equal to the original carrier frequency.

One of the advantages of frequency modulation is its freedom from distortion. Noise and other forms of distorting voltages in the atmosphere or receiver are added to amplitude modulation. Since FM does not depend on a changing amplitude to carry audio, noise has little or no effect on it. This is part of the reason for the clarity of sound that you get from an FM receiver.



Q35. In AM, the carrier ---------- changes to match the audio.

Q36. In FM, the carrier ---------- changes to match the audio.

Q37. An FM receiver is (more, less) subject to atmospheric noise than an AM receiver.

WHAT YOU HAVE LEARNED

1. Radiant energy is given off by electromagnetic waves. The electromagnetic spectrum includes cosmic rays, X rays, visible and invisible light, infrared, radar, as well as radio waves.
2. A radio transmitter is a device that produces electromagnetic waves in the radio portion of the spectrum. Its essential functions are the development and amplification of a carrier frequency and modulating it with an amplified audio frequency. A specific carrier frequency is assigned to each radio station. The distance that the carrier, with its superimposed audio, travels

Your Answers Should Be:

A35. In AM, the carrier **amplitude** changes to match the audio.

A36. In FM, the carrier **frequency** changes to match the audio.

A37. An FM receiver is **less** subject to atmospheric noise than an AM receiver.

is determined by the power that is developed in the final stage of the transmitter.

3. Energy in the form of voltage and current is fed from the transmitter to an antenna. This sets up electric and magnetic fields around the antenna that expand and collapse at the frequency of the carrier. Part of the energy is in the form of electromagnetic radiations and is transmitted through the atmosphere. The farther it travels, the weaker the signal becomes.
4. All carrier signals within range are picked up by the receiver antenna. The tuning control on the front of the receiver adjusts the input of the mixer so that only the desired station carrier frequency is received. At the same time, it adjusts an oscillator to generate an IF above the carrier frequency. Carrier and oscillator frequencies are joined in the mixer and the difference between the two, the intermediate frequency, is amplified and fed to the IF amplifier. Here the signal and its audio component are further amplified. The next stage (detector) extracts the audio component and passes it to the final stage (audio amplifier). The audio is amplified and fed to the speaker, causing the cone to reproduce the sound that originated at the studio.
5. Amplitude (AM) and frequency (FM) modulation are two methods of transmitting audio on a carrier. When AM is used, the amplitude of the carrier varies according to the loudness (amplitude) and frequency of the audio. In FM, the frequency of the carrier is varied instead of the amplitude. FM transmissions are less bothered by atmospheric and receiver noises.

15

Television Transmitters and Receivers

What You Will Learn

In this chapter you will learn how a television transmitter develops both picture and sound signals. You will gain more knowledge about antennas and the problems of sending electromagnetic waves through the atmosphere. You will also become familiar with how a television receiver converts electronic signals into picture and sound reproductions. Learning the basic principles of television transmitters and receivers is no more difficult than learning the principles of radio. The basic electronic principles are the same for both. You will find this to be true for any electronic equipment, regardless of how complicated it may seem.

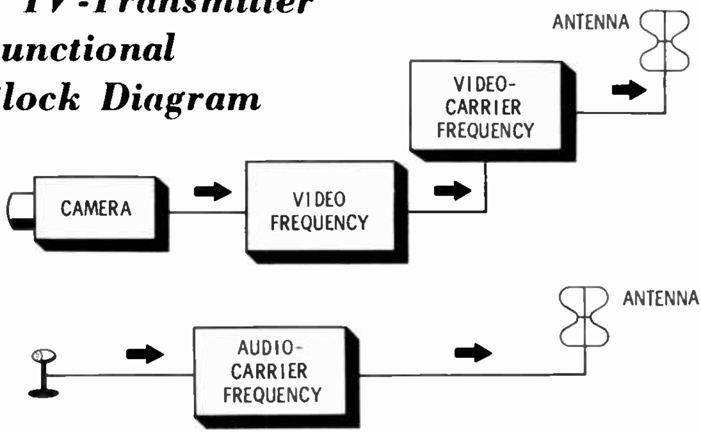
THE TELEVISION TRANSMITTER

There is actually very little difference between radio and television transmitters. As you recall, the functional block diagram of a radio transmitter contains a microphone, an audio-frequency section, a carrier-frequency section, and an antenna. A television transmitter has more operations to perform than a radio transmitter. Its functional block diagram, therefore, contains more sections. The functions of the two transmitters are quite similar, however.

Functional Block

The radio transmitter has the single problem of putting sound on a carrier. The TV transmitter must modulate two carriers, one with sound and the other with **video** (picture).

A TV-Transmitter Functional Block Diagram

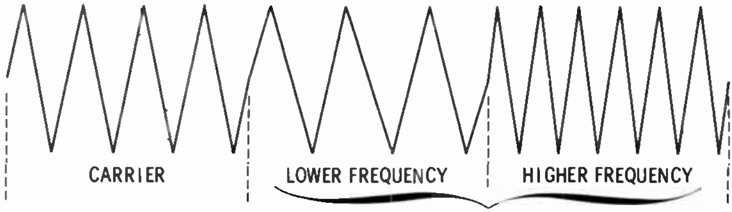


Video-Frequency Functions—The only difference between the functional blocks of a radio transmitter and a TV transmitter is the addition of a **video-frequency** function in the TV transmitter. The audio-frequency section is in a separate channel of its own. Shown in the TV block diagram is a camera which sends a weak picture signal to the video-frequency section to be amplified. The output of this section is a **video** frequency (higher than audio) used to modulate a **very high frequency** (VHF) generated in the carrier block. Superimposing the video (picture) on the carrier is done by amplitude modulation, the same process used in an AM radio transmitter.

Audio-Frequency Functions—A microphone feeding a signal to the audio-frequency section is shown at the bottom of the illustration above. The sound signal from this microphone is amplified and used to frequency-modulate a separate carrier. This modulated carrier is then fed to an antenna. In effect, there are two transmitters for TV—one for transmitting the picture and the other for transmitting the sound. In practice, a single antenna is usually used to transmit both carriers.

THE TV AUDIO TRANSMITTER

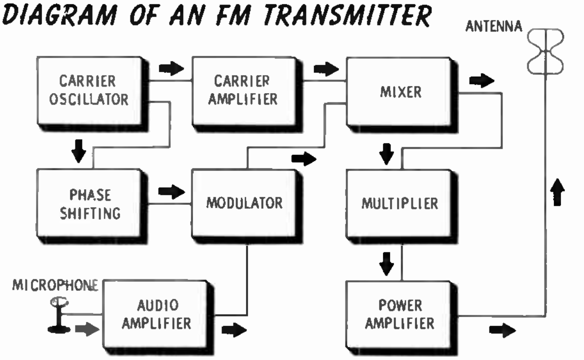
As previously stated, a TV audio transmitter uses the frequency modulation method. In the preceding chapter, you learned that FM is a process in which the frequency



Frequency Modulation

of a carrier is varied in accordance with the amplitude of an audio signal.

BLOCK DIAGRAM OF AN FM TRANSMITTER



Q1. **The sections of a functional block diagram of a radio transmitter are a microphone, _____ __________, _______ __________, and antenna.**

Q2. **Sound in an AM radio transmitter is placed on the carrier as a(an) __________ ____________; in a television transmitter, it is done by __________ ____________.**

Q3. **An audio frequency modulates a sound carrier; a(an) _____ frequency modulates a picture carrier.**

Q4. **The outputs of the _____ _________ and _____ __________ blocks of the sound transmitter are fed to the modulator.**

Your Answers Should Be:

A1. The sections of a functional block diagram of a radio transmitter are a microphone, **audio frequency**, **carrier frequency**, and antenna.

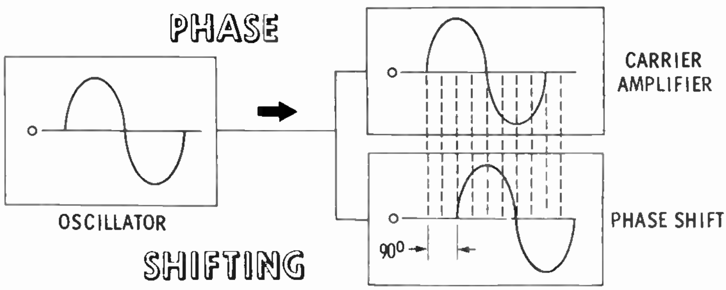
A2. Sound in an AM radio transmitter is placed on the carrier as an **amplitude modulation**; in a television transmitter, it is done by **frequency modulation.**

A3. An audio frequency modulates a sound carrier; a **video** frequency modulates a picture carrier.

A4. The outputs of the **phase shifting** and **audio amplifier** blocks of the sound transmitter are fed to the modulator.

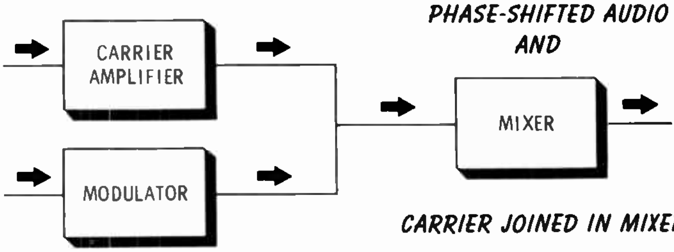
Audio Modulation of the Carrier

The oscillator in an FM transmitter, as in any other transmitter, develops a constant frequency at a uniform amplitude. The output of the oscillator is simultaneously fed to a carrier amplifier (where it is increased in amplitude) and to a phase-shifting circuit. A single cycle is shown in the oscillator block below. The same cycle appears in the output of the carrier amplifier. The corresponding cycle in the phase-shifting circuit shows that the signal has been shifted



(moved) to the right a quarter of a cycle. This is called **phase shifting.** The starting, maximum positive, return-to-zero, maximum negative, and ending points occur one quarter of a cycle later in the lower block than they do in the upper block. Since there are 360° (one way of designating the period of a sine-wave cycle) in a complete cycle, the lower waveform has been shifted in phase by 90°.

Modulator—Amplified sound signals from the audio amplifier and the phase-shifted carrier frequency meet in the modulator. The result of the meeting is a modulated output with an amplitude that varies in accordance with the amplitude of the audio, but still phase-shifted a quarter cycle.



PHASE-SHIFTED AUDIO AND CARRIER JOINED IN MIXER

Mixer—This circuit mixes the outputs of the carrier amplifier and the modulator to produce a variable frequency. This new signal is the carrier frequency changed by an amount determined by the amplitude variations of the audio. If the two inputs to the mixer had been in phase, this frequency variation of the carrier could not have occurred. Since equivalent points of the two waveforms are changing at different times, the audio variations of the modulator signal either add cycles to or subtract cycles from the constant frequency of the carrier. When the audio content of the modulator frequency goes positive, it causes a corresponding decrease in frequency of the carrier. When the audio content goes negative in its cycle, the carrier frequency increases a proportionate amount. The output of the mixer then is the basic carrier changing in frequency in accordance with the amplitude of the original sound.

Q5. The frequency of any transmitter is generated in a(an) ___________ circuit.

Q6. The phase-shifting circuit changes the phase (starting point) of the sine wave a(an) ________ of a cycle, or __ degrees.

Q7. Modulation occurs (before, after) power is amplified.

Q8. The audio frequency is placed on the carrier by ______ to and ____________ from the carrier cycles.

Your Answers Should Be:

A5. The frequency of any transmitter is generated in an **oscillator** circuit.

A6. The phase-shifting circuit changes the phase (starting point) of the sine wave a **quarter** of a cycle, or 90 degrees.

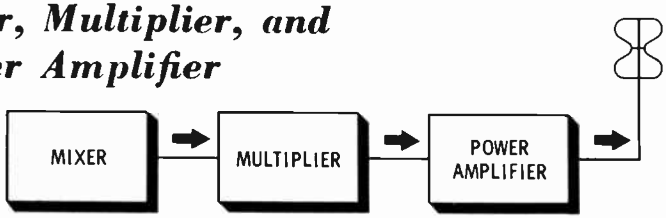
A7. Modulation occurs **before** power is amplified.

A8. The audio frequency is placed on the carrier by **adding** to and **subtracting** from the carrier cycles.

Amplifying the Modulated Carrier

Multiplier—The purpose of the multiplier stage is to amplify and increase the frequency of the modulated carrier. In some transmitters, several such circuits may be required. In addition to raising the amplitude of the carrier to that which is required for transmission purposes, multiplying the frequency also makes the modulated variations

Mixer, Multiplier, and Power Amplifier

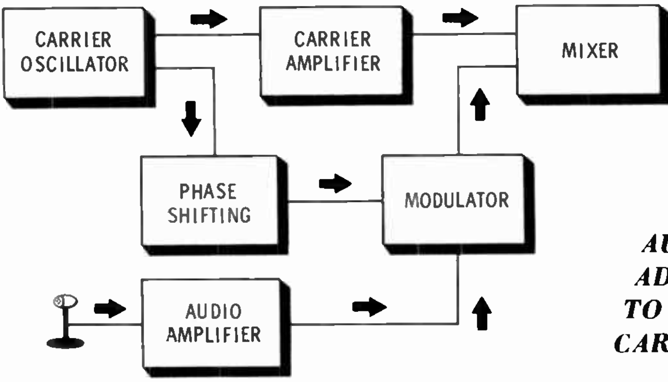


more pronounced. Those portions of the audio signal having higher amplitudes cause a wider variation of the carrier frequency than do those portions having lower amplitudes.

Amplifier—You will note that the carrier is modulated prior to the power amplifier stage. In amplitude modulation it is necessary to superimpose the audio in the final power stage, which is usually at very high power. Since the final amplifier of the audio-frequency section must have a power output that is close to 50% of that of the carrier amplifier, tubes and other parts must be large and expensive. In FM, the entire modulated carrier is raised to the correct power level in a single stage, making the FM transmitter more economical in this respect than its AM counterpart. The output of the power amplifier goes directly to the antenna.

Audio Transmitter Review

Sound from a television studio is added to the carrier wave by frequency modulation. The block diagram below shows the transmitter portion which mixes the two frequencies.

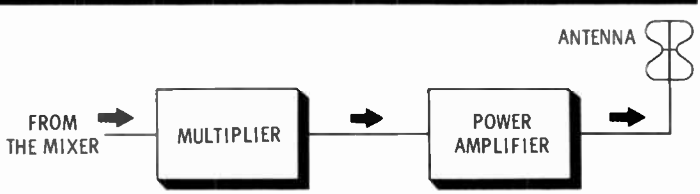


AUDIO ADDED TO THE CARRIER

The **oscillator** generates a stable frequency which is simultaneously fed to an **amplifier** and a **phase-shifting** network. The phase-shifting stage shifts the frequency by a quarter of a cycle. The carrier and the shifted signal are no longer in step. The amplified audio from the microphone is mixed with the out-of-phase signal in the **modulator.** The output of the modulator is a series of sine waves that vary in amplitude in accordance with the amplitude of the original sound.

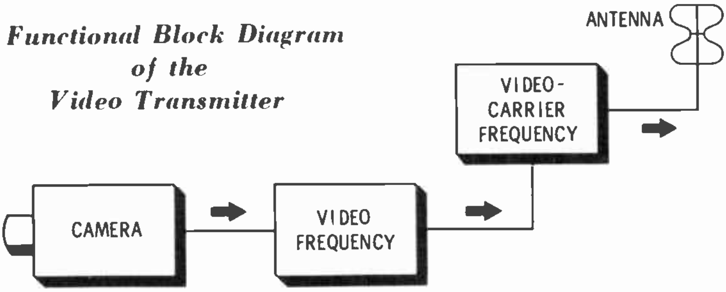
The outputs of the carrier amplifier and the modulator combine in the **mixer.** The output of the mixer is a signal that varies in **frequency** according to the **amplitude** of the modulating signal. The FM signal is then multiplied in frequency several times and increased in power by the stages shown below.

THE MODULATED CARRIER IS FED TO THE ANTENNA



A brief summary of what happens in the TV video transmitter might be helpful before its stages are discussed.

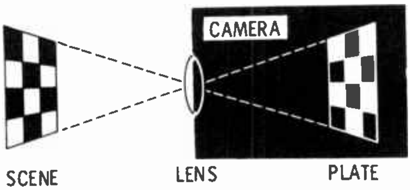
Functional Block Diagram of the Video Transmitter



In the video-frequency section, video signals from the camera are amplified and fed to the final power amplifier of the carrier-frequency section. Here, the carrier is amplitude-modulated by the video.

Camera—There are several different types of TV cameras. The **iconoscope, image dissector,** and **image orthicon** are examples. The latter is the type most frequently used in TV broadcasts. Although the manner in which they accomplish their purposes differs, their basic operating principles are the same.

The camera, much like its photographic counterpart, deposits a scene through a lens on a plate within the camera. Light rays from all parts of the scene are focused through the lens, reproducing the image on the plate. If the plate were a photographic negative, the light rays would excite deposits of light-sensitive materials in proportion to the intensity of light, varying from white through shades of gray to black.

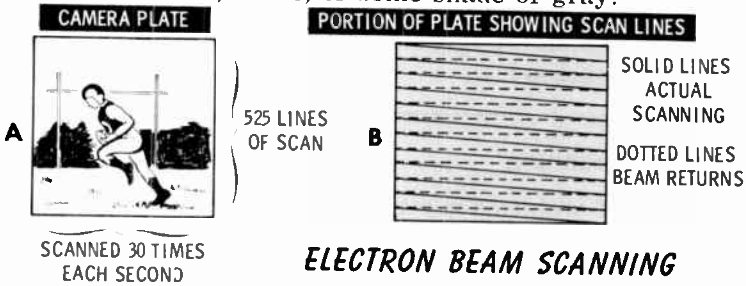


CAMERA OPERATING PRINCIPLE

A similar process occurs in a TV camera. The light-sensitive plate receives a picture of the scene. Tiny areas on the chemically treated plate are thereby electrically charged in proportion to the light intensity of that part of the scene.

Scanning

A very narrow beam of electrons is moved back and forth across the plate from top to bottom. The beam samples the intensity of the charge in each of the tiny areas. The amount of each charge indicates whether that portion of the scene is black, white, or some shade of gray.



ELECTRON BEAM SCANNING

As shown in part A above, the plate is **scanned** (movement of electron beam) in a sequence of 525 lines from top to bottom. A complete scan of the plate (525 lines each time) is made 30 times each second. The same procedure is duplicated on the screen of your receiver. In a TV receiver with a 17-inch screen, the electron beam in the picture tube travels across the screen at the rate of approximately 13,000 miles per hour.

Part B shows how this scanning is accomplished. The beam moves across the plate in the camera from left to right, sampling the intensity of each tiny area it passes. At the end of the line the beam is **blanked** (shut off) and returned to the left side of the plate to start the next line. The beam is turned on again and samples the second line. This process is continued until the bottom of the plate is reached. The beam is blanked and returned to the upper left-hand corner to start scanning again. When the beam is on and moving from left to right sampling the intensity on the plate, it is said to be **scanning.** When it is shut off and being returned to a new starting point, it is **retracing.**

Q9. The video is placed on the carrier by ____________________.

Q10. The image plate is ________ by an electron beam.

Q11. How many lines does the beam trace each second?

Q12. How many times a second is the beam blanked?

Your Answers Should Be:

A9. The video is placed on the carrier by **amplitude modulation.**

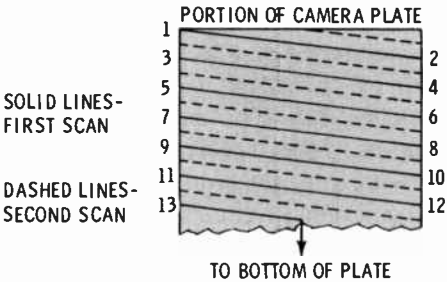
A10. The image plate is **scanned** by an electron beam.

A11. **15,750 lines per second.**

A12. It is blanked at the end of each line, **15,750 times each second.**

Interlaced Scanning

Because of problems in controlling the beam and of noticeable flicker to the viewer when **line-by-line scanning** is performed, the beam is caused to scan every other line.



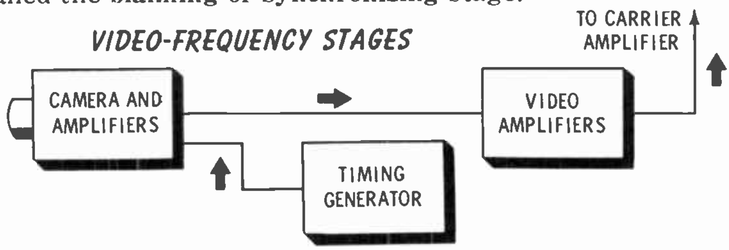
Interlaced Scanning

As the illustration shows, the first scan starts at line 1, samples the charged areas, and is retraced to line 3. This action continues to the bottom of the plate, scanning the odd-numbered lines. When it reaches the bottom, the beam returns to the top of the plate and scans the even-numbered lines. Each scan, top to bottom, requires 1/60 of a second. To scan the entire plate, the beam requires two passes, which takes a total time of 1/30 of a second. On the receiver screen a new image is being presented on every other line 60 times a second, a line-tracing frequency that cannot be noticed by the eye. If it were being done at the rate of 30 times a second, the eye might be able to see the changes, which would be recognized as a flicker. This process of scanning every other line is called **interlaced scanning.** The camera thus identifies the light and dark areas of a scene and converts this information to currents and voltages that change in proportion to the light intensity.

Timing Generator

The timing of the scanning events is very critical. The beam of electrons must begin at a precise point near the top of the camera plate and scan every odd-numbered line in 1/60 of a second. The electron beam must be blanked out precisely at the end of every line and at the end of the **field.** A complete scan of all the odd-numbered lines (or even-numbered lines) is called a field.

When the odd-numbered field has been completed, the blanked beam must be returned to a new position at a precise time to begin scanning the even-numbered field. Each action and position of the camera beam must be followed precisely by similar action in your TV receiver at home. The stage in the TV transmitter that establishes this precise timing is known as the **timing generator,** sometimes called the **blanking** or **synchronizing** stage.



The timing generator in the preceding illustration feeds pulse waveforms to the camera tube. The amplitude and timing of the pulses are such that they **synchronize** (cause all events to take place at precise time intervals) scanning, blanking, retracing, and positioning of the electron beam. The same timing pulses (for synchronizing the same events in the receiver) are fed, with the amplified video, to another stage of video amplifiers. From this point the entire signal—video and timing pulses—is passed to the final amplifier of the carrier for modulation purposes.

Q13. __________ scanning skips every other line.

Q14. By this method, a line on the receiver screen is changed __ times a second.

Q15. Scanning is synchronized by a(an) ______ __________.

Q16. What is contained in the video-output amplifiers?

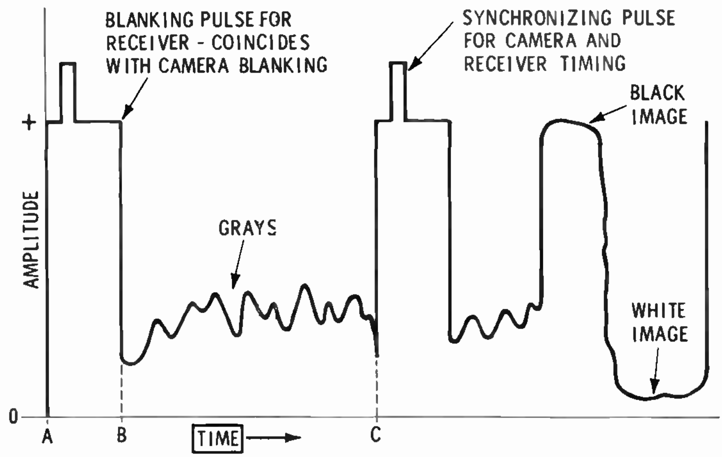
> **Your Answers Should Be:**
>
> **A13. Interlace** scanning skips every other line.
>
> **A14.** By this method, a line on the receiver screen is changed 60 times a second.
>
> **A15.** Scanning is synchronized by a **timing generator.**
>
> **A16. Video and timing pulses.**

Video Modulation

The video and timing pulses are placed on the carrier frequency by amplitude modulation. The process is similar to the method used by AM radio stations.

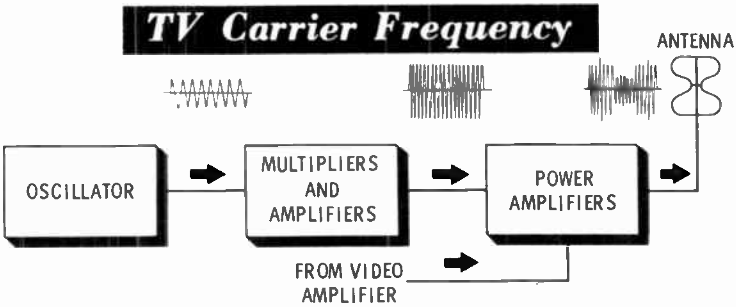
Video Signals—As you have learned from the preceding discussion, a video signal contains a great deal of information. A series of video waveforms is shown below. Remember that a waveform contains only two dimensions—amplitude and time.

COMPLETE VIDEO FOR TWO SCANNED LINES



Carrier Frequency—The carrier-frequency section is similar to the same circuits in a broadcast radio transmitter. (See the diagram on the opposite page.)

The oscillator generates a continuous and constant frequency. The output of the oscillator is increased in frequency and amplitude by the multiplier and amplifier sections. In the power amplifier, the carrier is raised to the desired power level required by the station, and is amplitude-modulated by the video signal.



For VHF (very high frequency—channels 2 to 13), the frequency of the carrier is between 54 and 216 megacycles. For UHF (ultra high frequency—channels 14 to 83), the carrier is between 470 and 890 megacycles. Transmission of signals at these frequencies is quite different from that for the lower radio frequencies. High frequencies have short wavelengths. A **wavelength** is the time duration, or length, of one cycle. The higher the frequency of a signal, the shorter is its wavelength.

Q17. The image scanned by the camera is changed into a(an) _____ frequency.

Q18. A video signal has __________ and ____ dimensions.

Q19. In the diagram on the opposite page, a full video cycle is from (A to B, B to C, A to C).

Q20. The beginning of a scanned line on the receiver screen coincides with (A, B, C).

Q21. Using the same letters, the electron beam is retracing between time ____ and time ____.

Q22. A black image appears on a (more, less) positive voltage than a shade of gray.

Q23. During retrace time in a video cycle, two pulses appear. What are they?

Q24. How many cycles are shown in the figure above?

Q25. VHF has (shorter, longer) wavelengths than UHF.

Q26. A TV video signal is __________ modulated.

Your Answers Should Be:

A17. The image scanned by the camera is changed into a **video** frequency.

A18. A video signal has **amplitude** and **time** dimensions.

A19. In the diagram, a full video cycle is from **A to C.**

A20. The beginning of a scanned line on the receiver screen coincides with **B.**

A21. Using the same letters, the electron beam is retracing between time **A** and time **B.**

A22. A black image appears as a **more** positive voltage than a shade of gray.

A23. During retrace time in a video cycle, two pulses appear. They are **blanking** and **synchronizing** pulses.

A24. **Two cycles** are shown in the figure.

A25. VHF has **longer** wavelengths than UHF.

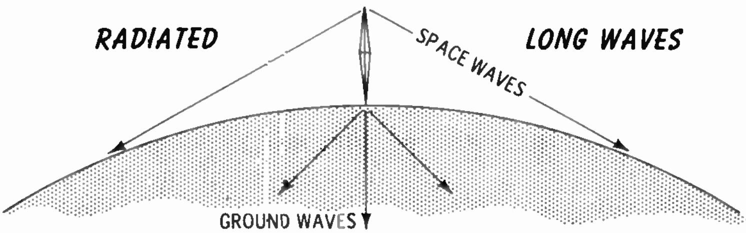
A26. A TV video signal is **amplitude** modulated.

TELEVISION TRANSMITTING ANTENNAS

An antenna, as you recall, develops an electromagnetic field around itself when current is passing through it. Current flows back and forth through an antenna in accordance with the rise and fall of the carrier-waveform frequency and amplitude.

Television Wave Propagation

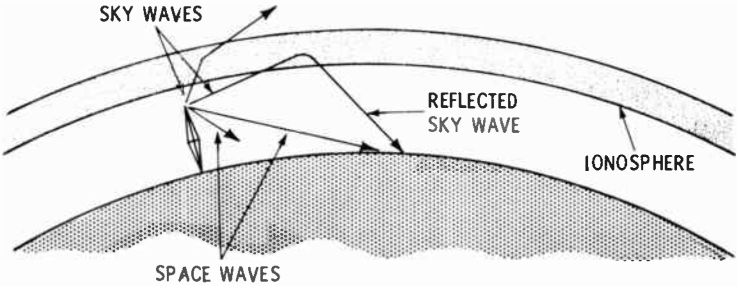
Since the wavelength of a TV carrier is shorter than that of a radio-broadcast carrier, the length of the TV antenna is correspondingly shorter. There is also a difference in the way short and long wavelengths travel through space.



The diagram illustrates the **propagation** (travel of electromagnetic radiation) of long waves as they radiate from the antenna of a commercial radio station. The frequency is between 535 and 1,605 kilocycles. The radiated energy has a **space wave** that travels essentially in a straight line. Low frequencies also have a **ground wave** that hugs the ground until the radiated power decreases so much with distance that reception is no longer possible.

The short wavelengths of a television transmission depend on a different method of wave propagation.

RADIATED SHORT WAVES



High frequencies radiate a space wave and a **sky wave.** Both of these waves travel essentially in straight lines. To receive a space wave, the receiving antenna must be within line-of-sight of the transmitting antenna. If the receiving antenna is beyond the horizon, the space wave (if it still retains sufficient power) passes over it.

Sky waves, also traveling in a straight line, head out into space. When the sky waves are 50 to 75 miles out, depending on the time of day, they encounter the **ionosphere,** a layer of charged particles that cause the short-wave radiations to bend. Waves that enter the ionosphere at a sharp angle are bent back to earth. At an angle close to 90° (perpendicular), the bending is not enough for the signal to return to earth, so it continues to travel toward higher altitudes. If they are of sufficient power, reflected sky waves can sometimes be picked up by receiving antennas.

Q26. TV frequencies have ______ and ___ waves.

Q27. ___ waves may be reflected by the ionosphere.

Q28. TV radiations are (short, long) waves.

Your Answers Should Be:

A26. TV frequencies have **space** and **sky** waves.

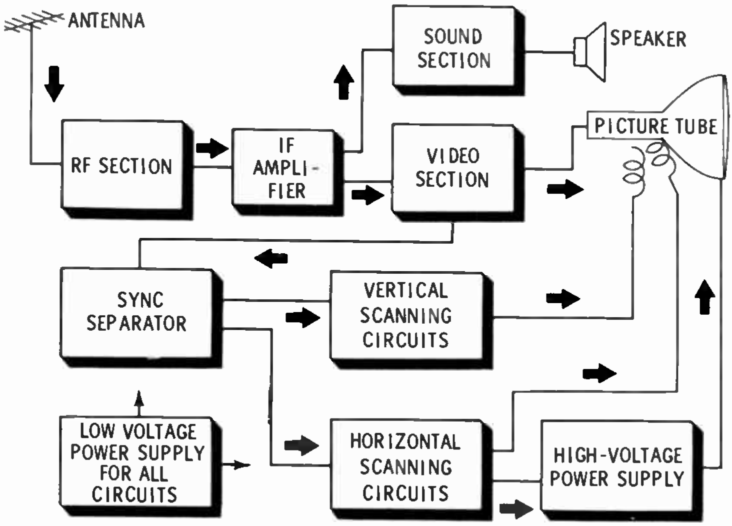
A27. Sky waves may be reflected by the ionosphere.

A28. TV radiations are **short** waves.

THE TELEVISION RECEIVER

There are many different models of TV receivers. They differ in the types and numbers of circuits used, as well as in the size of picture tube and style of cabinet. Since they all must process the same signals from a TV transmitter, the function of their circuits must be identical.

Block Diagram of a TV Receiver



The illustration above shows a single antenna bringing both the FM sound carrier and the AM video carrier to the RF (radio frequency) circuits. This is satisfactory since the sound- and video-carrier frequencies are fairly close together (the sound carrier is 4.5 megacycles higher).

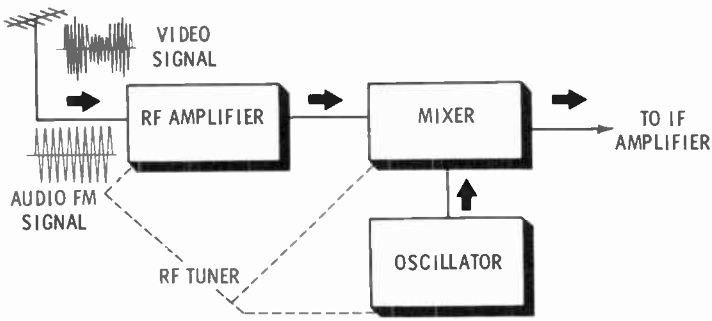
Both carriers are amplified and converted into an intermediate frequency (IF). The IF signals are amplified and then separated, each being sent to its proper section. In the sound section, the audio component of the frequency-modulated wave is extracted and sent to the speaker. In the video section, the picture signals and blanking pulses are taken from the amplitude-modulated wave and sent to the cathode-ray (picture) tube.

Synchronizing (sync) pulses time the controlling voltages of the vertical and horizontal circuits. Outputs of these stages cause the image to be placed on the screen of the cathode-ray tube.

RF Section

In most TV sets the RF section (sometimes called the **front end** or **tuner**), normally consists of an RF amplifier, a mixer, and an oscillator.

RF SECTION OF A TV RECEIVER



Dashed lines to two or more circuits in a diagram indicate that a single control has an effect on each circuit or part indicated.

Q29. _____ and _____ carriers are received by a single antenna.

Q30. The two frequencies differ by __ megacycles.

Q31. The carrier containing the synchronizing pulses is at a (lower, higher) frequency than the audio carrier.

Q32. Outputs from the RF section are fed to the _____ and _____ sections.

Q33. What stages are tuned by the receiver channel selector switch?

Q34. What section delivers the picture image to the picture tube?

Your Answers Should Be:

A29. **Sound** and **video** carriers are received by a single antenna.

A30. The two frequencies differ by 4.5 megacycles.

A31. The carrier containing the synchronizing pulses is at a **lower** frequency than the audio carrier.

A32. Outputs from the RF section are fed to the **sound** and **video** sections.

A33. **RF amplifier, mixer,** and **oscillator stages** are tuned by the selector switch.

A34. The **video section** delivers the picture image to the picture (cathode-ray) tube.

RF Amplifier—All the TV station carriers reaching your receiver appear at the input of the RF amplifier. In selecting a channel, the tuner provides the right combination of inductance and capacitance in this circuit so that only the video- and sound-carrier frequencies of that channel are amplified. All other channel frequencies are rejected. There are very few receivers that do not have an RF amplifier.

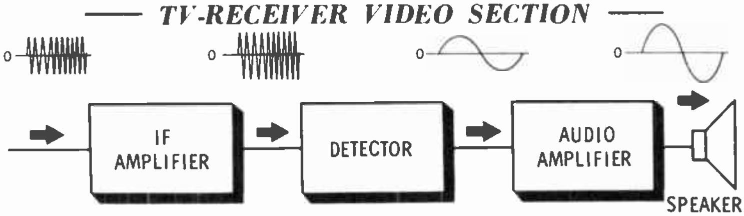
Mixer and Oscillator—The mixer is tuned to the same frequency as the RF amplifier. Its purpose is to develop the intermediate frequency for the IF amplifiers located in the sound and video sections. The mixer (converter) does this in the same manner as the mixer in the AM radio receiver. The oscillator develops a frequency that is the desired IF above the video- and sound-carrier frequencies. The oscillator and carrier frequencies are mixed to produce the IF difference frequency at the output of the mixer. This frequency is then fed to the IF amplifiers with the appropriate video and sound modulations still existing.

Fine-Tuning Control—Most sets have a **fine-tuning control** in addition to the channel selector. The fine-tuning control adjusts the value of a component (usually a capacitor) in the oscillator circuit. The change in value of this component causes an appropriate change in the frequency of the oscillator, allowing the IF for sound and video to be tuned more precisely.

Sound Section

You may have noticed the similarity between the mixer and oscillator of a radio receiver and the corresponding circuits in a TV receiver. In fact, most of the circuits of the sound section are similar in operation to those found in an FM radio.

— TV-RECEIVER VIDEO SECTION —



IF Amplifiers—The IF signal contains both frequency and amplitude modulation. The IF frequency is usually near 45 megacycles, which is a much higher frequency than the 455-kc IF usually found in an AM radio. This higher IF frequency modulated by both the audio and video signals is more difficult to amplify. Thus, the gain (amount of amplitude increase between circuit input and output) is low, and more than one stage of IF amplification is necessary. Depending on the quality of the receiver, the IF section will have two, three, or four IF amplifiers, one after the other. This row of amplifying circuits is sometimes called the **IF strip.**

Q35. Front end is another name for the __ ________.

Q36. What are the two carriers that enter the RF amplifier from the antenna?

Q37. What are the frequencies that become inputs to the mixer?

Q38. The selector switch tunes the mixer to the same input frequency as the __ __________.

Q39. The oscillator is tuned to a (higher, lower) frequency than the video carrier.

Q40. IF amplifiers are circuits in both the _____ and _____ sections.

Q41. There are (more, fewer) circuits in a TV IF strip than in the similar section of a home radio.

Your Answers Should Be:

A35. Front end is another name for the **RF section.**

A36. **Sound and video carriers** enter the RF amplifier from the antenna.

A37. **Sound, video and oscillator frequencies** are inputs to the mixer.

A38. The selector switch tunes the mixer to the same input frequency as the **RF amplifier.**

A39. The oscillator is tuned to a **higher** frequency than the video carrier.

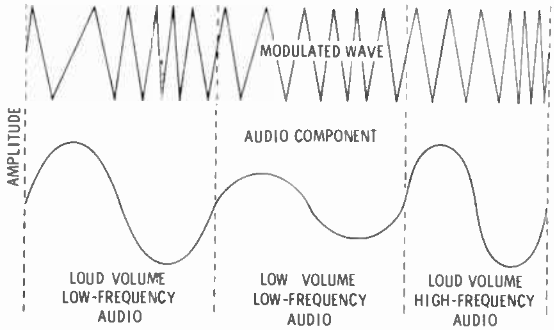
A40. IF amplifiers are circuits in both the **sound** and **video** sections.

A41. There are **more** circuits in a TV IF strip than in the similar section of a home radio.

Sound Detection and Amplification

Because the TV sound is contained in the form of frequency modulation, the method for removing the audio component is different from that for AM.

A Frequency-Modulated Wave



The Detector—FM and AM detectors have the same purpose—to remove the audio component from the modulated intermediate frequency. For FM, the variations in frequency are changed into voltage variations by the detector. The output of the detector (quite frequently called a **discriminator** because it discriminates between AF and IF), is an audio frequency representing the tone and amplitude of the sound originating at the studio.

The difference in volume, as shown in the illustration, is determined by the distance between cycles of the carrier (or IF). For a given carrier, its frequency is the same for each cycle of audio. Carrier frequency decreases (cycles farther apart) during the positive portion of an audio wave and increases (cycles closer together) during the negative portion. The greater the volume of the audio, the greater is the difference in carrier frequency between the positive and negative half cycles of the audio. A weaker volume shows less difference (carrier frequency will be more uniform throughout the audio cycle) between positive and negative half cycles of the audio.

High and low tones are determined by the number of times the periodic carrier-frequency variations repeat themselves. For low audio tones, repetition of cycles (audio frequency) is less often. For high tones, repetition of cycles occur a greater number of times per second.

The Audio Amplifier—The purpose and method of amplifying audio are identical in AM and FM receivers. The amplifier in either system raises the amplitude of the pure audio signal to the level required for operating the speaker. The volume control and tone control (if the TV set has one) are normally separate variable resistances in the first of two audio-amplifier stages.

Q42. Detectors are designed to remove ---------- modulation from the ------------- frequency.

Q43. The audio component of an FM signal is removed by a(an) -------------- circuit.

Q44. In frequency modulation, the distance between cycles of the carrier frequency determines the (volume, tone) of the sound.

Q45. A high tone requires (more, less) repetition of the IF variations than a low tone.

Q46. A discriminator separates the modulation frequency from the ------------- ----------.

Your Answers Should Be:

A42. Detectors are designed to remove **amplitude** modulation from the intermediate frequency.

A43. The audio component of an FM signal is removed by a **discriminator** circuit.

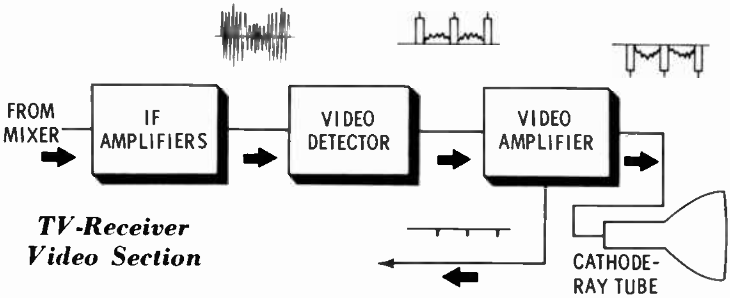
A44. In frequency modulation, the distance between cycles of the carrier frequency determines the **volume** of the sound.

A45. A high tone requires **more** repetition of the IF variations than a low tone.

A46. A discriminator separates the modulation frequency from the **intermediate frequency.**

Video Section

The purpose of the video section is to amplify the modulated picture signal and distribute its signal components to the correct stages of the set.



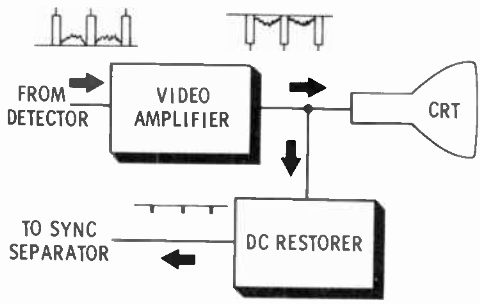
TV-Receiver Video Section

IF Amplifiers—The output of the IF amplifiers contains the video signal and is fed to the video detector, as shown in the diagram.

Contrast Control—The contrast control is actually a variable resistance in one of the video-amplifier stages. Its purpose is to vary the amount of output from the amplifier with which it is associated. This increases or decreases the amplitude difference between the voltages representing the white and black portions of the image. If the amplifier output is increased, the difference between the two voltages becomes greater and the contrast is increased.

Video Detector—Like the detector used in an AM radio, a TV video detector is usually a diode. As you remember from a previous chapter, a diode conducts current in one direction only. When the modulated signal is applied, the detector conducts only during the time the waveform is going positive. The varying frequency representing the sound, and the negative portion of the video signal cannot pass through the detector stage. Therefore, the output of the detector is identical to the picture signal as it left the camera and before it was placed on the carrier.

VIDEO AMPLIFIER AND DC RESTORER



Video Amplifiers—The output of the detector is a relatively weak signal, not strong enough to cause a reproduction of the picture. Video amplifiers are therefore required to achieve the necessary signal amplitude. These must be wide-band amplifiers because the frequency content of the picture signal covers a wide frequency range.

The output from the video-amplifier section is the reverse (upside-down) of the waveform that entered its input. This is the condition of the waveform that is desired. If the image and blanking pulses were positive going instead of negative going, the blacks of the image would appear as whites, and the whites as blacks.

Q47. The contrast control changes the amount of ------ of a video amplifier.

Q48. The video detector selects the (positive, negative) portion of the picture signal and rejects the ------------ frequency.

Q49. In the output of the video-amplifier section the sync pulse has a voltage (more, less) negative than the image.

Your Answers Should Be:

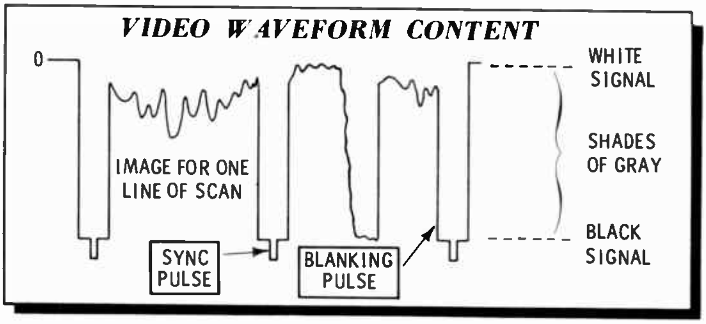
A47. The contrast control changes the amount of **output** of a video amplifier.

A48. The video detector selects the **positive** portion of the picture signal and rejects the **intermediate** frequency.

A49. In the output of the video-amplifier section the sync pulse has a voltage **more** negative than the image.

Image Display

In the illustration below, zero voltage is shown on the reference line. Any portion of the signal below this line is negative. As you recall, the camera image produces a signal in which whites are more positive than blacks and grays, and grays more positive than the blacks. The cathode-ray tube places the image on the screen with an electron beam similar to that used for scanning in the camera. Video

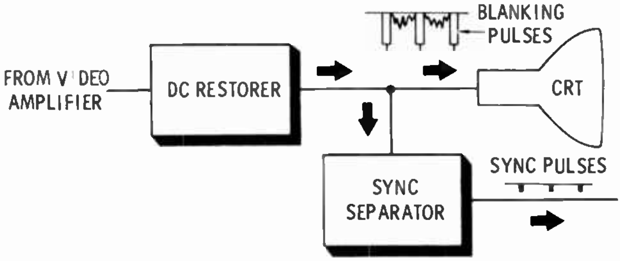


signals fed to the cathode-ray tube control the number of electrons striking the **fluorescent** screen. The fluorescent material on the screen gives off light in proportion to the number of electrons that strike it.

To reproduce blacks, the beam must be shut off. Whites require a maximum number of electrons. The video signal controls the number of electrons by the value of its negative voltage. Negative voltage repels electrons. A highly negative portion of the image signal (black) stops electron flow completely.

DC Restorer—To achieve proper values of the image and blanking voltages that control the number of electrons in the beam, a definite voltage reference level must be established and maintained. In other words, zero voltage is the reference shown in the illustration, and must be at the top of the waveform. If the waveform varies above or below this zero reference, the video and blanking will not appear on the screen properly. The circuit in most TV sets that maintains this level is called a **DC restorer.**

SYNC AND BLANKING PULSES



Brightness Control—Another front-panel adjustment, the **brightness control,** is a variable resistor in the picture-tube circuit. The purpose of this control is to adjust the position of the waveform on the zero reference level to a point that provides the best screen brightness for viewing purposes. If the control is adjusted so that the near-white amplitudes in the image are brought closer to the zero reference, more electrons strike the screen, making it brighter. When the control is turned in the other direction, so that even the white amplitudes are below the zero reference, fewer electrons strike the screen and the entire picture is darker.

Q50. The screen of a cathode-ray tube glows brighter if (more, fewer) electrons strike it.

Q51. To put "black" on the picture tube, the voltage representing black in the video waveform must be as (negative, positive) as the ________ pulse.

Q52. A zero reference level of the video waveform is established by the __ ________.

Q53. The __________ _______ adjusts the zero reference level for the desired brightness of the screen.

Your Answers Should Be:

A50. The screen of a cathode-ray tube glows brighter if **more** electrons strike it.

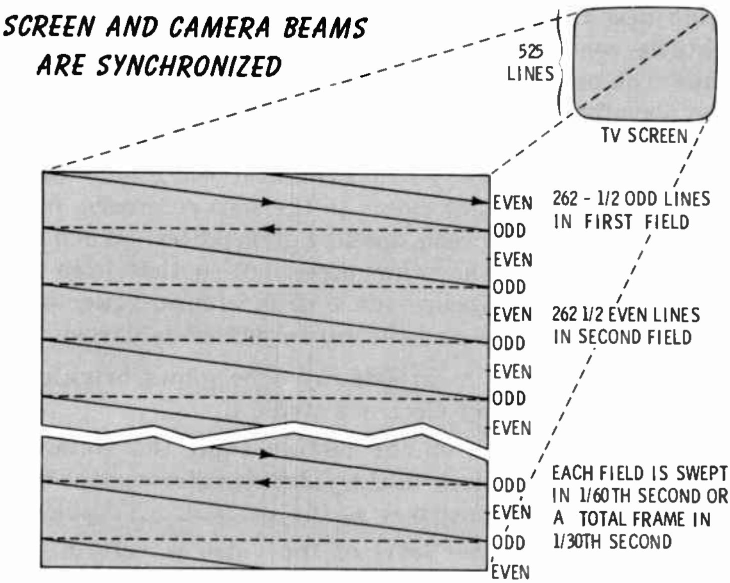
A51. To put "black" on the television screen, the voltage representing black in the video waveform must be as **negative** as the **blanking** pulse.

A52. A zero reference level of the video waveform is established by the **DC restorer.**

A53. The **brightness control** adjusts the zero reference for the desired brightness of the screen.

Scanning

In the discussion thus far, video and blanking pulses have been fed to the cathode-ray tube for each scanned line of the picture waveform entering the set. The picture portion of the waveform controls the intensity of the electron beam,



while the periodically appearing blanking pulses shut the beam off at the proper intervals.

Some method is needed to move the beam on the receiver screen from side to side and top to bottom in synchronization (in step) with the action that takes place in the camera. Each of the video waveforms represents one particular scan line among the 525 lines that should appear on the screen for a complete picture. Up to this point all of the video waveform has been used except the small **sync pulses** that are on top of the blanking pulses.

There are 525 horizontal lines in a complete picture on a TV screen. Each line represents an image line scanned by the TV camera and a screen line to be **swept** (reverse of scan) by the electron beam in the TV tube. The entire 525 lines are called a **frame.**

The camera sweeps every other line (interlaced scanning) for ease in electronic control and viewing (eliminates flicker). The receiver beam must do likewise, sweeping every other line precisely in sequence with the camera. In the first pass, called a **field**, the beam must start in the upper left-hand corner and trace every odd line, ending at the middle of the bottom line for a total of 262½ lines (½ of 525). The beam must then return to the top center of the screen and sweep each even line in sequence, completing 262½ lines of the field at the end of the bottom line.

In the process, the beam must excite the fluorescent screen with the correct intensity indicated by the corresponding portions of the video waveform. At the end of each line, the beam is blanked and must be rapidly returned to the left to start the next line of the picture. When the beam reaches the bottom of the screen, it must be blanked again and rapidly returned to the correct position (left or middle) at the top to sweep the next field. It must complete a **field** (262½ lines) in precisely 1/60 of a second and a full **frame** (complete picture) in 1/30 of a second.

Q54. There are ________ lines to a field and _ _ _ fields to a frame.

Q55. The sweep of the receiver beam must be _ _ _ _ _ _ _ _ _ _ _ _ _ with the _ _ _ _ of the camera beam.

Q56. The start and the position of each scan line on the CRT screen are controlled by the _.

Your Answers Should Be:

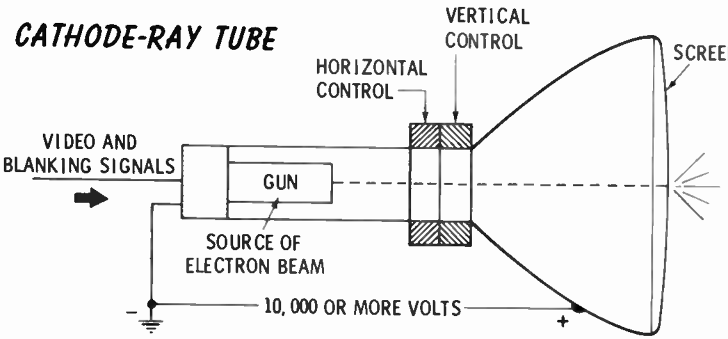
A54. There are 262½ lines to a field and **two** fields to a frame.

A55. The sweep of the receiver beam must be **synchronized** with the **scan** of the camera beam.

A56. The start and the position of each scan line on the CRT screen are controlled by the **synchronizing pulses.**

Moving the Electron Beam

You know that a negative voltage repels and a positive voltage attracts electrons. The cathode-ray tube (CRT) uses this effect to send an electron beam to the screen and control its movement.

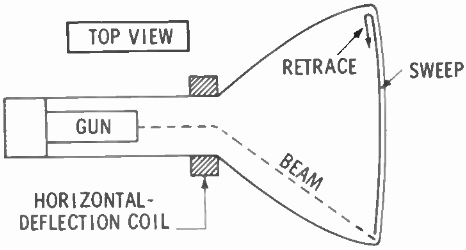


The basic construction and connections of a CRT are illustrated above. At the left end is shown an electron gun which shoots a narrow stream of electrons toward the screen. To speed the electrons on their way, the inner surface of the flared portion of the tube has a conductive coating energized with a voltage that is several thousand volts positive with respect to the electron source.

The CRT is connected to the output of the last video amplifier from which is received the video and blanking signals. The CRT element which controls the number of electrons responds to the varying amplitude of the video and releases the quantity required. This element also stops the flow of electrons when the blanking pulse appears.

During the time a video signal is present, the beam must be moved from left to right across the screen. When the beam reaches the right side, the blanking pulse shuts off the electrons and the beam moves back to start the next line.

Moving the Beam Across the Screen



A **horizontal-deflection coil** wrapped around the neck of the tube moves the beam from side to side. Current moving through the coil sets up a magnetic field which has an attracting and a repelling effect on electrons similar to positive and negative voltage. The stronger the field, the greater is its effect on the beam. To increase the strength of the field requires an increase in current through the coil. The illustration shows the beam deflected to the left.

The change in strength of the magnetic field during a sweep must coincide with the time duration of the scanned line. A gradual rise of current within the coil during this time period accomplishes this. The starting time is triggered by the sync pulses that ride on the blanking pulses. If the current decreases rapidly at the end of each line (during the blanking pulse), the sudden drop in magnetic field strength returns the beam to the left very quickly.

A similar magnetic field is set up by a second coil (the **vertical-deflection coil**) which controls the movement of the beam line by line from the top of the screen to the bottom. On completion of a field, the beam quickly retraces to the top.

Q57. The electron beam in the CRT is generated by a(an) ________ ___.

Q58. Electrons are drawn to the screen of the CRT by a(an) ________ ________.

Q59. ________ ______ move the CRT beam.

Q60. An increase in current through a deflection coil (increases, decreases) the magnetic field.

Your Answers Should Be:

A57. The electron beam in the CRT is generated by an **electron gun.**

A58. Electrons are drawn to the screen of the CRT by a **positive voltage.**

A59. **Magnetic fields** move the CRT beam.

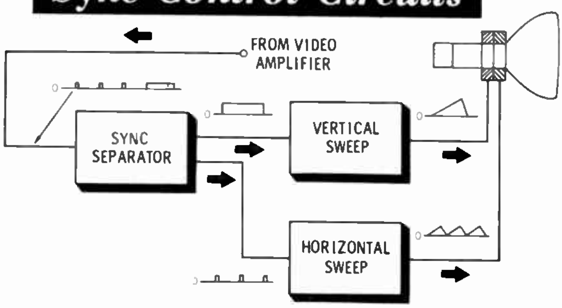
A60. An increase in current through a deflection coil **increases** the magnetic field.

CAUTION: A vacuum exists inside a cathode-ray tube, causing tremendous pressures to be exerted toward the center of the tube. If dropped, scratched, or carelessly jarred, the CRT may implode (explode inward), scattering pieces of glass and metal at a tremendous velocity.

Sync Control Circuits

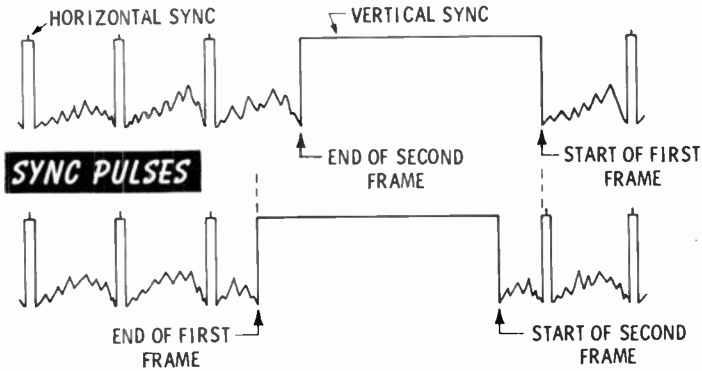
The beam movement is accomplished by steadily increasing the current flow in each of the deflection coils during precise time intervals. The starting times for these intervals are controlled by the sync pulses.

Sync Control Circuits



Sync Separator—Sync pulses arrive at the sync separator from the video amplifier. There is one narrow sync pulse for each line of scan. This pulse is intended to control the starting time of each horizontal sweep across the screen. When one field of 262½ lines has been completed, the video waveforms are followed by a sync pulse many times wider than the horizontal sync pulses.

This wide pulse is the trigger that develops a vertical sweep to move the beam from line to line down the face of the screen. Every other vertical sync pulse starts in the middle of a video waveform, accounting for 262½ lines in each frame of interlace scanning.



The above illustration shows the comparative widths of the horizontal and vertical sync pulses and the relative starting times of the first and second frames. The sync pulses are removed from the complete video waveform and sent to the sync separator.

The narrow and wide pulses are distributed to the appropriate sweep circuits (horizontal and vertical) by the sync separator. This is accomplished by capacitor and resistor combinations which can distinguish between voltage waveforms with short time durations and those with long durations. The short sync pulses are sent to the **horizontal-sweep circuit** and the long pulses to the **vertical-sweep circuit.**

Q61. Timing of the magnetic field developed in the ___________ and _________ deflection coils is controlled by ____ ______ extracted from the video waveform.

Q62. The sync separator separates the narrow and wide timing pulses. The narrow pulses control ___________ deflection and the wide pulses control _________ deflection.

Q63. Horizontal-sync pulses occur during the _________ portion of the video waveform.

Your Answers Should Be:

A61. Timing of the magnetic field developed in the **horizontal** and **vertical** deflection coils is controlled by **sync pulses** extracted from the video waveform.

A62. The sync separator separates the **narrow** and **wide** timing pulses. The narrow pulses control **horizontal** deflection and the wide pulses control **vertical** deflection.

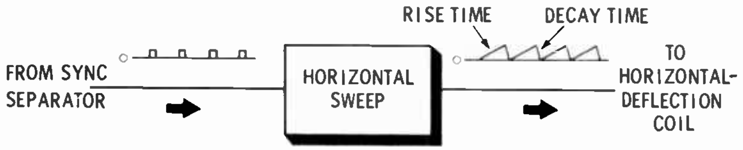
A63. Horizontal-sync pulses occur during the **blanking** portion of the video waveform.

Sweep Circuits

The two sweep circuits (horizontal and vertical) generate a linear rising voltage each time they receive a sync pulse. The **horizontal-sweep circuit** is triggered 525 times during the same time the **vertical-sweep circuit** is triggered twice.

Horizontal-Sweep Circuit—Horizontal sweep is produced by an oscillator which generates a slowly rising and rapidly decaying sawtooth waveform, whether the set is tuned to a transmitting station or not. This accounts for the **raster** (lines on the screen) when the TV receiver is on but no signal is being received.

HORIZONTAL SWEEP CIRCUIT



The purpose of the sync pulse is to trigger the oscillator so that oscillations start at the same time as the line scan in the camera. Capacitor and resistor combinations convert the oscillations to the sawtooth waveshapes shown in the diagram above. Rise time of the sawtooth causes the current in the horizontal-deflection coil to increase gradually, moving the beam across the screen in step with the line scan in the camera. At the end of the line, coil current decreases rapidly, returning the beam (which is now blanked) to the left side of the screen. There are 262½ lines to each frame, so the frequency of the horizontal oscillator must be 15,750 cycles per second.

Vertical-Sweep Circuit—The vertical-sweep oscillator and amplifier are almost identical to those in the horizontal-sweep section. The main difference is that the frequency of oscillation is much lower—60 times a second, to match the frequency at which each field is swept. The rise time (plus a short decay time) of the vertical sawtooth lasts for 1/60 of a second before another vertical-sync pulse arrives to start the next waveform. Gradual increase in current in the vertical-deflection coil moves the beam from the top to the bottom of the screen. The decay of the vertical sawtooth waveform brings the beam back to the top in time for the next sync pulse.

Height Control—In most TV receivers a **height** control varies the setting of a variable resistor in the vertical-sweep stage. Adjustment of the control moves the starting position of the sweep up or down. The resistor controls the amount of initial current that flows through the coil.

High-Voltage Power Supply

The several thousand volts required for the CRT are developed in the high-voltage power supply, a group of circuits usually contained in a metal cage inside the set. A diode discharging a capacitor through a transformer produces the high voltage for the CRT. Even after the set has been turned off, the capacitor can retain its charge for some time. Precautions should therefore be taken if work must be done inside this cage.

> **CAUTION:** There can be up to 30,000 volts connected to to a plug-in on the flared side of the CRT. The voltage is applied through a heavily insulated conductor. Even though the set is turned off, approach the sides of the cathode-ray tube with extreme caution.

Q64. What is the horizontal sync-pulse frequency?

Q65. What is the frequency of the vertical-sync pulses?

Q66. What are two precautions you should observe when near a cathode-ray tube?

Your Answers Should Be:

A64. The horizontal-sync frequency is **15,750 cps.**

A65. The vertical-sync frequency is **60 cps.**

A66. Cathode-ray tube precautions are:

1. **Handle with care to prevent implosion.**
2. **Do not come in contact with the extremely high voltage connected to the flared end of the CRT.**

WHAT YOU HAVE LEARNED

1. Television transmitters and receivers, like any other electronic equipment, consist of circuits designed to accomplish specific functions. Although there are a large variety of circuits, they all operate in accordance with a basic concept—the effect that voltage, current, and electronic components have on each other. These basic effects can be used to analyze any circuit, providing the student understands the underlying principles of each.
2. A television transmitter consists of two sections. One section uses a camera to scan a scene, and a group of circuits to modulate a carrier frequency with the image. The other section takes the output from a microphone and uses it to modulate a second carrier frequency.
3. Sound is superimposed on its carrier by frequency modulation. The procedure is one in which the frequency of the carrier varies in accordance with the amplitude of the sound—decreasing during the positive portions of the audio cycle and increasing during the negative portions. The FM carrier is then amplified to the required power level and fed to the antenna.
4. Video is obtained from the camera as it scans a scene with an electron beam, one line at a time. The video signal, with the addition of blanking and synchronizing pulses, is amplified and then used to modulate the picture carrier frequency. The amplitude-modulated carrier is raised to a specified power level and then fed to the antenna.

5. Video and sound carriers are of a high frequency and therefore have short wavelengths. These travel through the atmosphere as either space or sky waves. Short space waves travel on a line-of-sight path and cannot be received beyond the horizon. Sky waves enter the ionosphere where their paths are bent by an amount depending on the angle of entry. If the entry angle is small, the sky wave returns to the earth and can be received.
6. A TV receiver contains many circuits that can be grouped into a few electronic functions. These include the RF section (front-end), IF section, sound section, video section, vertical-sync control, horizontal-sync control, cathode-ray tube, and low- and high-voltage power supplies. Many of the functions are similar to those found in a radio receiver.
7. The RF amplifier, mixer, and oscillator select the desired channel among the many appearing on the antenna and convert the sound and video-carrier frequencies to appropriate intermediate frequencies.
8. The sound section, containing an IF stage for amplification, a detector (or discriminator) for removal of the audio component, and audio amplifiers for further amplitude gain, processes the signal for operation of the speaker.
9. The video section contains similar circuits to extract the video signal and amplify it to a level required for operating the beam-control portion of the CRT.
10. Vertical- and horizontal-sync pulses are taken from the video signal and channeled through corresponding vertical- and horizontal-sweep circuits. The sawtooth waveforms developed by these circuits control the movement of the electron beam, causing the image to be placed on the screen, a line at a time, in precise synchronization with the camera scan beam.
11. Highly dangerous voltages exist on the cathode-ray tube and inside the cage of the high-voltage power supply. Extreme caution should be used when working in these areas.

12. Most of all, you have learned a great deal more about electronics. You should now have acquired a fairly good understanding of how electronic circuits work. A mental image of circuit and equipment operation will give you a solid reference against which you can base the details of current, voltage, resistance, inductance, and capacitance principles that are explained in following volumes. You need a clear understanding of these principles if you plan to become technically competent when working with electronic equipment.

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