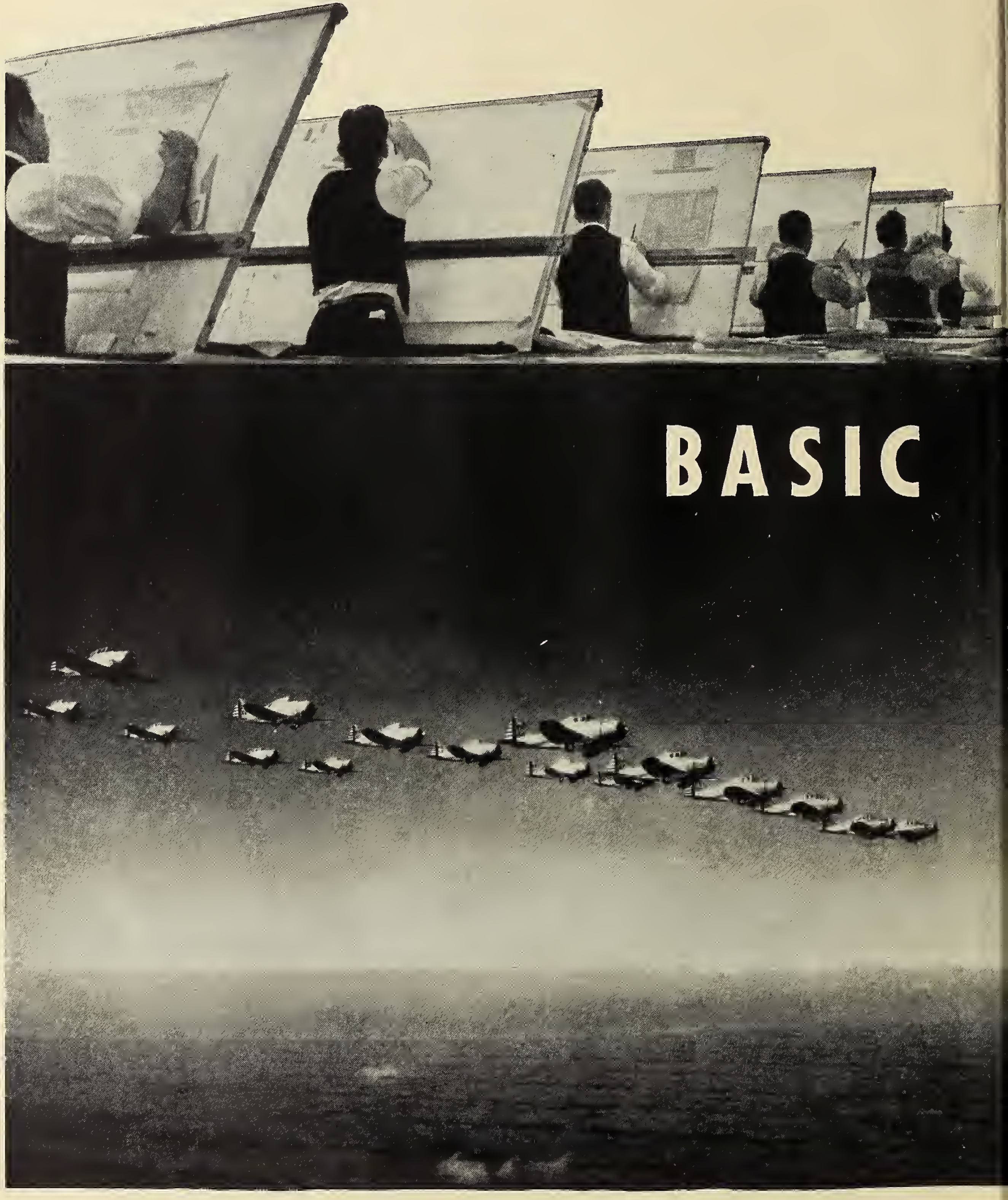
Basic Electricity

BEAUCHAMP and MAYFIELD

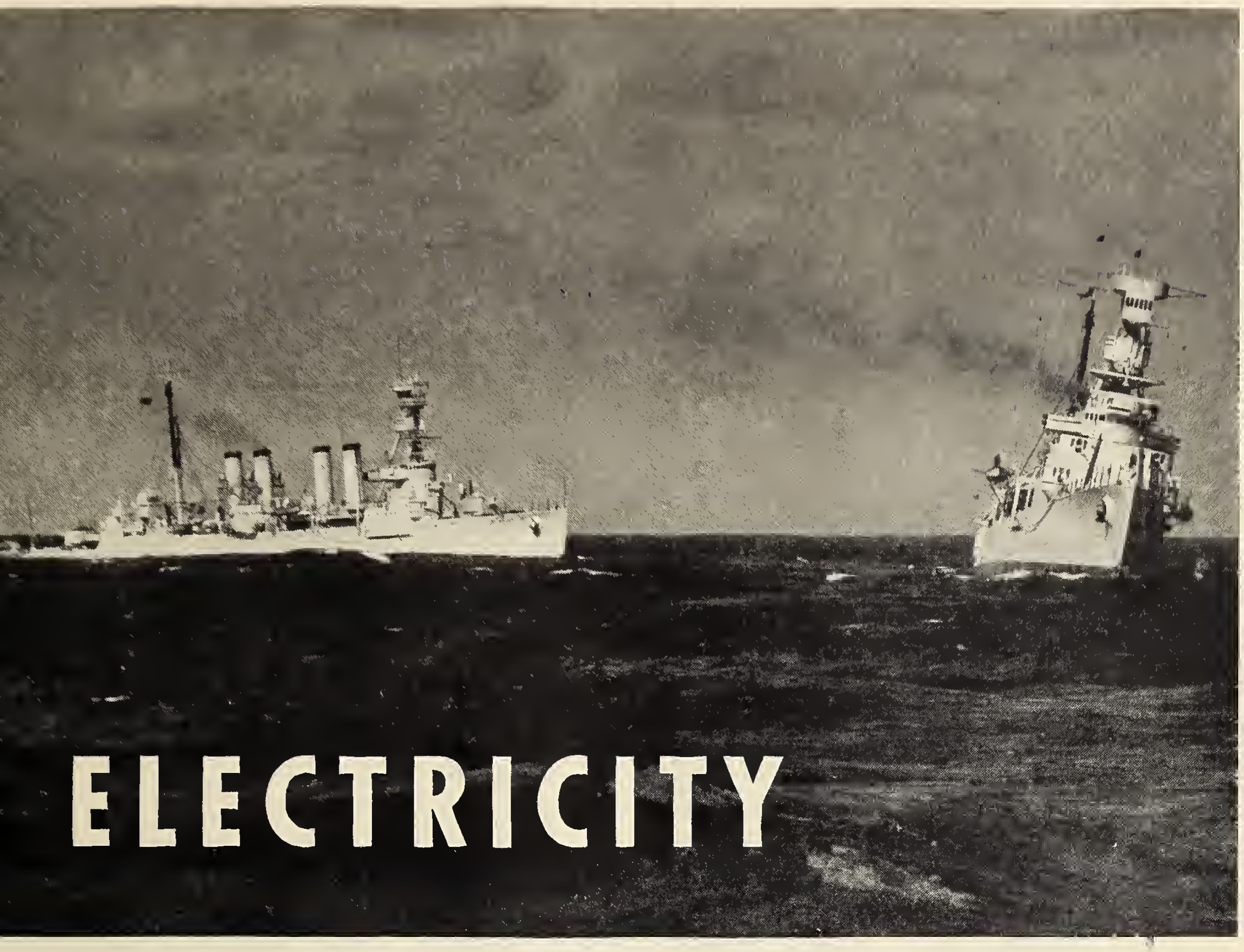
Basic Electricity

PREPARED AT THE REQUEST OF THE WAR DEPARTMENT AND THE U.S. OFFICE OF EDUCATION

IN CONFORMANCE WITH OFFICIAL PRE-INDUCTION TRAINING COURSE OUTLINE NO. PIT 101



BASIC



ELECTRICITY

BY WILBUR L. BEAUCHAMP

AND JOHN C. MAYFIELD

SCOTT, FORESMAN
AND COMPANY

CHICAGO ATLANTA DALLAS NEW YORK

Preface

433.1 PRINTED IN THE UNITED STATES OF AMERICA

IN PREPARING *Basic Electricity* for publication the authors worked with certain requirements definitely in mind. First, the content of the book had to cover and teach the fundamentals set forth in the outline approved by the War Department and the Office of Education. Second, and of equal importance, the treatment of the basic facts and principles had to be suitable for use in one semester of the third or fourth year of high school. And third, the authors kept in mind the purpose that lies back of this course which has been called forth by the necessities of the day.

Students and teachers are evidently aware of the fact that many students who take this course will in a short time be in the armed services of the United States or in some occupation essential to the maintenance of those services. It is an inescapable fact that our country needs trained specialists, and that one of the great contributions the schools can make is to supply an increasing number of students who have mastered the fundamentals of certain key subjects, and have thus fitted themselves to continue in a more specialized training.

In the light of actual experience in such specialized training, the authors have become keenly aware of the desirability of certain features in a basic course of preparation. These they have incorporated in this book, and perhaps a brief word of explanation would be in order.

The authors have recognized frankly that the book will be used by students of varying capabilities and interests. For the ambitious student, the expanded and more difficult material at the bottom of the page will furnish additional information and give wider understanding. For the less capable, the boxed-in review material at the top of the page, and the illustrations with their legends, will give a speedy and comprehensive review of the important matters in each chapter.

"Finding Out What You Know" at the start of each chapter is a set of exploratory questions designed to set minds to work, and to motivate the chapter. It is not expected that all the questions can be answered before reading the chapter; some are certainly to be looked on as goals.

"Checking What You Learned" and "Using What You Learned" provide questions to answer and problems to solve that will measure the achievement of the students in understanding both principles and vocabulary. Here again, the authors have provided material for different levels of ability.

For convenience, especially in schools where laboratory material is difficult to secure, the experiments have been grouped in uniform style at the end of each chapter. A minimum of apparatus is needed.

Finally, the authors realize that electricity is not an easy subject. But they believe that by simplicity of statement and the use of many analogies, a clear understanding of the basic principles and terminology of electricity is not beyond the abilities of the average student.

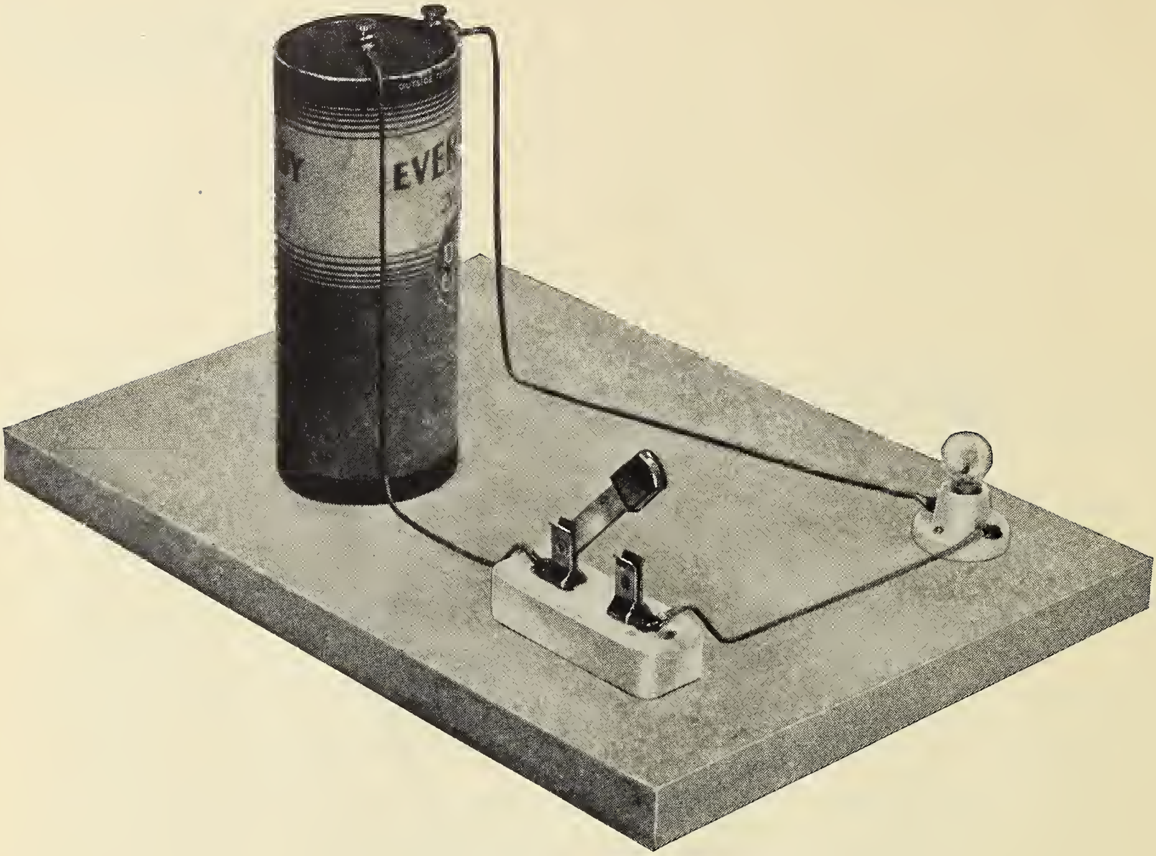
Contents

Illustrations

The drawings, prepared especially for use in this book, are the work of Raymond E. Craig of Chicago. For permission to reproduce the photographs used in this book, acknowledgment is made to these sources:

ii. *top* Westinghouse; *bottom* Ewing Galloway.
iii. *top* Ewing Galloway; *bottom* Keystone.
5. *top* Official photograph, U.S. Army Air Forces; *center* Keystone; *bottom left* Black Star; *bottom right* Cushing from Sawders.
9. *top* Westinghouse; *center left* Rosenwald Museum of Science and Industry; *center right* G. A. Douglas from Gendreau; *bottom* Union Pacific Railroad.
16. Bonneville Power Administration.
21. *top left* Philip Gendreau; *top right and bottom* Westinghouse.
35. *center* Philip Gendreau; *top and bottom* Westinghouse.
40. U.S. Army Signal Corps.
61. *top left and right* Philip Gendreau; *bottom left* Lambert from Frederic Lewis; *bottom right* Eugene Smith from Black Star.
65. *top* Square D Company; *bottom left* Keystone; *bottom right* Cushing from Sawders.
72. Gould Storage Battery Corporation.
99. *all* U.S. Army Signal Corps.
105. *battery at top* Gould Storage Battery Corporation; *others* Ewing Galloway.
112. General Electric.
124. *top* Brown and Sharpe Mfg. Co.; *bottom* Chicago Apparatus Company.
125. *bottom left* Lisle Corporation; *bottom right* Ewing Galloway.
132. Signal Electric Mfg. Co.
147. *top* Dean W. Davis & Co., Inc.; *others* Chicago Surface Lines.
150. U.S. Army Signal Corps.
171. *top right* O.W.I. Photo; *others* Westinghouse.
175. *top* O.W.I. Photos; *bottom* Hirz from Frederic Lewis.
180. Philip Gendreau.
189. *top left* Black Star; *top right* Hamilton from Frederic Lewis; *others* Westinghouse.
195. *top left and bottom left* Westinghouse; *top right* Keystone; *bottom right* Frederic Lewis.
204. U.S. Army Signal Corps.
220. *top* Kellogg Switchboard and Supply Photos; *bottom left* Baldwin Locomotive Works; *bottom right* G. A. Douglas from Gendreau.
221. *top left* American Bosch; *top right* Eicor; *bottom left* Westinghouse; *bottom right* Frederic Lewis.
230. National Machinery Co.
244. *top* Westinghouse; *others* General Electric.
245. *top* Westinghouse; *center* Baldwin Locomotive Works; *bottom* Philip Gendreau.
252. General Electric.
270. *top left and right* Philip Gendreau; *center* Keystone; *bottom* Northwest Airlines.
271. *top* Chicago Apparatus Company; *center* Simpson Electric Company; *bottom* U.S. Army Signal Corps.
276. *top right* U.S. Army Signal Corps; *top left* Philip Gendreau; *bottom* Ewing Galloway.
296. *top left* R.C.A. Photo; *top right* U.S. Army Signal Corps; *bottom* Frederic Lewis.
297. *top left* Kellogg Switchboard and Supply; *top right* Philip Gendreau; *bottom left and right* U.S. Army Signal Corps.

BASIC ELECTRICITY



I. The Electric Circuit

FINDING OUT WHAT YOU KNOW

1. Make as long a list as you can of the uses of electric current.
   After each use name some device or appliance that uses current in this way.

2. What must you do to an electrical device or appliance before it will work?
   Tell why this is necessary.

3. Name several sources of electrical energy and, if you can, give an example of the use of each source.

4. How do we make an electric current go where we want it to go?
   What do we use for this purpose?

5. Sometimes a fuse in an electrical wiring system "blows out."
   What does this mean? Why does it happen?

MOST OF US have some information about electricity, because electrical devices and appliances are fairly common in our everyday lives. We turn a switch, and an electric lamp gives us light. We push a button and hear the sound of an electric bell or buzzer. We press a lever, and a toaster supplies heat. Or we turn on an electric fan or washing machine and produce motion. We know that we can get light, sound, heat, and motion from these devices and from others that are operated in some way by electrical energy.

Many of us know more about electricity than just how to use such devices. At times we have noticed that these devices have two wires leading from them, usually ending in a plug with two prongs. And we know that the device will not work unless the plug is connected to a socket or an outlet in the wall. Those who have taken apart a socket or outlet, or repaired a broken wire in a plug, know that these things are just a means of connecting the two wires of the device to the two wires that supply electrical energy to the building.

Suppose, to begin our study of electricity, we start with these common, everyday things that are familiar to all of us, and leave the more technical side of the subject until later.

The Complete Circuit

First let us take this matter of the two wires. We know that two wires are needed, because we have noticed that a device will not work if either wire is broken. The two wires must run, unbroken,

Electric current: A flow of electrical energy.
Circuit: The path of an electric current from its source and back again.

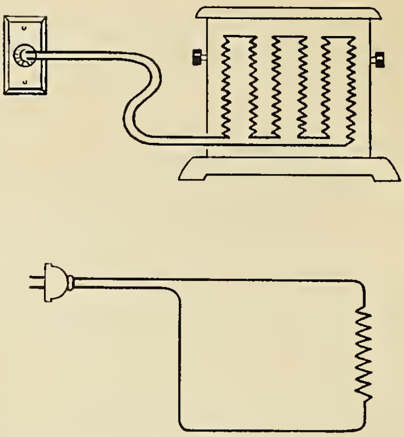


Figure 1. *In this diagram we do not show all of the circuit, which really includes the two wires leading from the outlet to the power house and into the machines that produce, or "generate," electrical energy.*

At the right is a much simpler way to show this part of the circuit. In this simpler diagram, the heating wires of the toaster are represented by a zigzag line. In electrical diagrams a zigzag line sometimes stands for any device that uses electrical energy.

from the outlet to the point where the electrical energy is used. In this way we know that the electrical energy we use in, say, a toaster flows along wires to the device and that the device will operate only when we provide a complete path for this flow of electrical energy, which we call an **electric current.**

The diagram in Figure 1 shows quite clearly what we could see if we took the toaster apart. We can trace on the diagram the path of one wire from the outlet to the toaster, through the toaster on a different kind of wire, then back to the outlet again by way of the second wire. The electric current that operates the toaster follows this path.

If we examine other devices, we find that they are like the toaster in this way: there is a path in each of them. Each one has a path for the electric current to follow—a path that leads into the device, through it, and back to the outlet again. Experiment 1 (page 13) shows how to connect an electrical device and a source of electrical energy so as to form a **circuit.**

There is something else to notice about most common circuits. When we examine different electrical appliances and devices, we usually find a switch for turning the electric current on and off. There is a switch on the wall to turn a ceiling light on and off. Many light sockets have switches that work by turning or pushing a button, or by pulling a chain. And there are switches on toasters, fans, washing machines, and other devices so that we can turn them off without removing the plug from the outlet. Experiment 2 shows how switches control an electric current.

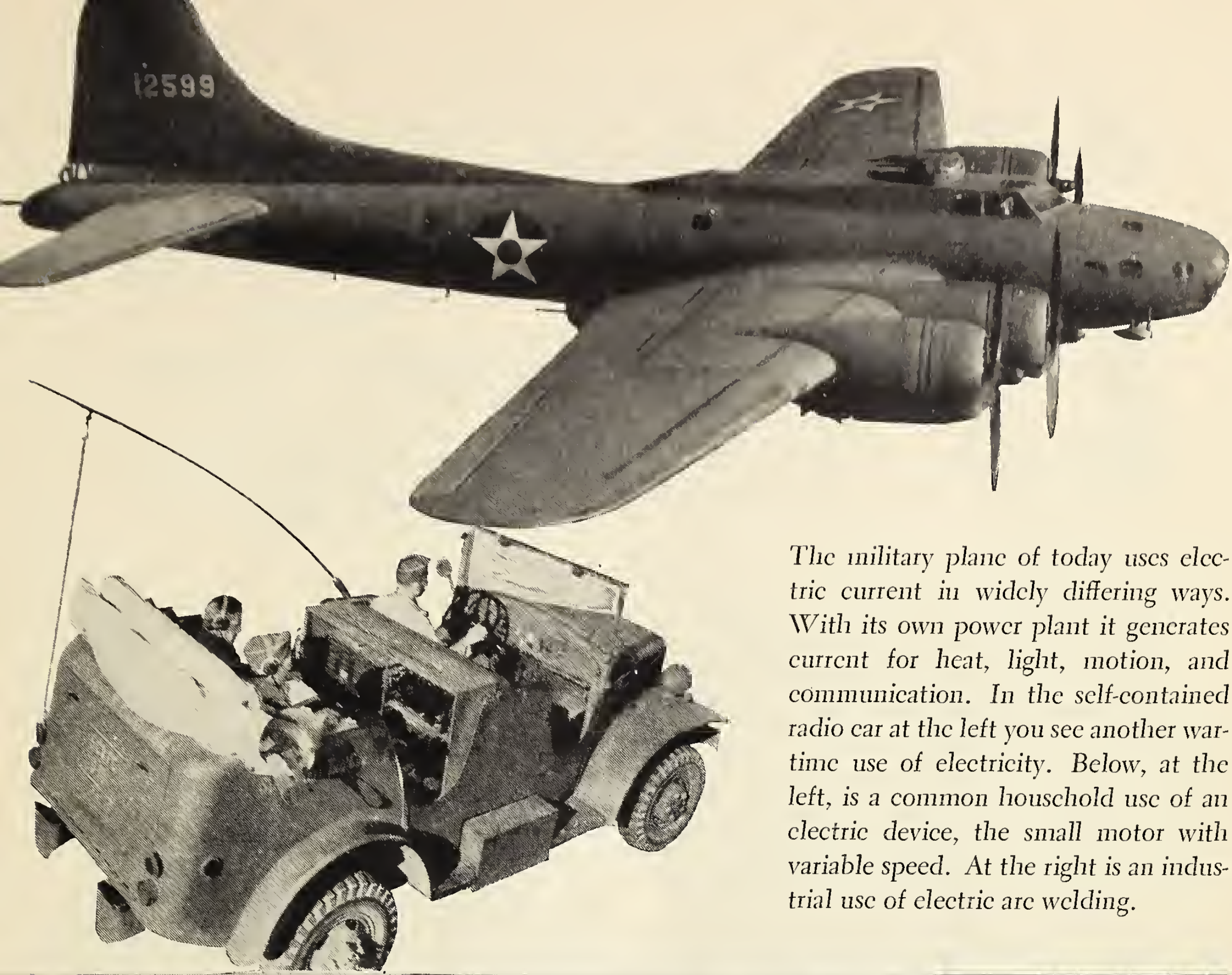
There is still another way in which these circuits are alike. In each of them there is a source of electrical energy. For most of us the commonest source is the outlet in the wall, and we do not give much thought to the wires leading from the house to the power station, perhaps miles away, where generators produce the electrical energy we use. We know that flashlights have a source of electrical energy—the batteries or cells we put in them. We know that automobile starters, lights, and horns use current from the automobile storage battery. Every circuit must have in it, somewhere, a source of electrical energy.

We have noticed four things that are true about our common complete circuits. Every one of them has in it:

1. A device or appliance that uses electrical energy. (Toaster, washing machine, motor, etc.)
2. A path for the electric current. (Wires, sockets, plugs, etc.)
3. A control. (Switch, push button, etc.)
4. A source of electrical energy. (Battery, generator, etc.)

Electrical Devices and Appliances

Suppose we take up the devices first, simply to get some idea of the different ways in which we use electrical energy. Actually there are hundreds of



The military plane of today uses electric current in widely differing ways. With its own power plant it generates current for heat, light, motion, and communication. In the self-contained radio car at the left you see another wartime use of electricity. Below, at the left, is a common household use of an electric device, the small motor with variable speed. At the right is an industrial use of electric arc welding.

Complete circuit: A complete circuit usually consists of a device or appliance, a path, a method of control, and a source of electrical energy.

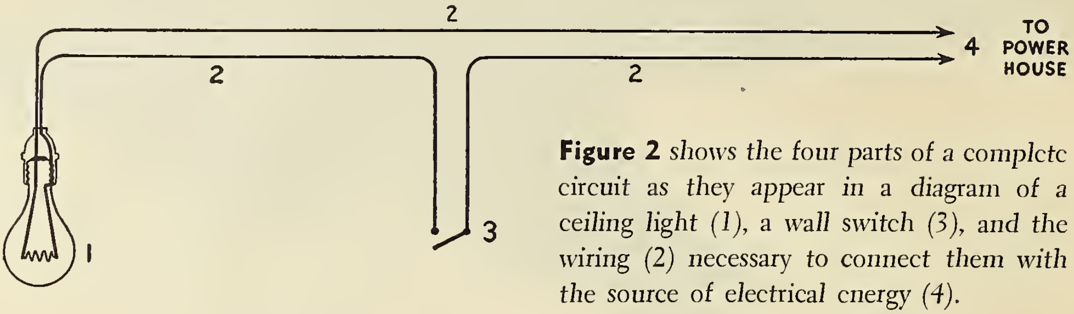


Figure 2 *shows the four parts of a complete circuit as they appear in a diagram of a ceiling light (1), a wall switch (3), and the wiring (2) necessary to connect them with the source of electrical energy (4).*

Energy: The ability to do work. Energy can change or move matter. An electric current can do this. Thus we know it has energy.

Matter: Anything that takes up space. Matter includes all solid materials, liquid materials, and gases.

different kinds of electrical devices and appliances, but when we look into the matter, we find that they can be classified rather simply.

Commonest of all, perhaps, are the devices that produce light—electric lamps, flashlights, arc lights, neon lights, fluorescent lamps. Although we use these devices to get light, they all produce more or less heat in making the light.

Next come the devices for producing heat, such as toasters, heating pads, irons, stoves, and electric furnaces. If you wished, you could classify light-makers and heat-makers together, and call them all heat-makers.

Devices for producing mechanical effects are quite common. Electric motors are used to run washing machines, vacuum sweepers, sewing machines, refrigerators, pumps, and many other kinds of machinery. The electrical energy is used to do work. The motor or other device changes the electrical energy into mechanical energy.

Electric bells are devices used to produce sound, and we might call them another kind of electrical device. Actually, though, the sound is produced by the motion of the bell clapper. The clapper is moved by electrical energy. For this reason you may want to classify these sound-makers with the devices for producing mechanical effects such as motion.

A last group of electrical devices is composed of those that make use of electrical energy to produce chemical changes. You probably know that silver and other metals can be plated by means of an electric current. Aluminum is freed from its ore by using electrical energy in this special way. Oxygen for welding, chlorine for purifying water, and other gases are produced by this means also.

There is no point in explaining, right here, *how* all these electrical devices and appliances work. You know *what* they do, and later on will understand *how* and *why* they work. For the

Electrolysis: The use of electric current to cause chemical changes in liquids. Such changes as plating and purifying metals by using electric current are caused by electrolysis, and will be discussed again in Chapter 4.

Conductor: A material along which an electric current may pass easily.
Non-conductor: A material that does not readily allow an electric current to pass.

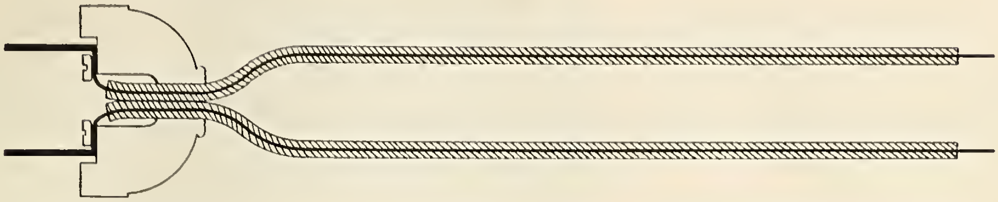


Figure 3 *shows the plug of an electrical device and a section of the two wires that are attached. You can see how the metallic wires are surrounded by material that does not conduct an electric current readily.*

present it is important to understand that the devices turn electrical energy into some other kind of energy we can use.

Paths for the Electric Current

One of the first things we noticed about the familiar electrical devices around the home is that each of them is connected with the source of electrical energy by means of wires. The diagram of any circuit shows that it is necessary to have two wires as a path for the electric current, one from its source to the device and one back again.

If we ask ourselves how the electric current is carried *to* and *from* a device by wires that often run side by side, we can discover several things by looking carefully at electrical wiring, plugs, and sockets. One of the first things we notice is that wires, plugs, and sockets are made from two quite different kinds of materials. These materials are metallic and non-metallic, and it is fairly evident that the current travels along the metallic materials.

Experiments and practical tests have shown that electric current moves easily through such things as metals, carbon, and certain solutions. Because an electric current can be conducted by these substances, we call them **conductors.** Experiments and tests have also shown that such things as glass, porcelain, rubber, wood, dry air, mica, and plastics do not easily conduct an electric current. These materials are called **non-conductors.**

When non-conductors are used to keep conductors separated from each other, they are called *insulators.* An insulator is nothing more than an extremely poor conductor of electric current. The rubber covering of an electric lamp cord, the black plastic coating on a heavy wire, the composition plug, and the porcelain of a light socket are insulators. The path of the electric current to and from a device, and sometimes inside it, is usually surrounded by insulators.

If we examine the ordinary electrical devices found around a house, we can see a variety of non-conducting materials that are used as insulators. The electric iron, for example, has a heavy cord in which the wires are covered by rubber or plastic and asbestos. Over both is a woven covering of cotton or rayon. Inside the iron the heating element, which gets very hot, is insulated by sheets of mica. If we take an ordinary metal socket apart, inside the brass shell we find a fiber lining and a piece of shaped porcelain or plastic to which the metal conductors are fastened. The fiber lining and the porcelain or plastic are insulators. In some motors we find wires that are insulated with enamel or varnish. Experiment 3 shows the importance of conductors and insulators.

Control of the Electric Current

Without insulators we might not be able to control the electric current and get it to the place where it is to be used. But merely insulating the

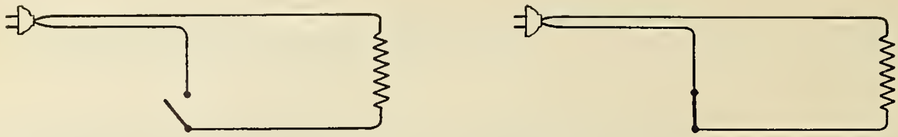


Figure 4 *shows at the left part of an open circuit—with the switch open; and at the right part of a closed circuit—with the switch closed. (The source of energy is not shown.)*

path that the electric current takes is not enough. We almost always need some way to turn the current off and on, and sometimes we must have ways to regulate the amount of current that is allowed to reach the device.

The commonest kind of control is a switch. You know that switches are on most light sockets and other devices, so that they can be turned ON and OFF. Actually a switch is just a convenient means of connecting and disconnecting a wire. When we turn a switch to OFF, we are doing the same thing as breaking one wire of the circuit. If you did Experiment 2, you know how switches control current in a circuit.

When the switch in a circuit is OFF, the circuit is broken, as you can see by looking at Figure 4. We call it an *open circuit*, for the switch is open. When we turn the switch to ON, we are connecting the wires again, thus completing the circuit. The switch is closed, so that now we have what is called a *closed circuit*.

The ordinary on-and-off switch is the commonest kind of control, but several others can be found without much trouble. The lever you push down in a toaster is also a switch. In some makes of toasters the switch is turned off by means of clockwork. If your home or school building has a thermostat on the wall, you can examine another kind of switch—one that is operated by heat. Changes in the temperature of the room cause the switch to open and close.

Another type of control is the fuse. Perhaps you have replaced one when a fuse "blew out." Something happened to the circuit so that the electric current did not go through the device where it was supposed to be used but took a "short" circuit back to the source again. Or perhaps too many devices were plugged in at one time. When this happened, so much current passed through that the fuse wire got hot enough to melt, for reasons that will be explained in Chapter 3. When the wire melted, the circuit was opened automatically. Fuses are a safeguard, as shown in Experiment 4.

Other kinds of control regulate the amount of electric current used by the device. Electric stoves have such controls, marked LOW, MEDIUM, and HIGH. Electric irons often have a regulator to control the amount of current used. The speed of electric trains is regulated by another type of control. Perhaps the commonest is the kind found on electric fans to regulate the speed of the fan.

Sources of Electrical Energy

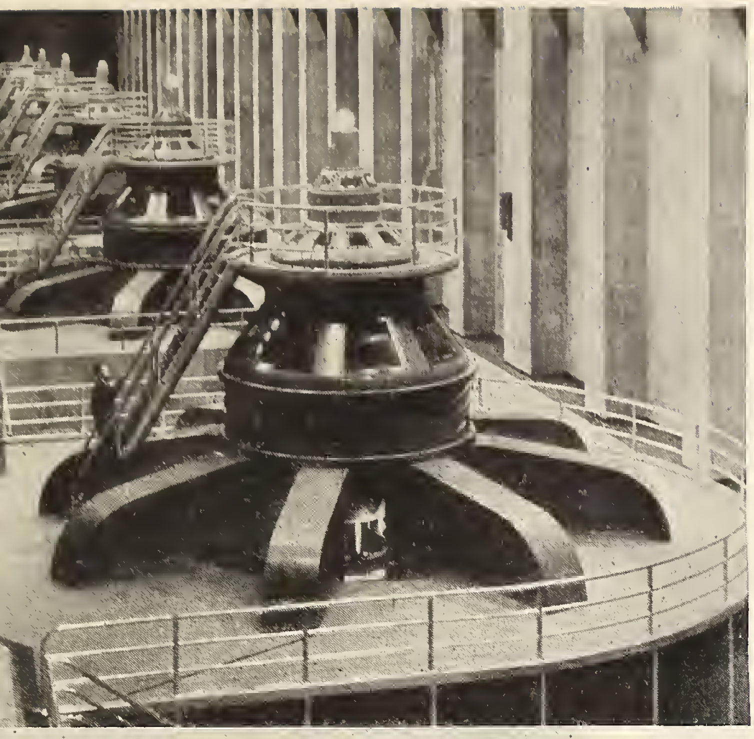
You know that a complete circuit must include a source of electrical energy as well as a path. It usually includes some method of control, and an

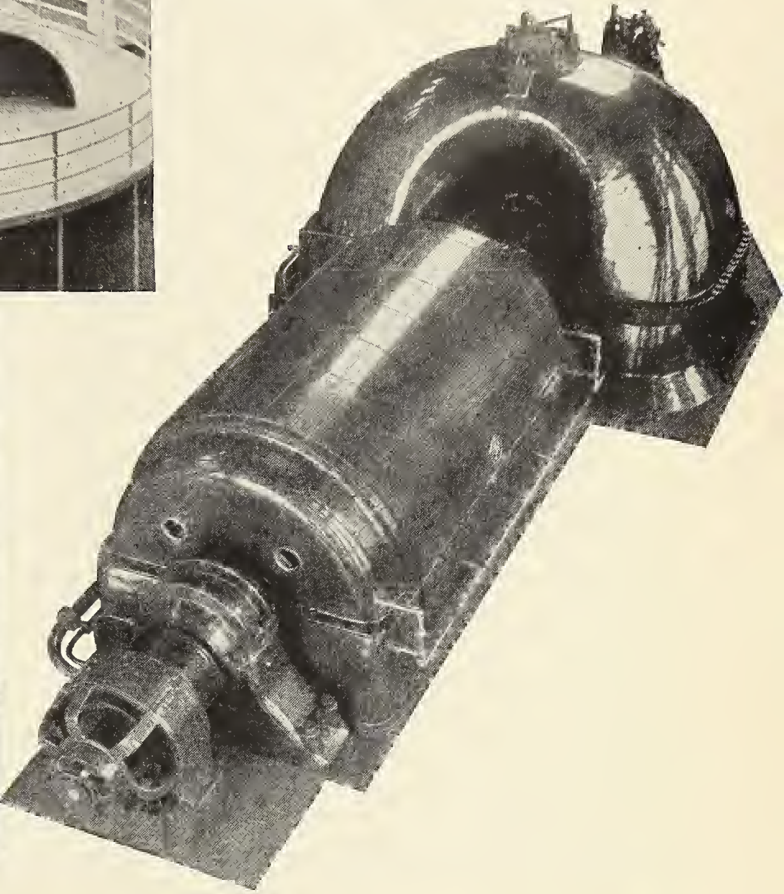
---

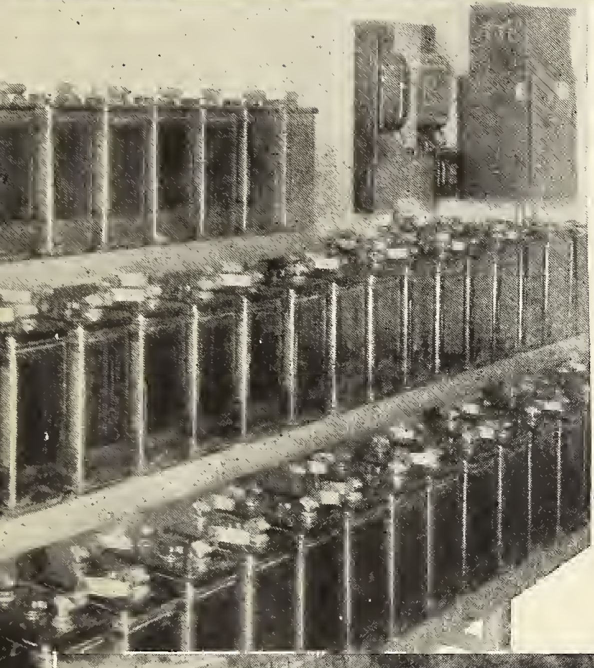
Rheostat: The commonest kind of control device to regulate the amount of current is called a rheostat. An explanation of the rheostat will be found in Chapter 3.

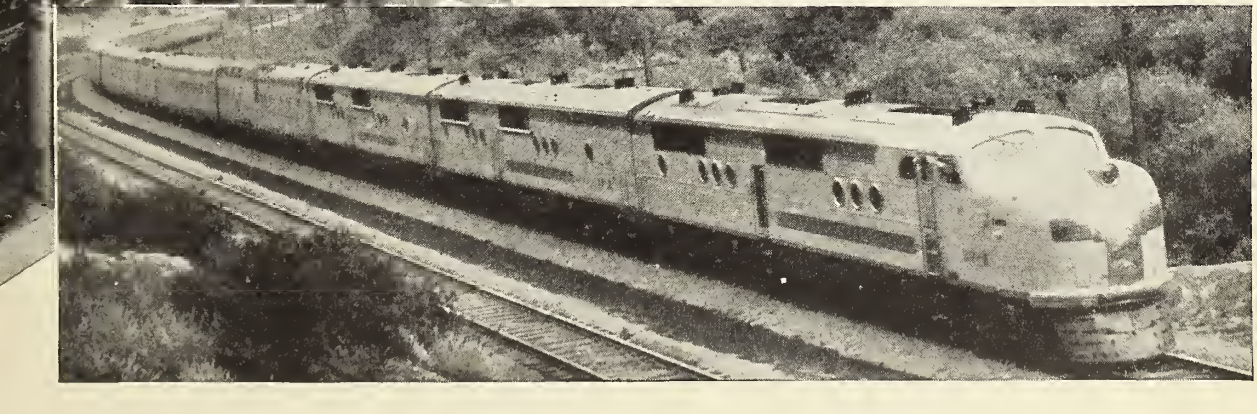
Circuit breakers: Besides fuses, mechanical circuit breakers are sometimes used to safeguard electric circuits. One type of circuit breaker also gets warm when there is a short circuit, or when too much current is being used, but instead of melting as a fuse wire does, the circuit breaker automatically throws a switch.

At the left is a row of generators in a modern hydroelectric station. They are moved by water turbines. Below, at the right, is a generator directly connected with a steam turbine. At the left is a battery of storage cells designed for emergency use in case the regular current supply fails. At the bottom is another type of power plant —the Diesel-electric train. In the first three cars are Diesel engines which drive generators.









Generator: A machine for producing electrical energy. A generator changes mechanical energy into electrical energy.
Cell: An electric cell produces electrical energy by means of chemical action.

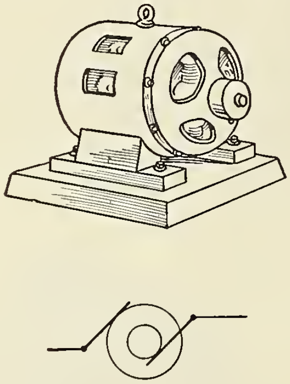
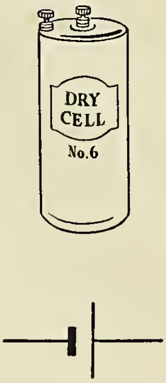


Figure 5 *shows at the left one very common kind of generator. Below it is shown the symbol used in circuit diagrams to represent a generator of electrical energy.*

At the right is shown one kind of cell and below it the symbol used to represent a cell of any kind in circuit diagrams.



electrical device or appliance. If you look again at Figures 1, 2, and 4, you will see that these diagrams do not show complete circuits. In each of them the source of electrical energy is indicated in some way, but it is not shown.

When we plug a vacuum cleaner into a wall outlet in a home, we are connecting the cleaner with the commonest source of electrical energy—the **generators** in a power station. When the switch is pressed and the cleaner starts, the complete circuit runs from the generators to the house, to the cleaner, through the cleaner, and back again all the way to the generator. As you will later see, it is not quite so simple as this, but the principle is the same.

Farm lighting systems have generators; so do automobiles. But they also have storage batteries to supply electrical energy when the generator is not running. Flashlights are run by batteries, too. These batteries, whether dry batteries or storage batteries, are composed of **cells.** A cell produces electrical energy by chemical action, which will be explained in Chapter 4.

Electrical energy is produced not only by generators and cells but in another way. When you scuff your feet along a rug on a dry, cold day, you are producing some electrical energy, as you can prove by touching someone and feeling an electric spark jump from your finger. Men have known about producing electrical energy by friction longer than any of the other ways. It is still used in laboratories, as you will discover when you come to the experiments in the next chapter. Electrical energy produced by friction is sometimes called "static electricity."

You do not pay much attention to electrical energy of this kind, except when you hear it snapping and crackling during a radio program. But it is not unimportant; for example, lightning is static electricity. So far men have not been able to make much use of it, because it is difficult to control.

The production of electrical energy by friction, cells, and generators will be taken up in detail in later chapters. The purpose in mentioning them in this chapter is to emphasize the idea of the circuit. The complete circuit, as you have been reading, must run from the source to the device, through the device and back to the source again. Look at the diagram on the next page, Figure 6. It shows two complete circuits, with different sources of electricity. The symbols used are ones that you will meet many times in your study of electricity.

If you would like to review this matter of the circuit, an easy way to do it will be to examine a simplified drawing of a circuit in an automobile. Figure 7 shows such a circuit in two ways: the upper picture shows drawings of the actual devices, while the lower picture makes use of symbols.

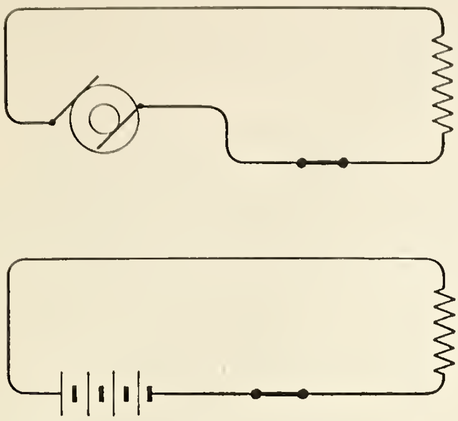


Figure 6. *The upper diagram shows a complete circuit with a generator as the source of electrical energy. The lower diagram shows a battery of cells as the source of electrical energy. Perhaps you are thinking that the symbol for the battery does not show how the circuit can be completed, because the short and long lines are not connected. In a real cell, however, the circuit is actually complete, for the two parts of the cell are joined by a liquid or other substance that conducts an electric current.*

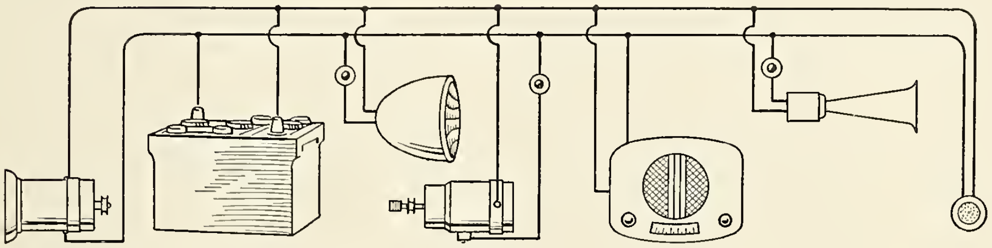
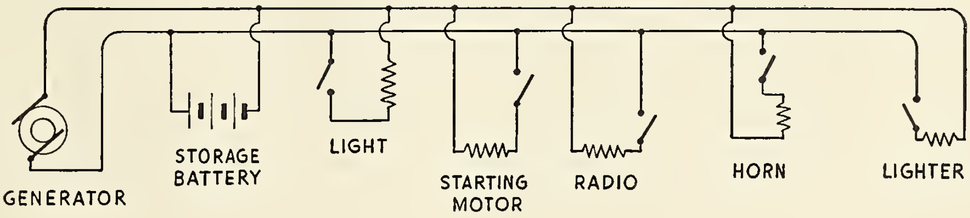


Figure 7. *The diagram below shows the symbols used to represent various electrical devices in an automobile. In order to keep the diagram simple, the controls are shown close to the devices. In the automobile they may be some distance away. (In these and other diagrams the "bridge" shows that one conductor crosses another without touching it.)*



In the automobile circuit you will see that there are two sources of electrical energy. One is a generator, which is run by the automobile engine. When the engine is not running, however, there must be some other source of electrical energy; so the diagram also shows a second source, the storage battery.

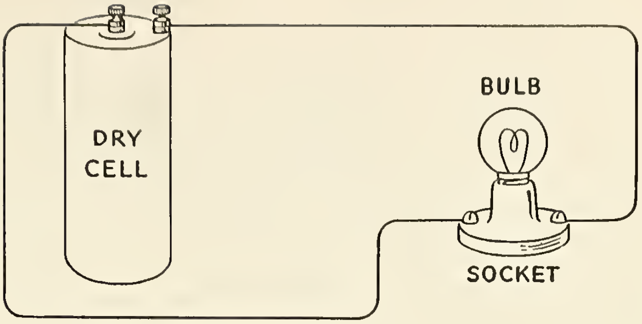
Several different types of electrical devices are used in an automobile. You can identify those that supply heat, light, sound, and motion. And in the path of wire that leads from the source to these devices, and back again, are various kinds of switches.

All this emphasis has been given to your study of the circuit because it is extremely important in understanding electricity. By this time you know that the electrical energy we use flows along a conductor in a circuit. In order to flow, and so be used, this electric current must have a complete circuit to follow, out from its source, through the device, and then back to the source again by way of the circuit wires. You know, too, that conductors carrying a current are kept from touching other conductors by means of insulators. You also know that any break in the circuit keeps the electric current from flowing, and that switches and fuses break the circuit in order to control the flow of current.

THINKING OVER WHAT YOU LEARNED

1. Turn back to page 3. Read over the answers you gave and make any corrections needed. If you could not answer some of the questions, answer them now.
2. **a.** What is an electric circuit? **b.** Name the parts usually found in a circuit and after each one give an example of that part.
3. **a.** State the difference between a conductor and a non-conductor of electric current. **b.** Between a non-conductor and an insulator.
4. **a.** What kind of circuit do you have when you turn on an electrical device? **b.** When you turn it off? Give reasons for your answers.
5. Name three ways of producing electrical energy. After each way you mention state whether or not it is commonly used. If it is not commonly used, tell why.
6. **a.** Draw a diagram showing a light bulb, battery, and switch connected in a circuit. **b.** Now draw the same circuit but use symbols for the various parts. **c.** Repeat **a** and **b**, using a generator in place of the battery.

Figure 8 *illustrates the equipment and circuit in Experiment 1.*



Experiment 1: **Making a Complete Circuit**

THINGS NEEDED: Dry cell (No. 6 size). Flashlight bulb (1.5 volt). Small socket for bulb. Two pieces of No. 18 insulated copper wire, each about 12 inches long. (See Fig. 8.)

WHAT TO DO: **a.** Remove one-half inch of insulation from both ends of each piece of wire. Connect one end of a piece of wire to the center post of the dry cell; connect the other end to one terminal of the small socket. Insert the flashlight bulb in the socket. Does the bulb light? Why?

b. Connect one end of the other piece of wire to the outside post of the dry cell. Touch the other end of the wire for an instant to each terminal of the socket. What happens? Which terminal of the socket must be touched to make the bulb light?

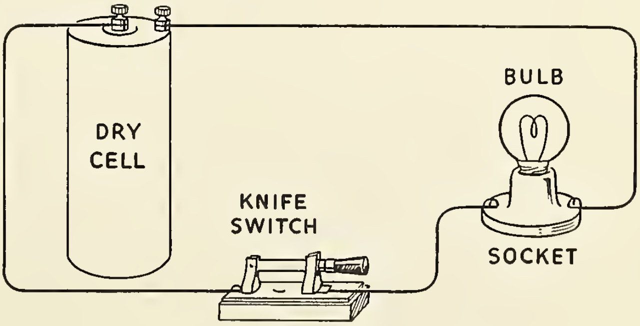
c. Fasten the second wire to the socket terminal that was touched to make the bulk light. Partially unscrew the bulb. What happens? Why? Tighten the bulb in the socket. Now what happens? Explain. In what other ways could you turn the light on and off? Show how you have a complete circuit. With the bulb lighted, trace the current in the circuit.

Experiment 2: **Controlling Electric Current**

THINGS NEEDED: Same as for Experiment 1. Electrical switches of various kinds (knife switch, wall switch, push button, telegraph key, etc.). Piece of No. 18 insulated copper wire about 12 inches long. (See Fig. 9.)

WHAT TO DO: **a.** Examine various kinds of switches to see how they are made. What parts do all switches have? Using the circuit in Part **c** of Experiment 1, disconnect the wire at the center post of the cell. Why does the light go out?

Figure 9 *illustrates the equipment and circuit in Experiment 2.*



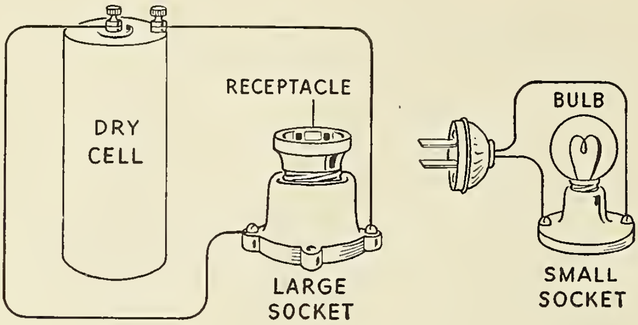


Figure 10 *illustrates the equipment and circuit in Experiment 3.*

b. Remove the insulation from both ends of the third wire and connect one end to the center post of the dry cell. Touch the other end of this wire to the end of the wire that was connected to the cell. Why does the bulb light when the ends of the two wires are touching?

c. Take one of the switches you have examined and connect both wires to one of the terminals. Throw the switch several times. What happens? Now move one of the wires to the other terminal of the switch and throw the switch several times. Why does the light go on and off?

d. One by one, connect the other switches in the same way. Explain how each causes the light to go on and off when the wires are properly connected. Do you have a complete circuit when the light is on? Name and point out the various parts of the circuit. Which part controls the current?

Experiment 3: **Conductors and Insulators**

THINGS NEEDED: Same as for Experiment 1. Ordinary porcelain lamp socket (no switch). Plug and receptacle to fit socket. Conductors of various kinds, sizes, and lengths (bell wire, lamp cords, cords for irons, toasters, etc.), with insulation removed from ends. Various electrical devices (doorbell, fan, toaster, etc.). Flashlight. (See Fig. 10.)

WHAT TO DO: **a.** Examine the various kinds of conductors. What part carries the electric current? What part keeps the wire from coming into contact with other conductors? How do these parts differ in the various conductors?

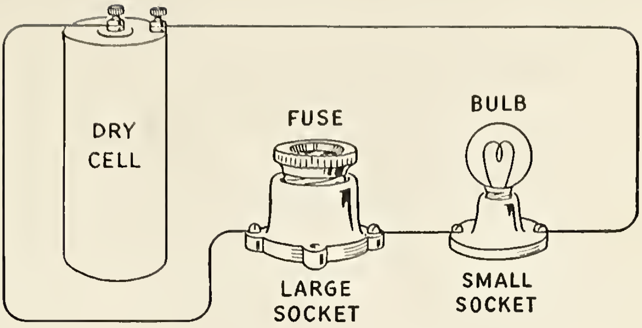
b. Using the circuit in Part **c** of Experiment 1, connect the large porcelain socket in place of the small socket. Insert the plug receptacle in the large socket. Connect two pieces of bell wire (No. 18) to the terminals of the plug; connect the other ends of the wires to the small socket containing the bulb. Insert the plug in the receptacle. Does the bulb light? Why? How can the current be controlled with a plug of this kind? Trace the current in this circuit, and point out the insulators that keep the conductors from touching.

c. One by one, connect other conductors between the plug and the small socket. In connecting flexible wires to the plug, why must the small strands of one wire be kept from touching those of the other wire? What other details must you watch if the current is to reach the device for which it is intended?

d. Examine the various electrical devices to see how they are made. In which ones does the electrical energy cause motion? In which ones heat? Point out the conductors that carry current through the device. What kinds of insulators can you find in each device? Which devices have a switch to control the current?

e. Take apart a flashlight and examine the various parts. What source of electrical energy does it have? What part uses electric current? How is this current controlled? What conductors and insulators can you find? Explain how the flashlight has a complete circuit. Now draw a circuit diagram of the flashlight, using the symbols you learned in this chapter. Remember to use a zigzag line for the flashlight bulb.

Figure 11 *illustrates the equipment and circuit in Experiment 4.*



Experiment 4: **Safeguarding the Circuit**

THINGS NEEDED: Same as for Experiment 1. Piece of No. 18 insulated copper wire about 12 inches long. Ordinary porcelain lamp socket (no switch). 5-ampere fuse to fit socket. Three pieces of No. 18 bare copper wire (two pieces 12 inches long and one piece about 24 inches long). Piece of paper. Screw driver, nail, or other piece of metal. (See Fig. 11.)

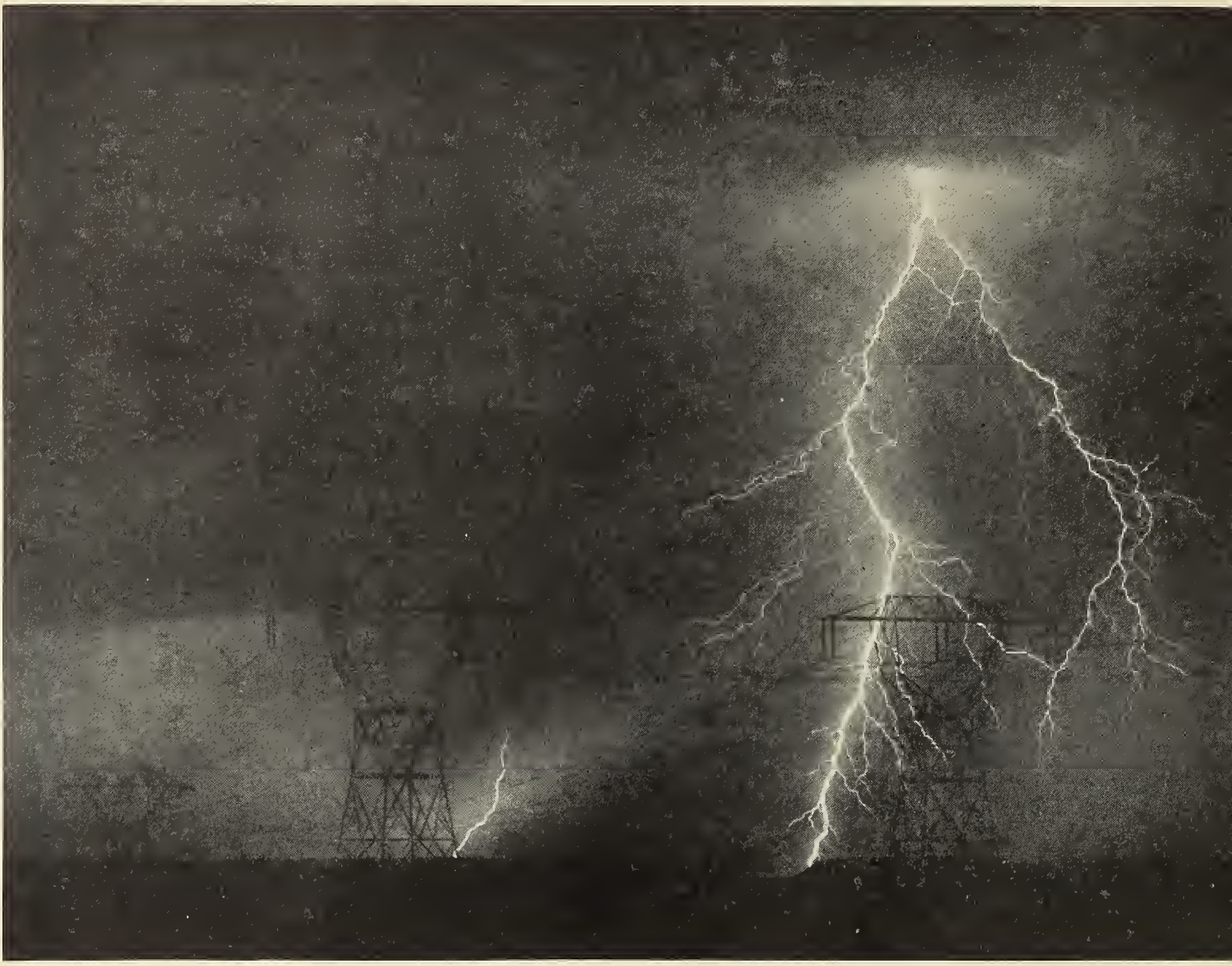
WHAT TO DO: **a.** Examine the fuse to see how it is made. Using the same circuit as in Part **c** of Experiment 2, connect the porcelain lamp socket in place of the switch, and insert the fuse. Why does the bulb light? Loosen and tighten the fuse several times. Explain how it acts as a switch in the circuit when you do this.

b. Replace the insulated wires with bare wires, connecting the shorter pieces from the cell to the fuse and from the fuse to the bulb; connect the longer piece from the cell to the bulb. Keep the bare wires parallel from the cell to the bulb and at least 2 inches apart. When you are sure that the wires are properly connected and are not touching each other, put the fuse into the socket so that the bulb will light.

At some point *between the cell and the fuse socket* touch the two wires together for just an instant. What happens? Now hold a piece of paper between the two wires and bring them together again. What happens this time? Explain the reason why wires carrying current should be insulated from each other.

c. Put a screw driver, nail, or other piece of metal across the two terminals of the cell for an instant. Does the light go out? Does it come on again as soon as you remove the metal piece? Try this at several points *between the cell and the fuse socket.* Why is it important that you touch the wires for only an instant?

d. Now put the piece of metal across the two wires at some point *between the fuse socket and the bulb,* and leave it there. What happens to the fuse? Remove the piece of metal. Does the bulb light? Why not? Explain why it makes no difference how long the metal piece remains across the wires in a part of the circuit protected by a fuse. What is the reason for placing the fuse as close as possible to the source of electrical energy in a circuit?



2. The Electric Current

FINDING OUT WHAT YOU KNOW

1. Tell how you can produce an electrical charge by friction.

2. What do we mean when we say that an object is electrically charged?

3. How many kinds of electrical charges are there? What is the name of each kind?

4. Explain the difference between a theory and a fact.

5. What is a condenser? Name some devices that use condensers.

6. Is it correct to say that we can "make electricity"? Explain your answer.

7. What is an electric current?

8. State three things that we need to know about an electric current.

Before going on to learn *how* and *why* an electric current flows through a circuit, we must know something of how electrical energy acts. Perhaps the easiest way to learn is to perform certain experiments or see them performed. The next best way is to read about the experiments and follow them step by step. At first, some of the information in the next few pages may not seem to have much bearing on the subject of electricity. But in a fairly short time you will see that all the ideas you gain from these pages fit together.

Frictional or Static Electricity

In the first chapter you read about the sources of electrical energy and learned that one method of producing electrical energy is through the use of friction. Electrical energy produced in this way is called frictional or static electricity. *Frictional* indicates that it is produced by rubbing. The friction of your shoes against a rug, for example, produces a small amount of electrical energy. The word *static* means "standing still" or "at rest." Because the experimenters of long ago mistakenly thought that electrical energy produced by friction did not move, they gave it this name.

Experiment 5 (page 37) is an easy one to do, but it is important if you wish to understand the basic facts about electrical energy. First you fasten a small round wad of dry paper (or a pith ball, if one is available) on the end of a short piece of silk thread, about 12 inches long. Then tie the thread to a support of some kind so that the wad of paper hangs free.

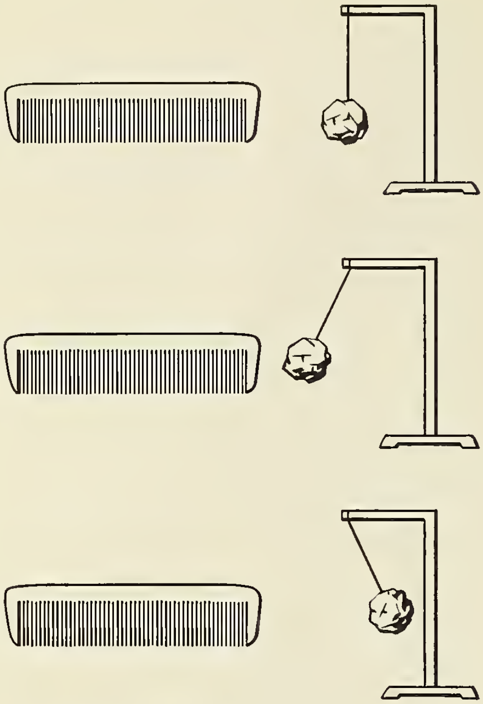


Figure 12 *shows that something happens to a hard-rubber comb when it is rubbed vigorously on the sleeve of a woolen coat.*

The first picture shows that the comb normally has no effect on a wad of paper hanging by a string.

The second picture shows the paper wad being attracted by the comb. Rubbing the comb has done something that causes the wad to swing toward it.

The third picture shows the paper wad being repelled by the comb. After touching the comb and clinging there for a minute or two, the wad swings away from the comb.

Move a hard-rubber comb (or a fountain pen) slowly toward the hanging paper. The hanging paper is not affected by the comb. Try the same thing with a glass rod or piece of glass tubing, and you will see that the glass rod has no effect on the paper either.

If you rub the comb vigorously on a woolen sleeve, you will produce a small amount of electrical energy. We say the comb has an *electrical charge*, or simply that it is *charged*. Now bring the charged comb slowly toward the hanging paper, and the paper will swing toward the comb. If you hold the comb quite still, the paper will cling to the comb for a moment. The charge in the comb evidently attracts the paper.

But the paper does not stick to the comb for long. In a moment or two it swings away from the comb. Then if you slowly move the comb toward it, and pursue the paper with the comb, the paper tries to move away. Now the comb seems to be repelling the paper.

Before going on, suppose we think about what we have just observed. Before the comb was charged, it neither attracted nor repelled the paper. After the comb was charged, it first attracted and then repelled the paper. Certainly we are justified in thinking that the electrical charge is in some way responsible for the actions of the paper, because the only change made was in doing something in some way to the comb. And we are also justified in thinking that something must have happened while the paper was clinging to the comb. Whatever it was, it made the comb repel the paper instead of attracting it as it did at first.

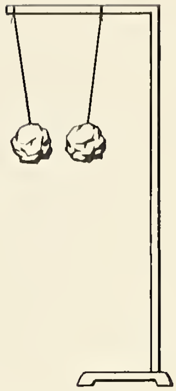
Now rub the glass rod briskly with a piece of silk cloth. This gives the glass rod an electrical charge. When you move the charged rod near the paper, the paper is first attracted to the rod. It clings a moment and then is repelled by the rod. The paper acts just as it did with the charged comb.

So far the charged rod and the charged comb seem to produce the same results with the wad of paper. What actually happens is that part of the charge passes between the comb or the rod and the paper while they are in contact. You can say that the paper becomes charged. But now

Figure 13 *shows what happens when two hanging wads of paper are charged.*

The first picture shows repulsion between the two wads. Charging both wads from the comb causes them to swing away from each other. Charging both wads from the glass rod also causes them to repel each other.

The second picture shows attraction between the two paper wads. Charging one wad with the comb and the other wad with the glass rod causes them to swing toward each other. Attraction or repulsion is greater if the distance between the wads is decreased.



you should do another experiment in order to see that there is a difference between the charge on the comb and the charge on the glass rod.

As the first step in Experiment 6, hang up another paper wad (or another pith ball) like the first one and about two inches away from it. Give the comb an electrical charge with the woolen cloth. Then charge one of the paper wads by slowly bringing the comb toward it, letting the paper be attracted toward the comb, cling to it for a moment or two, and then be repelled by it. Give the comb another charge and repeat this performance with the second wad of paper.

Now take a pencil or a thin piece of wood and move the thread on which one of the paper wads hangs so that one wad approaches the other wad. If you do this slowly and carefully, you will notice that the wads try to swing away from each other. In fact, if the wads are sufficiently charged, they will swing apart at once. The charges they received from the comb make them repel each other.

Touch both paper wads with your hand to remove the charges, or, as we say, to *discharge* them. You should do this each time to make sure that no charges remain on the wads.

Once more charge the comb by rubbing with the woolen cloth and charge one of the wads with it as before. Then quickly charge the glass rod by rubbing with a silk cloth and charge the other wad. Now one wad has received a charge from the comb, and the other has received a charge from the rod. When you move one wad closer to the other, as you did before, the wads attract each other. They cling together for a moment and then swing apart.

Do you see how you have demonstrated the fact that the charge on the comb is different from the charge on the glass rod? When many experiments like these, using different materials, showed scientists that there are just two kinds of charges, these two kinds were named. The comb, when rubbed with wool, is said to have a *negative* charge. This fact is often indicated by using the minus sign (—). The glass rod is said to have a *positive* charge. This is indicated by using the plus sign (+). The paper wad charged from the comb also had a negative charge, while the one charged from the rod had a positive charge.

Experiments such as the ones just described, and many others, show that charged bodies, like the paper wads after they touched the comb or rod, have very definite ways of acting. You saw that the two wads that had received negative charges from the comb repelled each other. If you did Experiment 6, you saw that, when the two paper wads had received positive charges from the glass rod, they would also repel each other. You also saw that when one wad was negatively charged from the comb, and the other was positively charged from the rod, they attracted each other.

From this behavior, two rules about electrical charges can be stated:

1. Two like charges always repel each other.
2. Two unlike charges always attract each other.

These two simple rules always hold true. In thinking about electrical charges, you will find it very helpful to remember them both.

CHECKING WHAT YOU LEARNED

1. Tell why the word *frictional* is a better word than *static* to use in describing the electrical energy produced in Experiment 5.
2. **a.** What happened when the comb was brought near the paper wad before it was rubbed on the woolen sleeve? After it was rubbed on the wool? **b.** What happened when the glass rod was brought near the paper wad before it was rubbed on the silk cloth? After it was rubbed on the silk?
3. **a.** How does Experiment 6 show that there are two kinds of electrical charges? **b.** What word is used to name the charge on the glass rod? On the comb?
4. Write down the two rules that tell how two electrical charges act toward each other. Then give an illustration of each rule. (If you can, use illustrations that are different from those in the book.)

Basic Information about Matter

To understand why the comb, rod, and wads act as they do when electrically charged, it is necessary to know something about how materials are put together. For example, if we could take the rubber in the comb apart, or take apart the glass in the glass rod, what would we have? What sort of materials are substances made of, and how are these materials put together to make these substances? Scientists call this the "structure of matter," and explain it by several theories. But first of all, it might be wise to come to some understanding about the word "theory."

When scientists study something they have observed and work out an explanation that seems to fit the facts but cannot be proved absolutely to be true, the explanation is called a *theory*. A theory is considered good only so long as it explains the facts observed. The various theories scientists use to explain the structure of matter have thus far held good because they explain the facts we can observe about matter.

According to one theory, all kinds of matter, or all the materials that make up the universe, are made up of particles called *molecules*. This theory is called the *molecular theory*. Most molecules are so small that they cannot be seen, even with the most powerful microscope. They are so small that even the tiniest bit of matter you can see with the naked eye is composed of millions of molecules.

Not only must you understand that molecules are smaller than anything else you have ever imagined, but you must also think of them as being separated from each other. The molecular theory states that the spaces between molecules of a gas, for example, are larger than the spaces between the molecules of a liquid. The spaces between molecules of a liquid are usually larger than those between molecules of solids.

Another part of the molecular theory states that molecules of all kinds of matter are always moving. It will probably be easy for you to believe that the molecules of a gas or a liquid can and do move. But it will be harder for you to believe that the molecules of a solid metal, such as iron, are moving. In a gas or liquid the molecules are thought to move about freely. However, in a solid they are thought to vibrate (move back and forth) close to the same place. In other words, they do not move about freely over and around one another in a solid.

According to the molecular theory, then, every material in every substance is made of molecules. A drop of water, for example, contains billions of molecules. If you could manage to divide that drop until you had a single molecule of water, you would then have the smallest amount of water that can exist.

But perhaps you already know that water is made of two chemical elements, oxygen and hydrogen. Therefore, each molecule of water contains some oxygen and some hydrogen. If the molecule of water can be separated into particles of oxygen and hydrogen, then there must be something even smaller than a molecule. To under-

The electron microscope, a recent invention, has enabled experimenters to see and photograph shadows of some of the largest molecules, such as those in rubber.

Research scientists are constantly seeking to discover more about the world in which we live. The two pictures above show one of the interesting machines they use for finding out more about the structure and nature of atoms—a 4,000,000-volt atom smasher, used to break apart atoms of various kinds. At the upper left is shown the large vacuum tube through which protons or neutrons travel at speeds of 10,000 miles or more a second to bombard the tiny atoms in the "target" at the base of the tube. At the upper right is shown the building with its strange pear-shaped dome housing this tube and the equipment necessary for operating the machine. The interesting photograph at the lower right shows how large insulators are tested in the laboratory. A bolt of man-made lightning flashing across the insulator produced the discharge shown in this picture.

Proton: A heavy, positively charged particle in the nucleus of an atom.
Electron: A light, negatively charged particle moving around the nucleus of an atom. Electrons can escape from most atoms and move around freely.

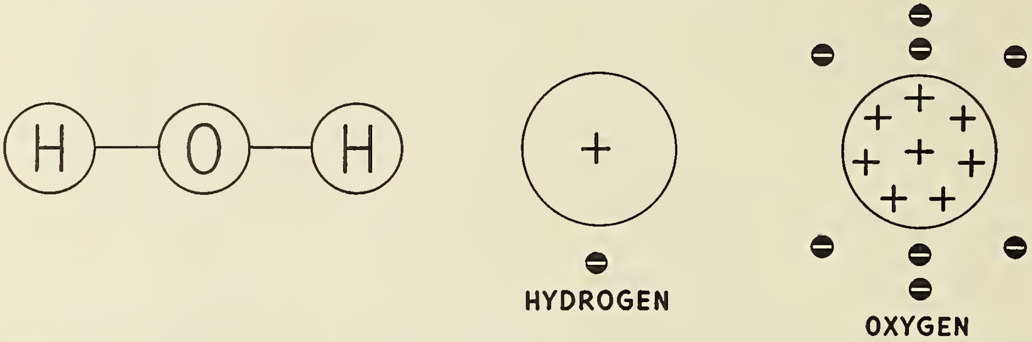


Figure 14. *The first diagram represents the atoms in a molecule of water. There are two hydrogen atoms (H) and one oxygen atom (O).*

The second diagram represents the protons (+) and electrons (—) in atoms of hydrogen and oxygen. In the hydrogen atom the nucleus contains one proton, whose positive charge is balanced by the negative charge of a single electron. In the oxygen atom, however, the nucleus contains eight protons, whose positive charges are balanced by the negative charges of eight electrons.

stand this, you need to know about another theory, the *atomic theory*.

These particles that make up a molecule are called *atoms*. In water, for example, each molecule contains two atoms of hydrogen and one atom of oxygen. Chemists show this by their formula for water, which is H_2O. Of course, hydrogen and oxygen are only two of the 92 different kinds of atoms represented by the 92 chemical elements, such as iron, copper, aluminum, zinc, lead, silver, gold, tungsten, carbon, sulphur, mercury, helium, neon, and so on. These 92 chemical elements, alone or in mixtures and compounds, make up all the substances that exist anywhere, no matter what their nature.

Scientists think that every atom contains two main kinds of still smaller particles. One kind has a positive charge; it is called a **proton.** The other has a negative charge and is called an **electron.** According to this theory, called the *electron theory*, electrons and protons are the "building blocks" of atoms. Every proton has the same amount of positive charge, and every electron the same amount of negative charge. The positive charge on a proton is equal but opposite to the negative charge on an electron.

Under ordinary conditions the positive charge in an atom just balances the negative charge, because an atom usually contains just as many electrons as protons. For example, an atom of

---

Neutrons, positrons, and other particles have been discovered in certain atoms. For example, the nucleus of an ordinary oxygen atom contains eight neutrons in addition to eight protons. A neutron is approximately as heavy as a proton, but it is neutral. Hence, the nucleus of the oxygen atom requires only eight electrons to balance its charge. Another particle is the positron. It is as heavy as an electron but has a positive charge equal to the negative charge on an electron. Still other particles, such as the **mesotron** and the **neutrino,** have been discovered, but so far little is known about them.

A negative charge is produced by a surplus of electrons.
A positive charge is produced by a shortage of electrons.

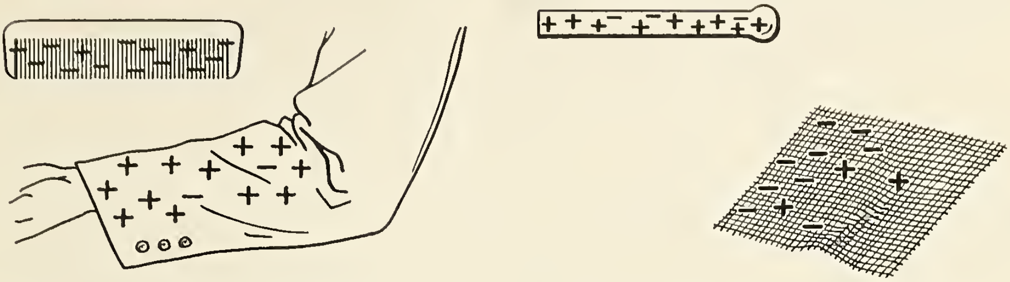


Figure 15 *shows what happens when an electrical charge is produced by friction.*

The first diagram shows a hard-rubber comb and the sleeve of a woolen coat after they have been rubbed together. Electrons from the woolen sleeve have passed to the comb, causing a surplus of electrons (negative charge) on the comb and a shortage of electrons (positive charge) on the sleeve.

The second diagram shows a glass rod and a piece of silk cloth after they have been rubbed together. This time electrons from the glass rod have passed to the silk cloth, causing a shortage of electrons (positive charge) on the glass rod and a surplus of electrons (negative charge) on the cloth.

When two different substances are rubbed together, electrons pass from one to the other.

hydrogen contains one electron and one proton. An atom of oxygen contains eight electrons and eight protons. When the positive charge in an atom balances the negative charge, we say that the whole atom is neutral.

The positive particles in any substance are much heavier than the negative particles. The positive particles, the protons, are found to be 1845 times as heavy as the negative particles, or electrons. The protons do not move as freely as the electrons. In fact, one or more protons form the *nucleus*, or center, of an atom, and the electrons normally move about this nucleus. You can think of electrons moving around the nucleus much as the planets move around the sun. Under neutral conditions electrons are held to protons in their own atoms.

CHECKING WHAT YOU LEARNED

1. Scientists use theories to explain observed facts. Must the facts fit the theory or the theory fit the facts? Why?
2. What three things does the molecular theory state about matter?
3. According to the theories of matter, **a.** what is the smallest amount of water that can exist? **b.** Of what is this made up?
4. **a.** What is a chemical element? **b.** How many different kinds of elements are there?
5. **a.** Describe an atom, naming its main parts. **b.** In what ways are these parts of an atom different from each other?
6. Why do atoms not always show an electrical charge?

Using the Electron Theory

Now let us check what we have learned thus far about the electron theory against what we observed in the experiments. This theory, if it is useful, should offer an explanation of everything we saw.

First we took an uncharged comb or glass rod and brought it near a wad of paper. Nothing happened. The comb was neutral, and so was the paper; there was no electrical charge on either of them. The comb had just as many electrons as protons. So did the paper. (Now you must not

Like charges repel: A negatively charged object repels another negatively charged object. A positively charged object repels a positively charged object.
Unlike charges attract: A negatively charged object and a positively charged object attract each other.

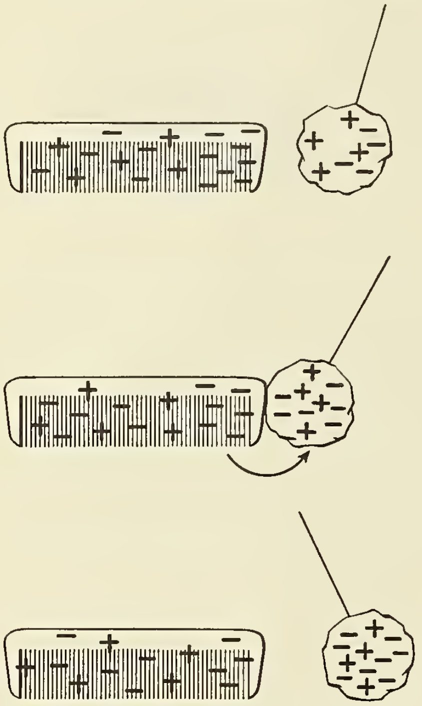


Figure 16. *The first diagram represents a neutral paper wad as it swings toward a comb having a negative charge. Note that the surplus of eight electrons on the comb repel the four electrons on the neutral wad, causing an attraction between the protons on the wad and the electrons on the comb, because the positive charge is closer than the negative to the negative end of the comb.*

The second diagram represents the paper wad in contact with the comb. Note that two electrons have already passed from the comb to the wad.

The third diagram represents the paper wad as it swings away from the comb. Note that four of the eight additional electrons originally on the comb have now passed to the wad, causing a repulsion between the negative charge on the comb and the negative charge on the wad.

(Each plus and minus sign stands for millions of protons and electrons.)

get the idea that the comb has the same number of electrons and protons as the paper. The comb, being larger, probably contains many more molecules than the paper, and so contains more atoms. With more atoms, the comb probably has many more electrons and protons than the paper. It would be very unusual to have the same number of protons and electrons in each object.)

When the hard-rubber comb was rubbed briskly with a piece of woolen cloth, some of the electrons from the woolen cloth passed to the comb. It was then no longer neutral, because it had more negatively charged electrons than were needed to balance its positively charged protons. Thus the comb had a surplus of electrons, or, as we say, a negative charge. Or we can say it was negatively charged.

If you had a good way to test the woolen cloth after rubbing the comb, you would discover that it was no longer neutral, either. It had lost some of its electrons, and so had a shortage of electrons, or, as we say, a positive charge. In fact, the positive charge on the cloth was exactly equal to the charge produced on the comb—except that it was of the opposite kind.

When the glass rod was rubbed with a silk cloth, the glass rod lost some of its electrons to the silk cloth. As the glass rod had fewer electrons than before, we say it was positively charged. The silk cloth, if you could test it, would be negatively charged. Just as with the comb and woolen cloth, the rod and silk cloth have equal but opposite kinds of charges.

Now perhaps you are wondering why the glass rod and the woolen cloth became positively charged, while the silk cloth and the rubber comb became negatively charged. Why not the other way round? Well, it just happens that some sub-

Charging by conduction: When a charged object is touched to a neutral object, a **like** charge is produced in the neutral object.
Charging by induction: When a charged object approaches a neutral object that is in contact with a conductor (but does not touch the neutral object), an **opposite** charge is induced in the neutral object.

stances, such as glass and wool for example, give up their electrons more easily than other substances do. When they give up electrons, they become positively charged. Other substances, such as the hard-rubber comb and the silk cloth, take on these electrons easily, and when they do, they become negatively charged. In fact, when any two different materials are rubbed together in this way, one gives up some of its electrons to the other. As a result, one material becomes positively charged and the other negatively charged. Since one material gains as many electrons as the other loses, the charges are equal but, of course, they are of opposite kinds.

How does this theory explain the action of the paper wad when the charged comb was brought close? First of all, remember that like charges repel and that unlike charges attract. When the negatively charged comb, with its surplus of electrons, was brought close to the paper wad, the electrons in the paper on the side toward the comb were repelled to the far side of the paper wad. You might say they crowded to the other side of the wad, away from the electrons in the comb. When that happened, there was an attraction between the negatively charged electrons in the comb and the positively charged protons in the paper near the comb. The attraction was so great that it overcame the weight of the paper, and the paper swung to the comb.

Next you noticed that the paper wad remained in contact with the comb for a moment or two. During this time electrons from the comb passed over to the wad. The comb shared its surplus electrons with the paper wad. As soon as the wad received surplus electrons from the comb, it became negatively charged, too. And when it became negatively charged, the paper wad swung away from the comb, because two negative charges repel each other.

The electron theory fits all the facts you have observed so far. If you care to go on, you can explain just what happened in the case of the glass rod and the paper wad. You can explain the action of the two paper wads when both were negatively charged, and the action when one was negatively charged from the comb and one positively charged from the glass rod.

There is still one more fact to be explained about Experiment 5. You noticed that when the charged comb was brought near the neutral paper wad, the wad was affected. The electron theory explains what happened. Electrons in the paper wad were repelled to the part of the wad farthest from the comb. If you provide a path of escape from the paper wad, by touching it with a wire or your fingers, the wad will lose some of its electrons. Then it will be positively charged because it will have a shortage of electrons. But if there is no path of escape, the wad does not lose any electrons. When the comb is taken away, the repelled electrons return to their original position, and the whole wad is neutral as before.

It is important for you to understand that an object can become charged without actually touching a charged object. In such a case we say the charge is *induced*, or that the object is charged by **induction.** An object may be charged by induction if electrons can leave or enter the body when it is in the presence of a charged body. Another way of producing a charge, as you have seen, is to touch the neutral object with a charged object. We call this charging by **conduction.**

CHECKING WHAT YOU LEARNED

1. Why did nothing happen when the uncharged comb or glass rod was brought near the wad of paper?
2. What change takes place when an object becomes negatively charged? Positively charged?

3. **a.** When the comb was charged by rubbing it on the woolen sleeve, what happened to the sleeve? **b.** When the glass rod was charged by rubbing it with the silk cloth, what happened to the cloth?
4. Tell what happens whenever any two different materials are rubbed together.
5. Why does rubbing produce one kind of charge in some materials and the other kind of charge in other materials?
6. Explain why the paper wad was at first attracted and then repelled by the charged comb.
7. How does charging by induction differ from charging by conduction? Give as many differences as you can.

USING WHAT YOU LEARNED

1. Will two charged combs attract or repel each other? How do you know? Plan a way to prove this and, if possible, try it out.
2. Make up an experiment to show what will happen if a charged comb and a charged glass rod are brought near each other. If you can, do your experiment. What will happen?
3. Why are non-conductors, such as the hard-rubber comb, glass rod, woolen sleeve, silk cloth, and paper wad, used instead of conductors in experimenting with electrical charges?
4. Explain what happened when you charged the glass rod and brought it near the paper wad.
5. If you bring a charged glass rod near a paper wad without letting them touch and then touch the wad with your hand, what happens? Why?

Storing Electrical Charges

If you did Experiments 5 and 6, you probably noticed that producing electrical charge by friction, a tiny bit at a time, was a tedious process. The early experimenters with electricity must have found it so, for one of the first electrical devices invented was a machine for producing larger quantities of electrical energy by friction. It consisted of a sulphur ball turned by a crank. When the ball was revolved against the palm of a hand, it produced an electrical charge. Later on, another experimenter invented the Leyden jar for storing electrical charges.

As improved and used today, the Leyden jar is simply a glass jar coated with tin foil on the outside and inside. In other words, it is made of two conductors (the tin foil) separated by an insulator (the glass). When the tin foil on the inside of the jar is negatively charged by being connected with a machine for producing electrical charge, a positive charge is induced in the foil on the outside of the jar. The outer foil is usually connected to the ground by means of a wire so that electrons can flow readily to or from the earth. As the electrons in the negatively charged inside foil repel the electrons on the outside foil, some of the repelled electrons on the outside foil escape or "leak off" through the wire to the earth. Then the outside foil, because it has a shortage of electrons, becomes positively charged.

A charge stored in a Leyden jar can be kept for some time. When one end of a wire is touched to the outer foil of the jar and the other end is brought close to the knob connected to the inner foil, the jar will become discharged. If the charge is a large one, a good-sized spark will result. Experiment 8 shows you how to charge and discharge a Leyden jar.

The picture of a Leyden jar in Figure 17 shows that the metal rod for conducting a charge to the inner foil of the jar has a round knob at the top. This is to keep the charge from escaping into the air. You can see that if the charge carried by the rod is spread over the surface of a sphere, the

---

Electroscope: When very small electrical charges are to be detected or compared, the **electroscope** is used. This instrument usually consists of two small, very light pieces or "leaves" of thin gold foil that hang from a metal rod. The leaves spread apart when charged and come together when discharged. They are much more sensitive to small electrical charges than paper wads or pith balls are. Experiment 7 shows you how to make and use an electroscope.

Electrophorus: A device for producing electrical charges. In its simplest form it consists of a disk of hard rubber, resin, or wax and a slightly smaller disk of metal fastened to a handle of some insulating material. Experiment 8 shows you how to make and use an electrophorus.

Condenser: A device for receiving and holding an electrical charge. It is sometimes called a **capacitor.**

Capacity: The quantity of electrical charge a condenser will hold under certain conditions.

Dielectric: An insulating material; especially that separating the plates of a condenser.

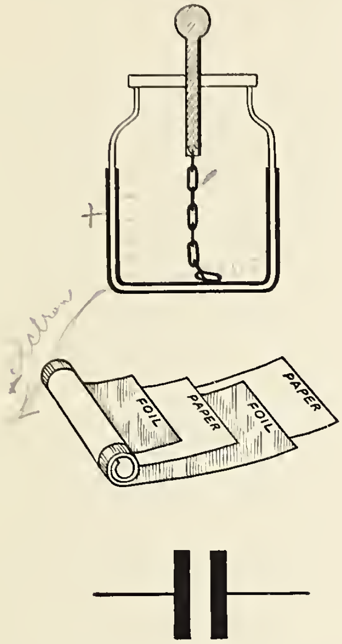


Figure 17. *The first picture shows a cross-section view of a Leyden jar. An electrical charge on the metal ball reaches the inner coating of tin foil by way of the metal rod and chain. The outer coating of tin foil is usually connected to the ground by a wire, which provides a path for the electrons repelled or attracted by the charge on the inner foil. The two coatings of foil cannot touch, because they are separated by the glass of the jar.*

The second picture shows how one type of fixed condenser is made. Alternate strips of waxed paper and metal foil are rolled on a core of wood in such a way that the paper separates the strips of foil.

The third picture shows the symbol generally used to represent a fixed condenser in an electrical circuit.

chances of the charge escaping are much less than if it were all concentrated on a sharp point.

That a charge escapes more readily from a point than from a sphere can be shown by discharging two equally charged Leyden jars, one with a wire having a round knob at one end, the other with a wire having a pointed end. The wire with the knob end must be brought closer to the knob on the Leyden jar before a spark jumps. In fact, it requires about four times the charge to produce a spark one inch long between two round knobs as it does to produce a spark of equal length between two sharp points.

This fact finds practical application in the so-called "lightning rod." The formation of rain drops in a cloud causes the cloud to become heavily charged. As it passes over the earth, it induces an opposite charge in objects below. Because tall objects are nearest the cloud, this induced charge tends to concentrate on them. If this charge becomes great enough on one of these objects, a large spark, or "flash" of lightning, leaps between the cloud and the object. If, however, the object is equipped with lightning rods, the chances of the flash occurring are lessened, for the sharp points at the upper ends of the rods allow the induced charge to escape into the air. Thus, you see that the purpose of the lightning rod is not to conduct a flash of lightning to the ground but rather to prevent the flash from ever occurring by weakening the charge that might cause it.

Devices like the Leyden jar are called **condensers** or, sometimes, *capacitors.* They are used

Electrolytic condenser: A type of condenser in which the dielectric is formed by chemical action.

Variable condenser: A type of condenser, usually with air dielectric, that can be adjusted to have different capacities.
Fixed condenser: A condenser constructed to have a definite fixed capacity under certain conditions.

in radios, in telephone circuits, in some motor circuits, automobile ignition systems, and in other ways. All of them act in the way a Leyden jar does—they take an electric charge and hold it until discharged.

All condensers are alike in this respect: They consist of two or more metal plates, usually the same material, separated by insulating material (called the **dielectric**). For example, the metal plates may be tin foil, thin aluminum, copper, or almost any metal. The dielectric may be glass, mica, waxed paper, or even air.

The quantity of charge a condenser will hold depends on several things. Naturally it depends on how much of a charge is supplied from the source of electrical energy. It also depends on the area of the metal plates—their length and width (but not their thickness). And it depends on the kind and thickness of the dielectric used to separate the metal plates.

The quantity of charge a condenser will store under certain conditions is called its **capacity.** The capacity of a condenser is much like the capacity of an automobile tire. You can fill a tire with air at 20 pounds pressure. If your pump will not supply air at a greater pressure than 20 pounds, you cannot get any more air into the tire. But if your pump will supply air at 40 pounds pressure, you can put twice as much air into the tire. The space inside the tire remains the same, but the amount of air in the tire increases as the pressure increases. In fact, when you double the pressure, you double the amount of air in the tire. Likewise, a condenser will store a certain quantity of electrical charge at one electrical pressure and twice as much charge when that electrical pressure is doubled. Of course, an automobile tire will hold more air at 20 pounds pressure than a bicycle tire will at the same pressure, because the automobile tire has more space inside it than a bicycle tire has. In the same way, a condenser of large capacity will store more electrical energy at a certain electrical pressure than a condenser of small capacity at the same electrical pressure.

Condensers that use air as a dielectric are constructed so that the distance between the plates can be varied. Or they are made so that plates of varying size can be used. Such condensers can be adjusted to have different capacities and are called **variable condensers.** A **fixed condenser** is one that holds a definite quantity of electrical charge under certain conditions.

The tuning device by which different stations are brought in on a radio is one type of variable condenser. Probably you have seen variable condensers and have noticed how the metal plates are arranged so they do not touch each other. The space between these plates is an air dielectric. The smaller condensers in a radio, the tubular paper ones, the ones in round metal cans and in oblong paper containers are different kinds of fixed condensers.

CHECKING WHAT YOU LEARNED

1. **a.** Describe a Leyden jar. **b.** For what purpose is it used? **c.** Tell what happens on the outer surface of a Leyden jar when the inner surface is charged.
2. Name the parts of a condenser and state the use of each part.

Capacity of a condenser is determined by the quantity of electrical charge it can hold for a given electrical pressure. Capacity is measured in **farads, microfarads,** and **micro-microfarads.** **Capacitance** is a technical term that usually means the same as capacity.

Electric current: A stream of electrons flowing along a conductor, or in other words, the movement of negative charges along a conductor. While there are two kinds of electrical charges, positive and negative, only one kind moves—negatively charged electrons.

3. **a.** What is meant by the capacity of a condenser? **b.** On what does the capacity of a condenser depend?
4. Name the two main types of condenser and tell in what particular way they differ from each other.

Moving Electrons in a Circuit

Let us see if it is possible to apply what we know about a circuit to what we have just learned about electrical charges and the movement of electrons. If you have actually tried one of the experiments in frictional electricity, you already know you must be careful about touching the charged objects, particularly with moist fingers. If you handle the charged comb too much, the charge in the comb seems to be lost, for the experiment fails. What has happened to the charge?

Electrons moved from the woolen sleeve of your coat to the comb, along the comb to your fingers, and then through your body to the ground. This movement of electrons was a weak flow of electrical energy, but it was a flow just the same. The electrons didn't move very fast—not nearly so fast as we are used to having electric current act in our homes—but that was because they were moving through such poor conductors as wool and hard rubber.

Are you able to imagine these electrons moving from one object to another, from the cloth to the comb, along the comb to your fingers, and so on? If you can, then you will see that what we need in a circuit is some kind of pump to keep a stream of electrons flowing, just as the water pump in an automobile keeps the water flowing in a circuit of piping through the engine, pump, radiator, and hoses.

For such an electron pump we use a generator or a battery of cells. Right here you are likely to make a perfectly natural mistake and begin to think about "making electricity." Electrical energy, which is what you probably mean when you say "electricity," is the result of a surplus of electrons. The electrons are already in existence; therefore you can't make them. All you can do is to arrange things so that the electrons will move in the form of an electric current.

Instead of thinking of *making* electrical energy, then, suppose we get into the habit of thinking of *producing* it. For example, a farmer doesn't make wheat; we say he produces it. He sets up certain conditions that he hopes will lead to the desired result. He plows, plants seeds, cultivates the growing plants, and finally reaps the crops. The wheat, however, made itself from materials stored in the seed and occurring in the air and soil. In much the same way we can say we produce electrical energy. By rubbing, touching, or merely approaching one material with another, we can cause a change in the arrangement of the electrons in the materials. The electrons are already there; we cannot make them. However, by rubbing, or by touching, or by just approaching the objects, we can cause some of the electrons to go from one material to another, or from one part of a material to another part. The same thing is true of a circuit. There are just as many electrons in the circuit *before* you close the switch as afterwards. The only change is that after you close the switch, the electrons are kept moving through the circuit by the source of electrical energy.

Here is a good place, also, to review something important: When an object has its normal number of electrons, it is neutral; it has no electrical charge, because its positively charged protons and its negatively charged electrons balance each other. When it has more than the normal number of electrons (a surplus), it is negatively charged. When the object has less than the normal number of electrons (a shortage), it is positively charged.

Equally important is this: While there are two kinds of charges, positive and negative, only one kind moves—the negatively charged electrons. This is the kind we mean when we talk about electrical energy moving in a circuit. Another way to put it is: An electric current is a stream of electrons flowing along a conductor.

CHECKING WHAT YOU LEARNED

1. Explain why you must be careful in handling charged objects while doing experiments. Give an example to illustrate your answer.
2. **a.** Tell what is meant by an electric current. **b.** What is needed to cause an electric current to flow in a circuit?
3. Why is it incorrect to talk about "making electricity"?
4. **a.** What term do we use to describe an object in which the electrons and protons balance each other's charges? **b.** In which there is a shortage of electrons? **c.** In which there is a surplus of electrons?
5. In what ways does an electric current differ from static electricity? Give as many different ways as you can.
6. Do positive or negative charges move in a circuit? Explain.

How the Electrons Move

There is good reason for emphasizing this matter of moving electrons. Your understanding of electric currents depends on this point. When an object has a surplus of electrons, the surplus electrons tend to move away. Why? Because they repel each other. Where will they move? If there is a path, they will move to any object that has fewer surplus electrons. Suppose we attempt to put this down on paper in some such way as this:

We have four objects of the same size which we will call A, B, C, and D. Object A is negatively charged, which means it has a surplus of electrons. For convenience we will say that there are ten surplus electrons, although there are probably millions of surplus electrons in negatively charged A. But ten will be an easy number to handle. Also for the sake of convenience we describe this object as A10—. (Remember that negative charges are usually indicated by the minus sign.) The next object is B, and as B happens to be neutral we will describe it as B0. C is another object, also negatively charged, but with only three surplus electrons, so we describe it as C3—. And D is an object that is positively charged. That means it has lost some of its electrons, let us say four. We can express this condition by describing the object as D4+. (You will recall that the plus sign is used to indicate positive charges.) Here are the four objects:

A10— B0 C3— D4+

If we bring A and B together, or if there is a path between them, such as wire would furnish, the surplus electrons in A start moving toward B. And they will move until we have this condition:

A5— B5—

In other words, the surplus electrons moved until there were the same number of surplus electrons in each object. When this condition was reached, the movement stopped because then neither object had fewer surplus electrons than the other.

Now suppose we bring A, which must now be described as A5—, in contact with C3—, or furnish any kind of path between them for the surplus electrons to use. What happens? One of the surplus electrons in A will move to C. Then we can describe the condition of the two materials as:

A4— C4—

Again we have a balance. There are just as many surplus electrons in C as in A. When that happens, the electrons stop moving between A and C.

Now suppose we touch or connect A, which we have described as A4—, to object D, which is positively charged. We described it as D4+, indicating that it has a shortage of four electrons. Again the surplus electrons in A4— move until there is a balance. And that balance comes when four surplus electrons have moved to D. Then neither object has a surplus of electrons or a shortage of electrons. Both are now neutral. We can describe this condition as:

A0 D0

If you remember this brief demonstration, you will not make the mistake of thinking, as some do, that electrons move only from negative to positive, or from negative to neutral. Electrons can also move from one negatively charged object to

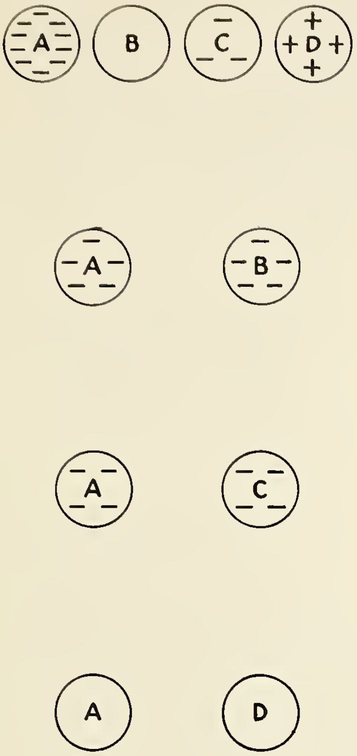


Figure 18. *The first diagram represents four objects of the same size and shape with different charges on them. The minus signs indicate a surplus of electrons, or a negative charge; the plus signs indicate a shortage of electrons, or a positive charge.*

The second diagram represents objects A and B after they have been in contact. Note that five of the ten surplus electrons on A have now passed to B, so that both objects are now equally charged.

The third diagram represents objects A and C after they have been in contact. Note that one of the five surplus electrons on A has now passed to C, thus balancing the charges on both objects.

The fourth diagram represents objects A and D after they have been in contact. Because all four of the surplus electrons on A have passed to D, which lacked four electrons, neither object has a charge. Hence, objects A and D are now neutral.

another negatively charged object, if the second object has a smaller negative charge. For example, one surplus electron in A5— flowed to C3— until both had four surplus electrons. Surplus electrons will move between two objects as long as there is a difference in the number of surplus electrons on them.

This difference causes what we call a **difference in potential**, or **potential difference**. By **potential** we mean the electrical energy produced by removing electrons from one object and adding them to another, or, by charging it. An electric current flows only when there is a difference in potential between two objects. And you have just seen that current stops flowing when there is no longer any difference in potential.

A result of potential difference is a force that drives surplus electrons from where they are to where there are fewer of them. We call this force **electromotive force**, which means the force that moves electrons, an electron-moving force. Electromotive force is often abbreviated **E.M.F.** As long as there is a potential difference between two objects, the electromotive force will cause a current to flow, providing there is a path. When there is no longer any difference in potential, the electromotive force disappears, and the current stops. That is simply another way of saying the electrons stop moving when the charges balance each other.

The fact that the electromotive force disappears when a difference in potential no longer exists can be shown in other ways. Figure 19, for example, shows an arrangement of tanks, pipes, and valves. Tanks A and B rest on the ground, while tank C is buried so that the top is level with the ground. Let us say that all tanks are 10 feet high. Tanks A and B are connected at the bottom by a pipe containing valve 1, while tank B drains into tank C through another pipe containing valve 2. As you examine Figure 19, you will see how the flow of water from one tank

Potential: The electrical energy produced by removing electrons from one object and adding them to another, or in other words, by charging the objects, or by moving electrons from one part to another part of the same object.

Potential difference: The difference in the amount of electrical energy in two charged objects or two points on the same object. Often abbreviated **P.D.**

Electromotive force: The force resulting from potential difference that will cause a current to flow. Often abbreviated **E.M.F.**

Ground: The earth, or **ground,** is usually taken as the reference point from which to measure positive and negative charges.

Zero potential: A term used to describe a lack of electrical charge or a neutral condition. The earth is considered to be at **zero potential,** so is a neutral object.

to another can be controlled by opening and closing valves 1 and 2.

Now let us look at Figure 19 from the standpoint of what you have learned about electrical charges in this chapter. Let us say that tanks A and B correspond to objects A and B, which like a hard-rubber comb are capable of gaining electrons, while tank C corresponds to object C, which like a glass rod is capable of giving up electrons. The pipes and valves then correspond to paths along which electrons can move. If we now let each foot above ground level represent a surplus of 10 electrons, and each foot below ground level a shortage of 10 electrons, differences in height will correspond to differences in potential—and gravity will correspond to electromotive force. Since in electricity the earth is usually taken as the reference point from which to measure potential in much the same way that altitude is measured from sea level, we can say that the ground level corresponds to **ground**, or a point of **zero potential.**

The first picture in Figure 19 represents object A with 100 surplus electrons, object B with neither a surplus or a shortage of electrons (hence, neutral), and object C with a shortage of 100 electrons. You can see that the potential difference between A and C is twice that between A and B, or between A and ground.

The second picture represents objects A and B with 50 electrons each. When a suitable path was provided, the electromotive force caused electrons to move from A to B until each had the same amount of negative charge. Then the movement stopped because there was no longer any difference in potential between A and B. You can see that the difference in potential between A and ground is one half of what it was originally.

The third picture represents objects A and C with half of their original charges. When a suitable path was provided, 50 electrons from B passed to C, which now has a shortage of only 50 electrons. Thus the potential difference between A and C is now half of what it was originally. Object B is again neutral, and there is again a potential difference between A and B, though this, too, is now only one half of the original difference in potential.

The fourth picture represents objects A and B again with equal charges, each one half as large as before. When a suitable path was provided, electrons again moved from A to B until there was no longer any difference in potential between A and B. Of the 100 surplus electrons originally on A, 50 have passed to C and 25 to B, leaving A with one fourth of its original negative charge. Object C, however, still has half of its original positive charge.

The fifth picture represents all objects at zero potential, or without charge; the difference in potential between each object and ground is now zero. When suitable paths were provided, 25 electrons from A and 25 electrons from B passed to C, which had a shortage of 50 electrons. Since all three objects are now without charges, no further movement of electrons can take place. The elec-

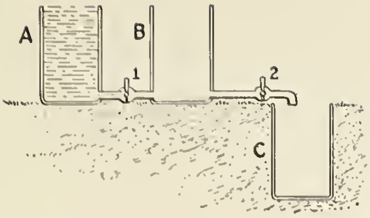
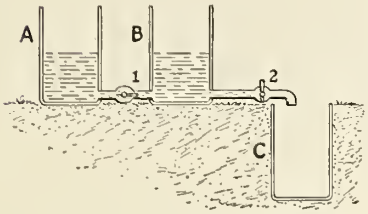
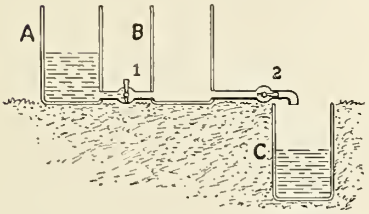


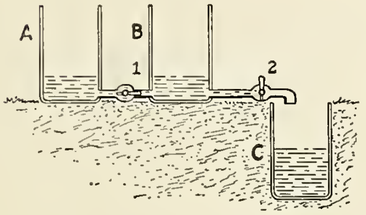
Figure 19. *The first picture shows tank A with 10 feet of water in it. Note that valves 1 and 2 are closed and that tanks B and C are empty. Let us now open valve 1. . . .*



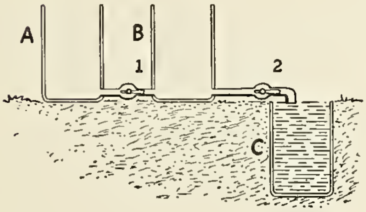
The second picture shows what happened after valve 1 was opened. The water in tank A flowed into tank B until each tank had 5 feet of water in it. Then the flow stopped because there was no longer any difference in height between the water level in the two tanks. Let us now close valve 1 and open valve 2. . . .



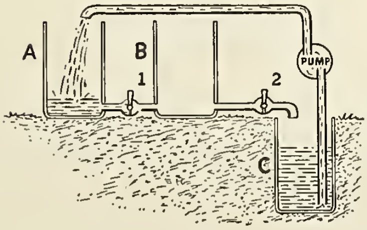
The third picture shows what happened after valve 2 was opened. This time the flow continued until all the water in tank B had flowed into tank C. Although tank C now has 5 feet of water in it, the water level in tank C is still 10 feet below that in tank A. Let us close valve 2 and open valve 1. . . .



The fourth picture shows what happened when valve 1 was opened again. Water again flowed until there was no longer any difference in height between the water level in the two tanks. The water level in tank C, however, is still 5 feet below the ground level, and 7½ feet below the water level in tanks A and B. Let us now open valve 2. . . .



The fifth picture shows what happened when valve 2 was opened. The water in tanks A and B flowed into tank C, which is now full. Note that gravity has caused all the water originally in tank A to flow into tank C, but that this force acted only so long as there was a difference in height. Let us now close both valves and add a pump. . . .



The sixth picture shows the pump returning the water to tank A. Note that work must be done to raise the water to its former level so that a difference in height will again exist between tank A and tanks B and C.

Ampere: The unit used to measure the rate of current flow.
Ohm: The unit used to measure resistance to the flow of an electric current.
Volt: The unit used to measure the electromotive force or the potential difference causing it.

tromotive force has disappeared because there is no longer any difference in potential.

The sixth picture represents a generator or cell "pumping" electrons from C to A. In other words, mechanical or chemical energy is being changed to electrical energy; for, as the "pump" removes electrons from C and adds them to A, an electromotive force again results from the difference in potential.

There are three important things we need to know about an electric current in order to make good use of it. First of all we must be able to measure how fast the current flows along a conductor. In other words, we need to know how many electrons move past any point in the conductor in one second. This rate of current flow is measured in a unit called the **ampere**.

Another thing we need to know is how much opposition the current must overcome as it moves along. Opposition to the flow of current is called *resistance*. It is measured by a unit called the **ohm**. You already know that some materials conduct an electric current better than others. This is because different materials have different resistance.

The third thing we need to know is the force that causes the electrons to move from one place to another—the electromotive force. You can think of the electromotive force as the pressure that acts on the electrons and overcomes the opposition or resistance to their movement through a conductor. The electromotive force is measured by a unit called the **volt**.

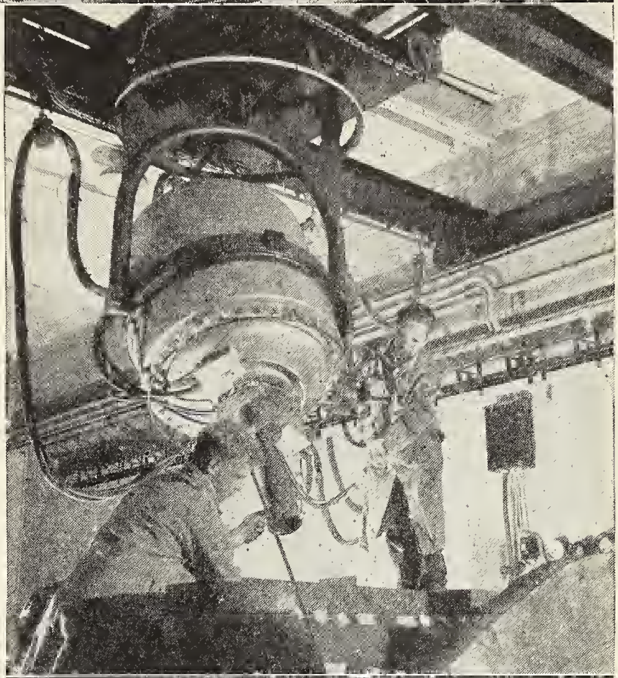
In the next chapter you will learn more about resistance and its relation to the rate of current flow and to electromotive force.

CHECKING WHAT YOU LEARNED

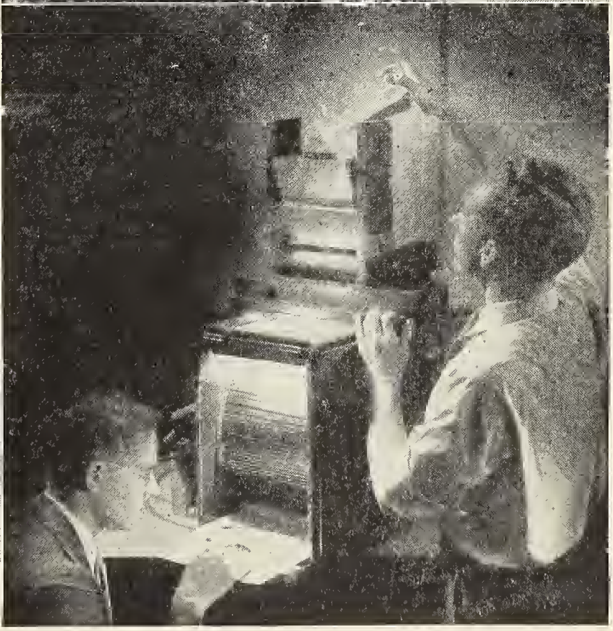
1. **a.** Explain why electrons tend to move away from a negatively charged object. (**b**) In order to move away what must they have? **c.** Where will they move?
2. The following situations represent pairs of objects, charged or uncharged, connected by a wire. On a separate sheet of paper indicate whether or not a movement of electrons will take place and in what direction they will move. Then after each answer give your reasons. **a.** Negatively charged, positively charged. **b.** Positively charged, neutral. **c.** Negatively charged, less negatively charged. **d.** Neutral, neutral. **e.** Neutral, negatively charged. **f.** Positively charged, negatively charged. **g.** Positively charged, more positively charged.
3. What is meant by potential? By potential difference?
4. **a.** When will electrons move in a path between two objects? Why? **b.** When will the electrons stop moving between the objects? Explain.
5. Why is the ground or earth said to be at zero potential?
6. Name the three things we need to know about an electric current. After each one give a brief explanation of its meaning and also state the unit used to measure it.

USING WHAT YOU LEARNED

1. Why must people who work with gases, explosives, and other materials that take fire easily be very careful about producing frictional electrical energy? What precautions against this danger would you suggest in factories where such work is done?
2. A good lightning rod consists of a sharp-pointed piece of metal raised above the nearest object or surface and connected by means of a straight wire to a metal pipe driven deep into the ground. Explain why this arrangement is desirable.



Here are four electrical devices whose operation depends upon the repulsion and attraction of electrical charges. At the top is an air cleaner in which dust is first given a positive charge and then trapped on negatively charged plates. At the right is a high-powered X-ray machine for detecting flaws in large castings. At the lower left is an electronic timer for controlling the various operations of a welding machine with split-second accuracy. And the device at the lower right separates metallic ore from dirt by means of electrical charges.



3. The air in a room where printing is done must be kept moist. Otherwise when sheets of paper are run through a printing press, it would soon be hard to make one sheet lie on top of another in a flat pile. Why must the air be kept moist?
4. On a winter day a man noticed that he got a shock each time he walked across the room and touched the door knob. However, he did not get a shock when he sat in a chair and touched the knob of another door near the chair. Explain.
5. What happens during a thunderstorm to the objects on the ground such as houses, trees, and the like over which a large negatively charged cloud is passing? Why?
6. If you rub a copper rod on an iron rod and then try to attract a paper with either rod, nothing happens. **a.** Are electrical charges produced on the rods? Why? **b.** Explain why neither rod attracts the paper wad after being rubbed.
7. Why is it hard to store much of a charge in a Leyden jar if the outer coating is insulated from the ground?
8. How can you discharge a Leyden jar or condenser safely?
9. Why do charges on a conductor tend to stay on the outer surfaces?
10. Explain why a tall steel smokestack is less likely to be struck by lightning than a brick chimney of the same height.

THINKING OVER WHAT YOU LEARNED

1. On a sheet of paper write down the titles of the six main topics of this chapter, leaving several lines after each title. Then in the space you left, write down, in complete sentences, the big ideas or principles you learned in studying that topic. This will help fix in your mind the important things in the chapter.
2. Show that you understand the meaning of each of the following terms. You may use it in a sentence or give a definition for it in your own words.
a. electrical charge, **b.** neutral, **c.** electromotive force, **d.** positive charge, **e.** atom, **f.** rate of current flow, **g.** potential difference, **h.** molecule, **i.** resistance, **j.** dielectric, **k.** fact, **l.** proton, **m.** condenser, **n.** theory, **o.** electron, **p.** electrical energy, **q.** negative charge, **r.** electric current.

Experiment 5: **Attraction and Repulsion by Electrical Charges**

THINGS NEEDED: Small, round wad of dry paper (or pith ball). Silk thread about 12 inches long. Support for paper wad and thread. Hard-rubber comb (or fountain pen). Glass rod (or glass tubing). Woolen cloth. Silk cloth. (See Fig. 12.)

WHAT TO DO: **a.** Fasten the paper wad (or pith ball) on one end of the silk thread and tie the other end of thread to the support so that the paper wad hangs free. Move the hard-rubber comb (or fountain pen) slowly toward the paper wad. What happens? Try the same thing with the glass rod (or glass tubing).

b. Now rub the comb vigorously back and forth on the woolen cloth. Then move the comb slowly toward the paper wad. What happens? Let the comb and paper wad touch and remain in contact for a few moments. Again notice what happens. Try to touch the paper wad with the comb now. What happens when you pursue the paper wad with the comb?

c. Rub the glass rod briskly with the silk cloth. Then repeat Part **b**, using the glass rod instead of the comb. What happens when the rod is used in place of the comb?

Experiment 6: **Two Kinds of Electrical Charges**

THINGS NEEDED: Same as in Experiment 5. Small, round wad of dry paper (or pith ball). Silk thread about 12 inches long. Pencil (or thin piece of wood). (See Fig. 13.)

WHAT TO DO: **a.** Hang up another paper wad (or pith ball) about 2 inches from the first one used in Experiment 5. Charge the comb by rubbing it on the woolen cloth and then touch it to one of the paper wads. Hold the comb against the paper wad until the wad is repelled. Charge the comb again and then touch it to the other paper wad until the wad swings away. Now take a pencil (or thin piece of wood) and move the thread on which one of the paper wads hangs so that the wad approaches the other wad. What happens? (*Note:* If the air is very dry and the paper wads receive a good charge, it may not be necessary to move the thread to get results.)

b. Touch both paper wads with your hand to discharge them. Repeat Part **a**, but charge each paper wad by rubbing the glass rod with the silk cloth instead of rubbing the comb on the woolen cloth. What happens this time when you use the charged rod?

c. Again touch the paper wads with your hand to discharge them. Now charge one paper wad by touching it with the charged comb. Then charge the other by touching it with the charged rod. Move the thread on which one of the paper wads hangs so that the wad approaches the other wad. What happens? Are the charges on the two paper wads the same? Why? Is a charge produced on the comb by rubbing it on wool the same as the charge produced on the glass rod by rubbing it with silk? Why do you think that your answer is correct?

Experiment 7: **Making and Using an Electroscope**

THINGS NEEDED: Electroscope (or materials to make one: brass curtain rod with round knobs on the ends, bottle, one-hole cork or rubber stopper to fit bottle, aluminum foil or tin foil, scissors, Scotch tape, hacksaw). Hard-rubber comb. Woolen cloth. Glass rod. Silk cloth. (See Fig. 20.)

WHAT TO DO: **a.** If you do not have an electroscope, you can easily make one. Saw off about 3 inches from one end of the curtain rod. Twist this piece of rod through the one-hole stopper until the knob and about 1 inch of rod are left on one side. With a scissors cut two strips of aluminum or tin foil about ¼ inch wide and 2 inches long. Fasten these strips with Scotch tape on opposite sides of the longer end of the curtain rod sticking through the cork or rubber stopper. (The strips of foil should extend up about ½ inch from the end of the rod. The Scotch tape should be wrapped around the rod and over the strips of foil.) Now carefully insert the stopper in the neck of the bottle, being sure that the strips of foil do not twist or stick together.

b. Charge the comb negatively by rubbing it on the woolen cloth. Bring the charged comb near

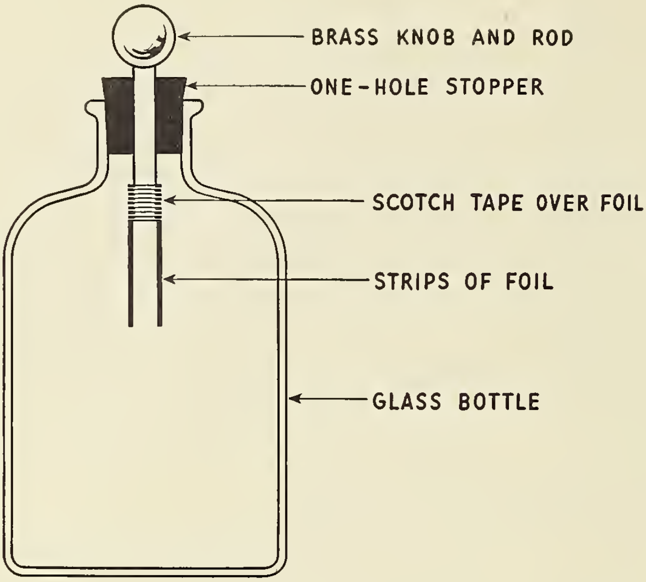


Figure 20 *illustrates the equipment for Experiment 7.*

the knob of the electroscope. What happens? Now remove the comb. Notice what happens. Touch the comb to the knob and then remove it. What happens now? Touch the knob of the electroscope to discharge it. Next charge the glass rod positively by rubbing it with the silk cloth. Bring the charged rod near the knob of the electroscope. What happens? Remove the rod and notice what happens. Then touch the rod to the knob and then remove it. What happens now? Bring up the charged comb. What happens? How can you use an electroscope to detect the presence and kind of electrical charge?

c. Touch the knob of the electroscope to discharge it. Now charge the comb as before. Bring the charged comb close to the knob of the electroscope. Touch the knob with your finger. Remove your finger from the knob and then remove the charged comb. What happens? Why is this different from what happened in Part **b**? What kind of charge is left on the electroscope? If you do not know, you can easily find out. Charge the glass rod as before and bring it near the knob of the electroscope. What happens? What kind of charge is present on the electroscope? Why? (If you wish, you can repeat Part **c**, charging the glass rod first instead of the comb. Then you can determine the kind of charge left on the electroscope by bringing a charged comb near the knob. What do you notice?)

Experiment 8: **Making and Using an Electrophorus**

THINGS NEEDED: Electrophorus (or materials to make one: hard-rubber or wax plate, metal disk smaller than plate, wooden handle, metal drill, screw). Piece of woolen cloth (fur is better if available). Electroscope from Experiment 7. Hard-rubber comb. Woolen cloth. Leyden jar and discharging rod. Wire. (See Fig. 21.)

WHAT TO DO: **a.** If you do not have an electrophorus, you can make one. Drill a small hole in the center of the metal disk. Fasten the wooden handle perpendicularly to the disk with a screw.

b. Rub the woolen cloth or fur briskly over the hard-rubber or wax plate. What kind of charge is produced on the plate? Set the metal disk on the plate. What kind of charge does it have on its lower surface? On its upper surface? Now touch the upper surface with your finger. Remove the finger and take hold of the insulated handle and remove the disk from the plate. What kind of charge does the metal disk have? If you do not

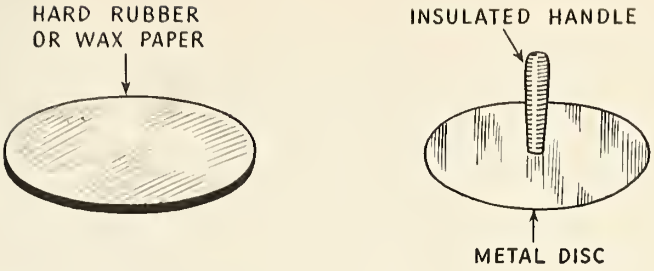
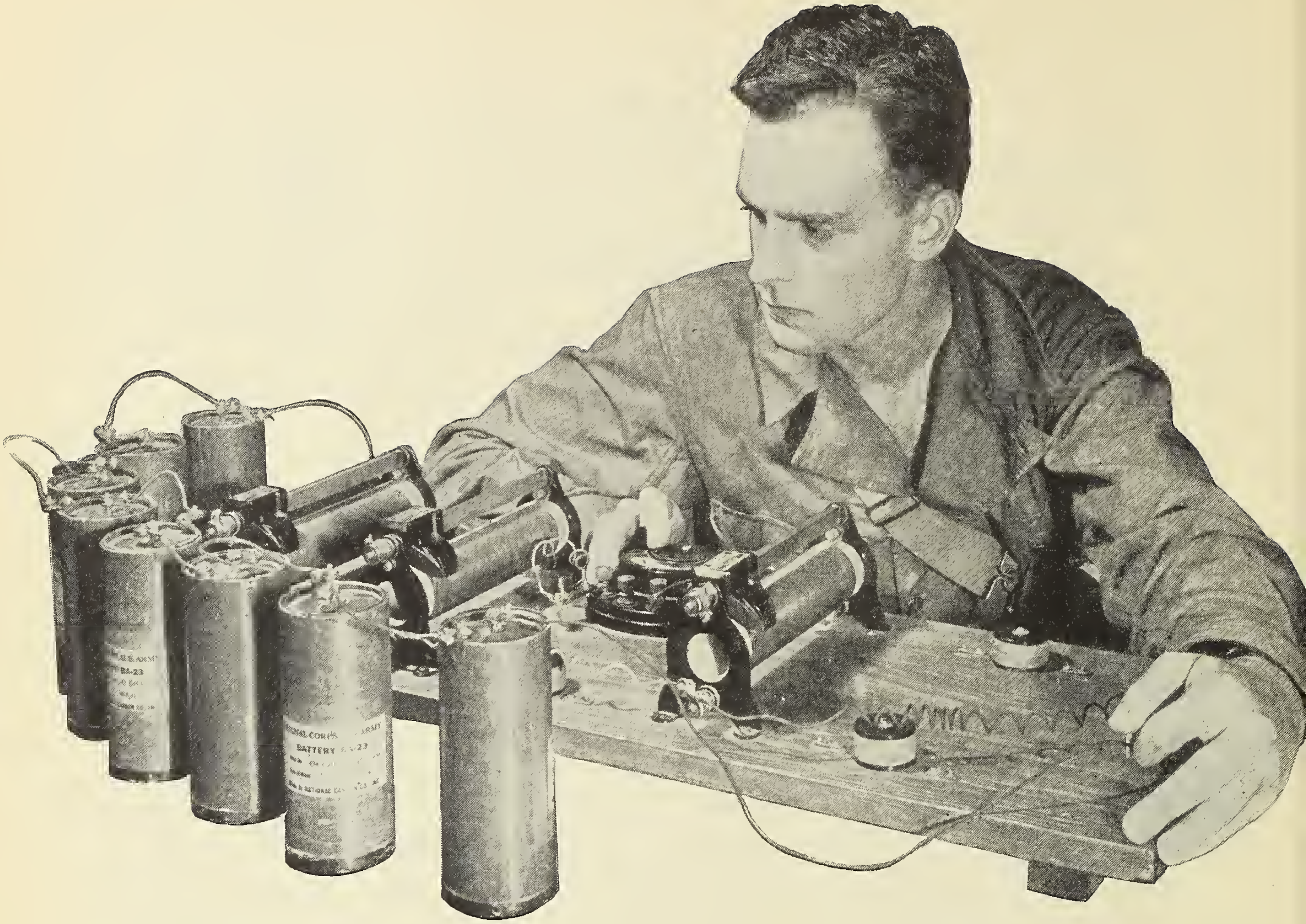


Figure 21 *illustrates the equipment for Experiment 8.*

know, bring the electrophorus near the knob of an electroscope which has a negative charge on it. (Charge the electroscope negatively by charging the comb and then touching the comb to the knob.) What happens? What kind of charge does the metal disk have? How do you know?

c. Set the Leyden jar on a wire or surface connected with the ground. (A wire connected to a cold-water pipe makes a good ground.) Charge the metal disk of the electrophorus as in Part **b** and bring it close to the knob of the Leyden jar. What happens? What kind of charge is produced on the inner coating of the jar? On the outer coating? Explain why each charge is produced. Charge the metal disk again and transfer the charge to the Leyden jar. Repeat this several times. (It is not necessary to rub the hard-rubber or wax plate each time you charge the disk. Why?) Now touch one end of the discharging rod to the outer coating of the Leyden jar. Then bring the other end near the knob of the jar. What happens? Why? Did a current flow along the rod? How do you know? Why should you touch the discharging rod to the foil first?



3. Resistance to Electric Current

FINDING OUT WHAT YOU KNOW

1. Why is a force needed to make an electric current flow through a conductor?

2. How does the length of conductors affect the flow of current in a circuit?
How does the size of the conductor affect the flow?
How does the material affect it?

3. What is the relationship between current, pressure, and resistance in a circuit?

4. How can the flow of current in a circuit be increased? How can it be decreased?

5. Name some devices used to control the flow of current in a circuit.

6. Why does an electric iron, toaster, or other heating device get hot?

7. How does an electric light bulb work?
What else is produced when electrical energy is changed to light?

8. Name some devices used to safeguard a circuit and tell how each one works.

In the last chapter you read that an electric current meets with opposition, called resistance, when it passes through any conducting material. Resistance is extremely important because it affects the flow of the electric current.

You might understand resistance better if you will think about running through a field of grass. If the grass is short, you do not think of it as offering much opposition to you, since it does not hold you back enough to notice. If the grass is knee-high, it offers noticeable opposition to you. To run as fast as you did in the short grass, you must put more force into your stride. If the grass happens to be the variety we call bamboo, and is twelve feet high, it will offer great opposition to you. You would find it very slow going against the opposition of the bamboo.

Resistance in a conductor is like this grass. As the resistance in a circuit increases, the rate of current flow becomes less. To keep up the same rate of flow as there was in the circuit with less resistance, the electromotive force must be increased.

The amount of resistance to the flow of an electric current varies with different materials. You already know that some materials are good conductors of electric current; in other words, they have a low resistance. Other materials are poor conductors—that is, they have a high resistance. Extremely poor conductors have such a high resistance that they are used as insulators. Even with much pressure (electromotive force) back of the current, these insulators do not permit a noticeable current to flow. Because circuits are composed of various conductors insulated with

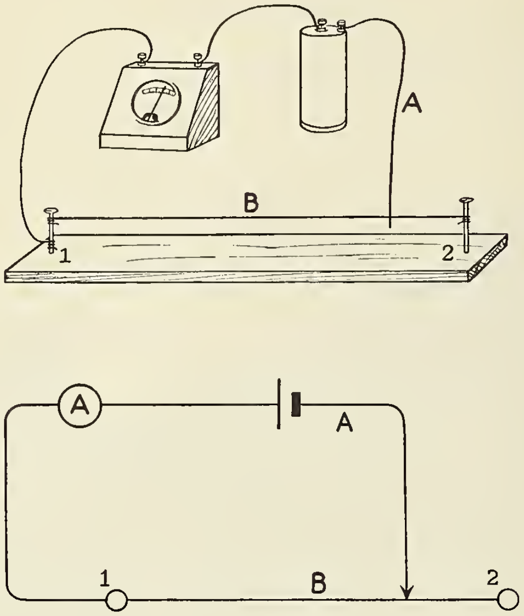


Figure 22. *The first picture shows a dry cell, an ammeter, and conductors so arranged that the length of the wire in the circuit can be varied by sliding the end of wire A along the bare wire B, which is stretched between nail 1 and nail 2. When the end of wire A touches nail 1, current cannot flow through wire B. When wire A touches nail 2, current can flow through all of wire B.*

The second picture is a diagram of this circuit, using symbols. Note the symbol used for the ammeter. A circle indicates a meter of any kind; the "A" shows this meter is an ammeter. Note, too, that the end of wire A is indicated by an arrow to show that it can be moved along wire B. An arrow is used in electrical diagrams to show a variable control of any kind.

various non-conductors, you can see that the different resistances of these materials is important.

The kind of material, however, is not the only thing that determines resistance to the flow of an electric current. Resistance also depends on other things: length, size (cross-sectional area), and temperature. A few simple experiments will demonstrate these facts, and also give you some information on which you can base some conclusions about resistance.

Resistance in Conductors

In Experiment 9 (page 70) you send a current through wires of different kinds, lengths, and sizes, to discover the factors which determine the resistance of conductors. You compare the amount of current flowing through iron and copper wires of the same size and length connected as in Fig. 22. The *ammeter,* an instrument for measuring the current in amperes, shows that more current passes through the copper wire than through the iron wire. This shows that iron offers more resistance than copper to the current flow.

Next you compare the amount of current which flows through two iron wires of different thickness. Less current flows through the small wire (wire of small diameter, or cross section) than through the larger wire (wire of larger diameter, or cross section). In the third part of the experiment you compare the flow of current through different lengths of the same kind and size of wire. Less current flows through the long wire than through the short wire.

If you tested wires of the same length and cross section, but of such materials as silver, copper,

---

Wire sizes: The size of the cross section of a wire is indicated by its gauge number. The larger the gauge number, the smaller the cross section of the wire. No. 18 wire is generally used for doorbell circuits. Ordinary house-wiring circuits of 110 volts usually have No. 14 wire for the lighting circuits, while circuits for electrical appliances use No. 12 wire, or even larger. Cross sections of wires of several gauges are shown in their actual sizes by the dots at the right:

aluminum, tungsten, and iron, you would find they had different resistances. In fact, the resistances of most metals and of many alloys (mixtures of metals) have been tested, and the results are available in tables like the following:

Resistance in ohms per foot (at 68° Fahrenheit)

MATERIAL	NO. 12	NO. 18	NO. 24	NO. 30
Silver	.0015	.0060	.0243	.0935
Copper	.0016	.0064	.0257	.1032
Aluminum	.0026	.0105	.0421	.1690
Tungsten	.0053	.0211	.0845	.3399
Iron	.0092	.0370	.1490	.5980

You can see how this table bears out the observation you made with the No. 30 copper and iron wires. The resistance of 10 feet of No. 30 copper wire is 1.03 ohms, while the resistance of 10 feet of No. 30 iron wire is 5.98 ohms.

The table also bears out the other observations made in Experiment 9. We found that more current flowed through No. 18 iron wire (of larger diameter) than through the No. 30 iron wire. The table shows that 10 feet of No. 18 iron wire offers .370 ohm resistance, while 10 feet of No. 30 iron wire offers 5.98 ohms resistance. In other words, the smaller the diameter (or cross section) of a wire, the greater the resistance offered.

When the current flowing through 10 feet of No. 30 iron wire was compared with the current flowing through 5 feet of the same wire, it was found that less current flowed through the longer wire. The table shows that 10 feet of No. 30 iron wire has a resistance of 5.98 ohms, while 5 feet of No. 30 wire has a resistance of 2.99 ohms. Since wire offers a certain number of ohms resistance per foot, the longer the wire the greater the resistance offered.

It is not very hard to understand why lengthening a conductor or decreasing its cross-sectional area should increase its resistance. If you lengthen a wire, the current must flow through a longer path. As you might suppose, the longer the path the more opposition or resistance the current meets. When you decrease the size of a wire, you make the path smaller. It is not surprising that the current has a harder job in getting through a smaller wire. But why do different materials offer different resistances to the flow of current even when the materials have the same length and cross section? Scientists think the reason for this is that different materials have different numbers of "free" electrons. A free electron is one that can easily escape from an atom. As you know, an electric current is a stream of electrons flowing in a conductor. The more free electrons available in the conductor, the more easily the current will flow. Silver, copper, and aluminum have many free electrons; they are very good conductors. Tungsten and iron do not have so many free electrons; they are good conductors but not so good as silver, copper, or aluminum. Glass, porcelain, rubber, wood, silk, wool, dry air, and pure water have few free electrons; they are such poor conductors we call them insulators. Now you can see why there is no such thing as a perfect conductor or a perfect insulator. In a perfect conductor all the electrons would be free. If all the electrons were free, there would be no atoms because atoms must contain electrons as well as protons. And if there were no atoms, there would be no molecules to make up the conductor because molecules are composed of atoms. In a perfect insulator all the electrons would be firmly attached to atoms, and none would be free. No such material that could be used as an insulator has ever been found.

Resistance and E.M.F. It should be perfectly obvious from the facts you observed in Experiment 9 that conductors in a circuit should be made of material with low resistance and of sufficient cross section to keep the resistance low. If the resistance is high, a great deal of electrical energy is used in making the current flow.

Every circuit, of course, offers a certain amount of resistance. Experiment 9 showed you that with a given E.M.F. only a certain amount of current will flow. If we are operating a bell or other device in a circuit, it often happens that the resistance of the circuit is so great that not enough

Mils and circular mils: The diameter of wire is measured in mils. A mil is 1/1000 of an inch. The cross-sectional area of wire is measured in circular mils. A wire that is one mil in diameter has a cross section whose area is one circular mil. Handbooks of electricity contain wire tables that give the diameter in mils and the area in circular mils for wires of different gauge numbers.

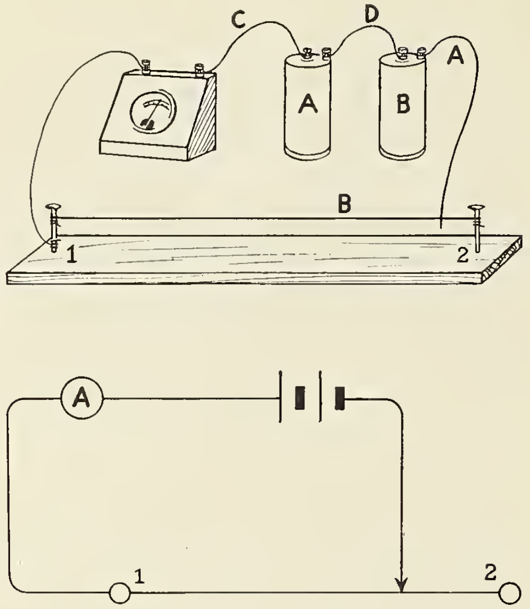


Figure 23. *The top picture shows the same arrangement as used in Figure 22, except for the number of cells. Note that wire C from the ammeter is connected to the center post of cell A, that wire D is connected between the outside post of cell A and the center post of cell B, that wire A is connected to the outside post of cell B. Two dry cells connected in this way supply an E.M.F. of 3 volts.*

The lower picture is a diagram of this circuit, using symbols. Note that wire D, above, is not shown between the two cells. In circuit diagrams a battery of two or more cells is always shown in this way unless some important part of the circuit, such as a switch or meter, is connected between the individual cells.

current can be forced through the device by a single cell, and the device will not operate. A single dry cell has an E.M.F. of only 1.5 volts. Experiment 10, which shows the effect on the current of increasing the E.M.F., gives you a method of operating the bell. Two dry cells are connected so that the center post of one cell is connected to the outer post of the other cell, and then wires are run from the remaining posts to the device, as shown in Fig. 23. The E.M.F. of the cells is doubled. Two cells so connected supply 3 volts. (You will see why this is true in Chapter 4.)

A comparison of the ammeter readings when one cell was used with the readings when two cells were used showed you that more current is forced through a given resistance when the E.M.F. is increased. Here then is a solution of the problem of how to get more current flowing in a circuit. If one cell will not operate a device, more cells can be added. Each dry cell that is added can be connected so as to increase the E.M.F. by 1.5 volts. Increasing the E.M.F. in a circuit that has a given resistance thus increases the amount of current flowing in the circuit.

This relation between pressure, rate of flow, and resistance can also be shown by an analogy, such as the one illustrated in Figure 24. The tank in each picture represents a source of electrical energy, and pipes 1 and 2 correspond to conductors. Containers A and B are capable of holding equal amounts of water and are a means of comparing the rate of flow through pipes 1 and 2.

Temperature and resistance: The resistance of many materials also varies with changes in temperature. As the temperature rises, the resistance of most ordinary metals increases. For example, the tungsten filament in a light bulb may have a resistance of 20 ohms when cold, but when the current is turned on and the filament becomes hot, the resistance increases to about 400 ohms. As the temperature falls, the resistance of most ordinary metals decreases—a fact that needs to be taken into account when designing electrical apparatus for use in airplanes that are to be flown at high altitudes, where it is very cold. Certain other substances, such as carbon, glass, and porcelain, act in just the opposite way. Their resistance decreases with a rise in temperature and increases with a fall in temperature.

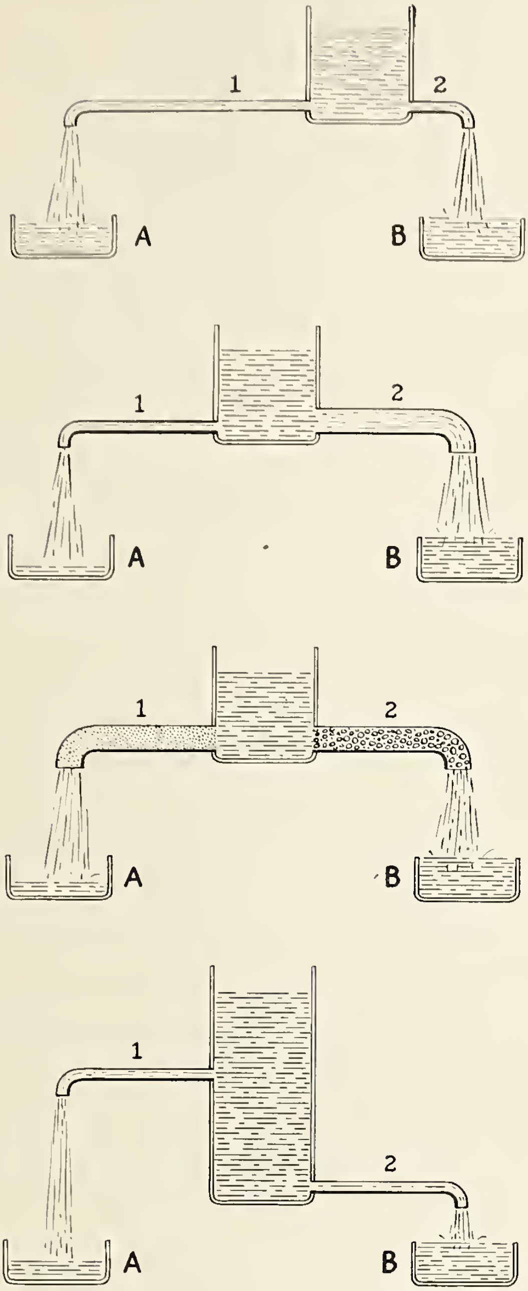


Figure 24. *The first picture shows water flowing through two pipes of the same size, or cross section, but of different lengths. The water meets with less opposition in passing through short pipe 2 than through the longer pipe 1 of the same diameter. Thus, container B becomes full first.*

The second picture shows water flowing through two pipes of equal length but of different diameters. Container B becomes full first because pipe 1 offers more resistance to the flow than pipe 2.

The third picture shows water flowing through two pipes of equal length and cross-sectional area. But pipe 1 is filled with fine sand, while pipe 2 is filled with pebbles. The water meets with more opposition in flowing through pipe 1 than in flowing through pipe 2. Hence, container B becomes full first.

In the fourth picture the two pipes are of equal length and cross-sectional area, but the pressure of the water in pipe 1 is half that of the water in pipe 2. Hence, container B becomes full first, since the greater pressure causes more water to flow through pipe 2 than through pipe 1 in the same length of time.

In this way they correspond to ammeters in an electrical circuit. If we then let gravity represent electromotive force, difference in height corresponds to difference in potential.

In the first picture of Figure 24 we see how the length of a conductor affects the rate of flow. With the same pressure (E.M.F.) less current flows in a long conductor than in a short one of the same size, or cross section because the longer one offers more resistance. In other words, the rate of flow (number of amperes of current that pass through the conductor) is less at A than at B.

The second picture shows how the size of a conductor affects the rate of flow. With the same E.M.F. less current flows through a conductor of small cross section than through one of larger cross section. In other words, the rate of flow (number of amperes) is less at A than at B.

The third picture shows how the kind of material affects the rate of flow. With the same E.M.F. and with conductors of the same length and cross section, less current passes through a material, such as tungsten, which offers considerable opposition to the flow, than through a material, such as copper, which offers less opposition to the flow. In other words, the rate of flow (number of amperes) is less at A than at B.

The fourth picture shows the effect of pressure on the rate of flow. With conductors of the same length, cross-sectional area, and material, less current flows at a certain E.M.F. than it does at twice this E.M.F. In other words, the rate of flow (number of amperes) is less at A than at B.

CHECKING WHAT YOU LEARNED

1. What is meant by resistance in a circuit?
2. List the three main things on which the resistance of a conductor depends. After each one tell what effect changing it has on current flow.
3. If you want to send a larger current through a circuit, there are two different things you can do. Tell what they are, and after each one explain why it will increase the flow of current. Which is the more practical method of increasing the flow of current through a small device?
4. What reason do scientists give in explaining why some materials are better conductors than others?
5. Why is an ammeter used in Experiments 9 and 10?

USING WHAT YOU LEARNED

1. Silver is a better conductor than copper or aluminum, and iron is much cheaper than copper or aluminum. Why do you think that copper or aluminum wires instead of silver or iron wires are used in most electrical wiring and transmission lines?
2. Refer to the table on page 43. **a.** How does the resistance of 10 feet of No. 24 copper wire compare with that of 100 feet of No. 12 aluminum wire? **b.** With that of 50 feet of No. 12 tungsten wire?
3. Again refer to the table on page 43. **a.** About how many times as great is the resistance of one foot of No. 18 copper wire as that of the same length of No. 12 copper wire? **b.** Compare the resistances of one-foot lengths of No. 18 and No. 24 copper wire and also of No. 24 and No. 30 copper wire. What do you find?

Ohm's Law

Experiment 9 showed you how the current in a circuit varied as you changed the resistance of the circuit in any one of three ways: by changing the length of a conductor, by substituting conductors of different cross section, and by substituting conductors of different materials. Experiment 10 showed you how the current in a circuit increased when the electromotive force was doubled. A simplified diagram of the circuit you used in Experiments 9 and 10 is shown in Figure 25. You can see that this circuit contains a cell, a resistance, and an ammeter to show the amount of current flowing. And you already know that any change in either the amount of electromotive force or the resistance will cause the ammeter to indicate a change in the amount of current flow.

Suppose we begin by assuming that the cell in this circuit furnishes an electromotive force of 1 volt and that the resistance of the whole circuit is 1 ohm. Under these conditions the ammeter will indicate a current of 1 ampere. Now without changing the electromotive force, let us change the resistance of the circuit. If the resistance is increased to 2 ohms, the ammeter will indicate a current of .5 ampere. If the resistance is decreased to .5 ohm, the ammeter will indicate a current of 2 amperes. In other words, with a constant E.M.F. the rate of current flow is cut in half when the resistance of the circuit is doubled, and doubled when the resistance is cut in half.

Now let us keep the resistance of the circuit at 1 ohm and change the electromotive force. If the E.M.F. is increased to 2 volts, the ammeter will indicate a current of 2 amperes. If the E.M.F. is decreased to .5 volt, the ammeter will indicate a current of .5 ampere. In other words, when the resistance of the circuit remains constant, doubling the E.M.F. doubles the rate of current flow, and halving the E.M.F. cuts in half the rate of current flow.

So long as we are working with amperes, volts, and ohms this relationship between rate of current flow, pressure (E.M.F.), and resistance holds

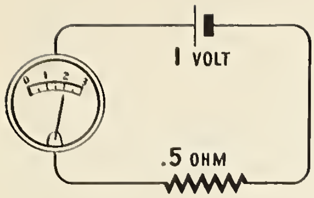
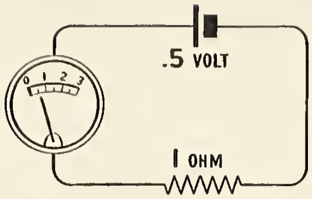
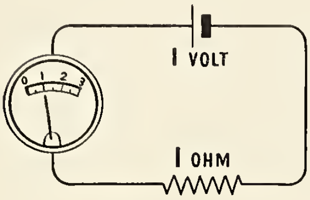


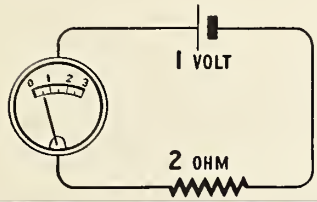
Figure 25 *shows the relationship between volts, ohms, and amperes in a circuit. The ammeter indicates the current with different voltages and resistances.*



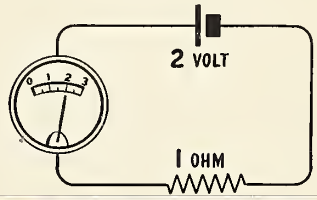
These two diagrams show how the current varies as the resistance is cut in half (as above) or doubled (as below).



These two diagrams show how the current varies as the voltage is cut in half (as above) or doubled (as below).



Above is shown the basic relationship that exists between the three units: volt, ohm, and ampere.



good. In every case, the rate of current flow (in amperes) is equal to the pressure (in volts) divided by the resistance (in ohms).

This is usually expressed as a formula: $I = \frac{E}{R}$ in which **I** stands for the **I**ntensity of the current flow in amperes, **E** stands for the **E**lectromotive force in volts, and **R** stands for the **R**esistance in ohms.

This formula is a statement of **Ohm's Law**. As you have seen, there is nothing particularly mysterious about it. Georg Simon Ohm, whose name is given to the unit of resistance, discovered that there is a definite relationship between the current, the pressure, and the resistance in a circuit. This relationship is stated in the law which bears his name.

You will find Ohm's Law so useful in using what you learn about electricity, that you should know how to use this formula in all its forms. You have already seen that to find the current in amperes, you divide the pressure in volts by the resistance in ohms. Now you will see how to find the resistance or the pressure when you know two of the other elements in the formula.

For example, in Experiment 9 the dry cell supplied an electromotive force of 1.5 volts. Let us say that, with the wire from the outside post of the dry cell touching nail 2 (see Fig. 22), the ammeter indicated a current of 2 amperes in the circuit. You want to know the resistance of this circuit, but the formula you have learned is for finding the current. Let us adapt our formula, then, to this problem.

Starting with the original formula $I = \frac{E}{R}$

we can multiply by R and cancel: $IR = \frac{ER}{R}$ or $IR = E$

We can divide this by I and cancel: $\frac{IR}{I} = \frac{E}{I}$ or $R = \frac{E}{I}$

We can use this last formula for finding the resistance by substituting the values we know.

Then $R = \frac{1.5}{2} = 1.5 \div 2$ or $R = .75$ ohm

These formulas are simply convenient ways to state the relationship between current, pressure, and resistance in an electric circuit. The formula you just used shows that resistance is simply the ratio of the voltage to the current. To find the

Ohm's Law: The current (in amperes) flowing in any circuit is equal to the pressure (in volts) divided by the resistance (in ohms). This relationship is expressed in three formulas: $I = \frac{E}{R}$ $R = \frac{E}{I}$ $E = IR$

In these formulas, **I** stands for the **I**ntensity of the current flow in amperes, **E** stands for the **E**lectromotive force in volts, and **R** stands for the **R**esistance in ohms. The values of these units of measurement is such that an electromotive force of 1 volt causes a current of 1 ampere to flow through a resistance of 1 ohm.

Resistance: The opposition to the flow of current. It is measured by the ratio of voltage to amperage. Thus, in the Ohm's Law formula $R = \frac{E}{I}$ the resistance in ohms is equal to the E.M.F. in volts divided by the current in amperes.

resistance in ohms, then, you divide the E.M.F. in volts by the current in amperes.

Now let us suppose that the resistance of the whole circuit is doubled. Instead of a resistance of .75 ohm, the circuit now has a resistance of 1.5 ohms. You want to know how much pressure is needed to send a current of 2 amperes through this circuit. In developing the formula for finding resistance, you obtained a formula that gave you

$$IR = E \text{ or } E = IR$$

By substituting the values you already know, you get

$$E = 2 \times 1.5 \text{ or } E = 3 \text{ volts}$$

This is the third way of stating the relationship between current, pressure, and resistance in an electric circuit. When you know the current in amperes and the resistance in ohms, use this formula to find the E.M.F. in volts. Or, to find the pressure, or E.M.F., in volts, multiply the current in amperes by the resistance in ohms.

These three formulas are so useful in applying Ohm's Law to many practical problems in electricity that you will find it well worth your while to memorize these formulas and be able to use them readily. For example, let us see how these formulas can be applied to a practical situation involving a house-wiring circuit.

We want to install an electrical outlet in the garage, which is 125 feet from our house. Since two wires are required for this circuit, we know that we will need 2 x 125 feet, or 250 feet, of copper wire; and because this much copper wire is rather expensive, we want to use the smallest size that will safely carry the current we need.

Let us assume that we plan to use the garage as a workshop occasionally, and that we have a motor which requires 8 amperes. Allowing 2 amperes more for electric lamps, we decide that the maximum current we will ever need is 10 amperes. From the instructions that came with the motor we learn that for efficient operation the electromotive force should not drop below 104 volts. Knowing that the voltage at the meter in the house is 110, we subtract 104 from 110 and discover that we can allow 6 volts for overcoming the resistance of the 250 feet of wire in this circuit.

Our next step is to figure the resistance of the wires in the circuit. You can see that this problem is equivalent to finding the resistance in ohms of a circuit in which an E.M.F. of 6 volts will cause a current flow of 10 amperes. To solve the problem, we use Ohm's Law, which applies not only to an entire circuit but also to any part of a circuit. Knowing the values of E and I, we use the formula:

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

Substituting the two values known:

$$R = \frac{6}{10} \text{ or } .6 \text{ ohm}$$

We now know that the resistance of the wires between the house and the garage should not exceed .6 ohm. Since we want to know the resistance in ohms per foot in order to use a wire table (similar to the one on page 43 but more complete), we divide .6 ohm by 250 feet and find that the wire should have a resistance of about .0024

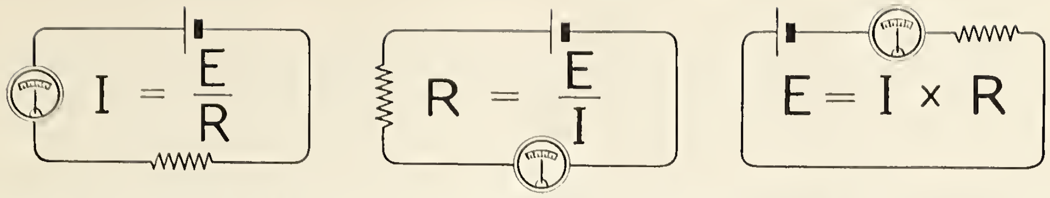
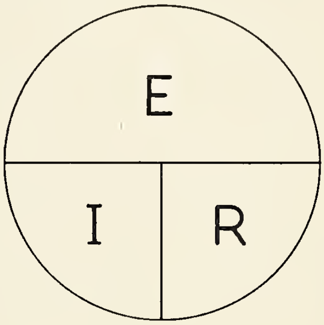


Figure 26 *shows the three ways in which Ohm's Law is usually expressed in formulas. The diagrams make use of symbols you know to help you remember that* **I** = **I***ntensity of the current flow in amperes, that* **E** = **E***lectromotive force in volts, that* **R** = **R***esistance in ohms. When you know the values for any two of these letters, you can find the value for the third by using the proper formula. The diagram at the left shows that the current in amperes is equal to the voltage divided by the resistance in ohms. The middle diagram shows that the resistance in ohms is equal to the voltage divided by the current in amperes. And the diagram at the right shows that the voltage is equal to the current in amperes times the resistance in ohms.*

After you have learned to use these formulas, you will find the circular diagram at the right very helpful in deciding which formula is needed. Simply cover the letter representing the value sought, and the uncovered letters will show you how to find this value. For example, if you cover the letter **E**, *you can see that you must multiply* **I** *by* **R** *to find the voltage. If you cover* **R**, *you can see that you must divide* **E** *by* **I** *to find the resistance in ohms. And if you cover* **I**, *you can see that you must divide* **E** *by* **R** *to find the current in amperes.*



ohm per foot. Consulting the wire table, we see that No. 14 copper wire has a resistance of .0025 ohm per foot and decide this is close enough.

It then occurs to us that in cold weather we will probably need an electric heater in our workshop, and we wonder what will happen to the voltage at the garage outlet when we add 5 amperes more for the heater. Again we make use of Ohm's Law. Since we know that I (the total current needed) is 10 + 5, or 15, amperes and that R (resistance of the wires) is 250 × .0025, or .625, ohm, we use the formula: $E = IR$

Substituting the two values known:

$$E = 15 \times .625 = 9.375 = 9.4 \text{ volts}$$

Subtracting 9.4 volts from 110 leaves only 100.6 volts available at the garage outlet when a current flow of 15 amperes is needed. This will not be satisfactory, since we must have at least 104 volts for the motor. So we decide that No. 14 copper wire is too small and wonder if No. 12 will be adequate. Looking again at the wire table, we see that No. 12 copper wire has a resistance of .0016 ohm per foot. Multiplying this by 250 feet, we find that with No. 12 wire the resistance of the wires between the house and the garage will be .4 ohm. We now want to know how much current will be available at the garage outlet if we allow 6 volts for overcoming the .4 ohm resistance of the wires. Since we know the values for E and R, we use the Ohm's Law formula: $I = \frac{E}{R}$

Substituting the two values known:

$$I = \frac{6}{.4} \text{ or } 15 \text{ amperes}$$

Thus we see that No. 12 wire will be worth the extra cost, since it will provide the 15 amperes of current we need for motor, heater, and lamps without causing the voltage to drop below the 104 volts we need for the motor.

Sizes of conductors. Besides showing how the Ohm's Law formulas can be applied to a prac-

Voltage drop: The difference in voltage between two points in a circuit through which a current flows. The voltage drop is equal to the current in amperes multiplied by the resistance in ohms between the two points. Also called **drop in potential.**

tical situation, this example has explained one reason why wires of different sizes are used in electrical circuits. You know that every conductor offers opposition to the flow of an electric current. You also know that this resistance is determined by the length, the cross-sectional area, and the material of which the conductor is made. In house-wiring circuits it is customary to consider the large wires at the meter as the source of electrical energy. If we assume that the voltage at the meter is 110, it should be apparent by now that at any other place in a house-wiring circuit the voltage will be 110 *minus* whatever is needed to overcome the resistance of the wires between that place and the meter. This difference in voltage between a source of electrical energy and a device using electric current is called the **voltage drop**, or **drop in potential.** Since by Ohm's Law $E = IR$, you can see that the voltage drop is equal to the current in amperes times the resistance of the connecting wires in ohms.

An important thing to remember is that there will be *some* voltage drop between *any* two points on any conductor in any circuit in which a current is flowing.

Most electrical devices operate at reasonable efficiency if the voltage drop does not exceed 5 per cent of the voltage for which they are designed. In a 110-volt circuit this is equivalent to a drop of 5.5 volts. It was for this reason we needed 104 volts at the garage outlet in the preceding example. For reasons that will be explained in a later section of this chapter, safety regulations in most localities require the use of copper wire no smaller than No. 14 in house-wiring circuits. Whether larger wire is needed usually depends, as in the house-to-garage circuit in the example, on the length of the wires, the current needed, and the allowable voltage drop. And as you have seen, Ohm's Law can be used with a wire table to solve problems of this kind. However, two facts must be kept in mind when you are using Ohm's Law for this purpose. Remember that **E** in this case is the voltage drop, or the *difference* between the voltage at the source and the voltage at the device. Remember, too, that **R** is the resistance in ohms of *both* wires connecting the source and the device, since a device 50 feet from the source obviously requires at least 100 feet of wire.

CHECKING WHAT YOU LEARNED

1. **a.** What happens to the current in a circuit when the resistance is increased without changing the voltage? **b.** When the voltage is increased without changing the resistance? **c.** Explain your answers.
2. If the voltage in a circuit is increased, what is the effect on the resistance? Why?
3. **a.** State Ohm's Law in words. **b.** Give the three formulas based on Ohm's Law. **c.** In order to solve problems with these formulas, what things must you know for each one?
4. **a.** What is meant by voltage drop in a circuit? **b.** To find the voltage drop in a circuit, what things must you know? **c.** How can you find the voltage at a device connected in a circuit?

USING WHAT YOU LEARNED

1. **a.** Why is the voltage at a device lower than at the source of electrical energy? **b.** What

Measurement of resistance is usually done in one of three ways: (1) by using an ammeter to measure the current and a voltmeter to measure the voltage; (2) by using a special meter, called an ohmmeter; (3) by using the Wheatstone bridge to compare the unknown resistance with resistances already measured. These methods will be discussed in greater detail in Chapter 11.

happens to the voltage that is "lost" between the source and the device?

2. How much current will a 6-volt battery send through a circuit whose resistance is 30 ohms? .3 ohm? 300 ohms?
3. At a pressure of 110 volts a current of 5 amperes flows through a circuit. What is the resistance of the circuit?
4. **a.** In a circuit of 50 ohms resistance a current of 4.4 amperes is flowing. What is the E.M.F. at the source of electrical energy? **b.** If the E.M.F. is reduced by half, how much current will flow in the circuit? **c.** What will be the resistance of the circuit when this current is flowing?
5. A motor uses 2.2 amperes of current at 110 volts. What is the resistance of the motor?
6. **a.** How much pressure is needed to send .04 ampere of current through a telegraph circuit with a resistance of 250 ohms? **b.** If the voltage is increased by 25 per cent, how much current will flow through the circuit?
7. The voltage at the meter in a house-wiring circuit may vary as much as 5 volts from the average of 110 volts. If the resistance of the entire circuit is 5 ohms, what is the difference between the largest currents that will flow at the lowest and highest voltages?

Controlling Current by Resistance

You have seen in Experiments 9 and 10 how changes in the resistance of a circuit cause the current flowing in that circuit to vary. This fact is extremely useful when we want to control the current used by a lamp or motor. It is easier, for instance, to vary the brilliance of a lamp or the speed of a motor by sliding a conductor along a bare wire than by connecting and disconnecting cells. But a ten-foot board with two nails and a resistance wire is not a very convenient device, particularly when you must hold the sliding copper wire in place all the time. What we need is a device that is compact, easily adjusted, and steady enough to hold an adjustment. The **rheostat** is such a device, as you can see by performing Experiment 11.

You already know that the longer a wire is, the greater is the resistance it offers. This fact is used in constructing a rheostat. Wire with a high resistance is wound around some insulating material, such as porcelain, in order to form a coil. If wire is coated with enamel to insulate the turns of the coil from one another, then a narrow space from one end of the coil to the other is scraped off. This is to allow a metal slider to make contact with the turns of wire. The slider moves on a metal bar. One connection is made to the bar; the other, to one end of the resistance coil. (See Figs. 27 and 28 on page 52.)

By moving the slider along the bar, the amount of wire through which the current must pass can be increased or decreased. In this way the amount of resistance in the circuit can be increased or decreased. The rheostat, then, is simply a convenient device for varying the resistance in a circuit and thus regulating the current. Experiment 11, parts **a** and **b**, shows that the rheostat does control the current flow.

You have already seen that varying the resistance of a circuit will vary the current flowing through the circuit. In accordance with Ohm's Law, when the resistance is increased, the current will decrease; and when the resistance is decreased, the current will increase. But why does this happen? You know that a current will not flow unless there is an E.M.F. driving it through the circuit. When you increase the resistance, the E.M.F. must overcome more opposition in order to make a current flow through the circuit. Less current will flow, because some of the E.M.F. is used up in overcoming the extra resistance to current flow. If a *voltmeter,* an instrument for measuring electrical pressure (E.M.F.) in volts, is available, you can easily show that this is true by doing parts **c** and **d** of Experiment 11.

When the voltmeter is connected to the cells (see the instructions for part **c** of Experiment 11), it shows a reading of about 3 volts. This is the voltage available to drive the current through the circuit. In part **c** of the experiment you connect a voltmeter to the terminals of a rheostat. When a voltmeter is connected in this way (see Fig. 29), it is said to be connected *across* the device. As the movable contact slides along the coil in this experiment, you notice that the light given off by the lamp changes. You also notice that the voltmeter reading changes with the change in the light. When the lamp is bright, the voltmeter reads 0 or very nearly so. When the lamp is dim, the voltmeter reading is higher.

Rheostat: A device used to control the current in a circuit by varying the resistance of the circuit. It is usually made so that moving a knob or handle changes the length of wire included in the circuit.

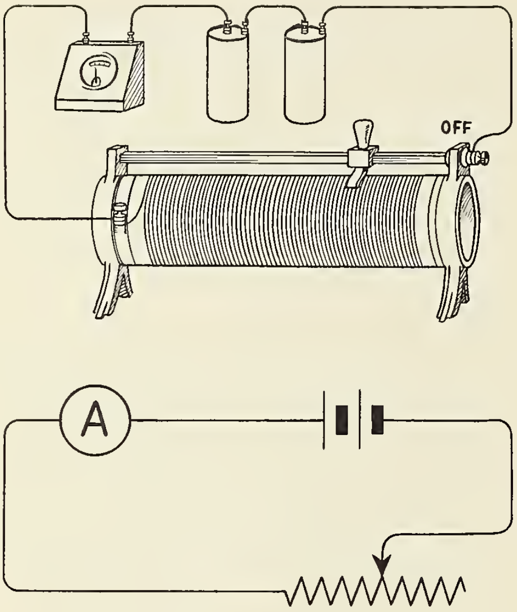


Figure 27. *The upper picture shows a circuit consisting of two dry cells connected together, an ammeter, and a rheostat. If you trace the path of the current through this circuit, you will see that the circuit becomes shorter as the sliding contact on the rheostat is moved toward the left. (Caution: Move the sliding contact back to the* OFF *position if the rheostat wire becomes hot.)*

The lower picture shows a diagram of this circuit. Note particularly the symbol generally used to represent a rheostat in diagrams of electrical circuits. As you already know, a zigzag line indicates resistance to current flow, and an arrow indicates a variable control.

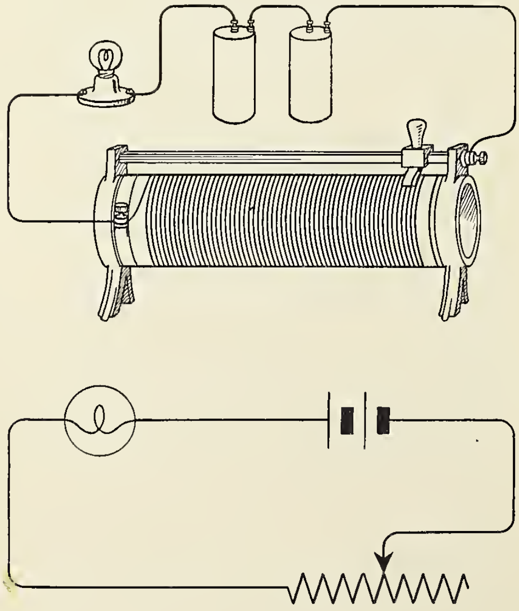
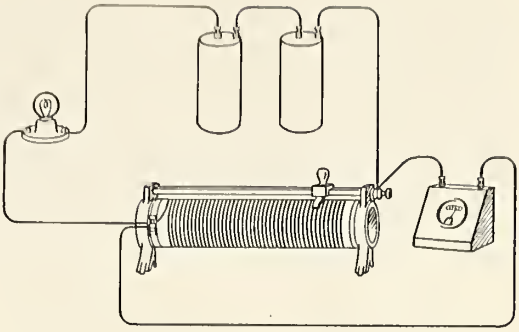


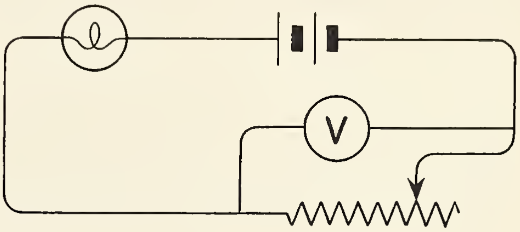
Figure 28. *The upper picture shows a circuit consisting of two dry cells connected together, a small socket containing a 3-volt flashlight bulb, and a rheostat. As the sliding contact on the rheostat is moved toward the left, the bulb becomes brighter, showing that as the circuit through the rheostat is shortened, more current can flow through the bulb. A rheostat used in this way is sometimes called a "dimmer."*

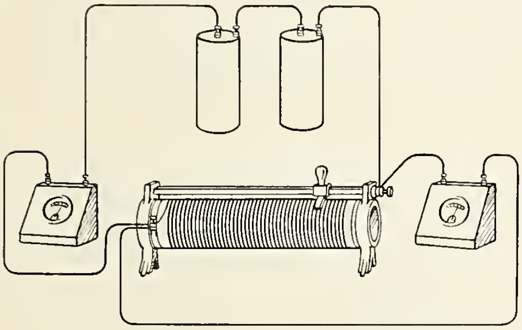
The lower picture shows a diagram of this circuit. Note the symbol used to represent a lamp bulb as a device for changing electrical energy into light. When the lamp bulb is used merely as a resistance in a circuit, the symbol sometimes shows a zigzag line instead of a loop.

Figure 29. The upper picture at the right shows a circuit consisting of two dry cells connected together, a small socket containing a 3-volt flashlight bulb, a rheostat, and a voltmeter. Note particularly that in this circuit the wires from the voltmeter are connected to the terminals of the rheostat.

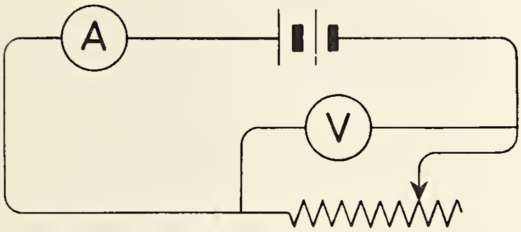


The lower picture at the right shows a diagram of the circuit above. Note the symbol used to represent a voltmeter in diagrams of electrical circuits.





The upper picture at the left shows the same circuit as the picture at the top, except that an ammeter has been substituted for the small socket containing the flashlight bulb. (Caution: Move the sliding contact back to the OFF *position if the rheostat wire becomes hot.)*



The lower picture shows a diagram of the circuit above. Note that the symbols for the meters have the letters "A" and "V" to tell what kinds of meter are being used.

Now let us see if we can explain what happens. First, what does the voltmeter measure? The voltmeter shows the difference in electrical pressure (voltage) between the two points where the voltmeter is connected. If the voltmeter reads 2 volts, this means that there is a difference of 2 volts between the two points. There is this difference because 2 volts of the 3 volts at the source have been used to force the current through the resistance between the two points where the voltmeter is attached. There is only 1 volt left to force the current through the lamp. If the sliding contact of the rheostat is moved so that the voltmeter reads only 1 volt, only 1 volt is being used to drive the current through the rheostat. This leaves 2 volts to force current through the lamp. The

Resistor: A device used to reduce the current by adding resistance to the circuit.
Variable resistor: A resistor with a movable contact to vary the amount of resistance added to the circuit. It is also called a **variable resistance.** A rheostat is a variable resistor.
Fixed resistor: A resistor without a movable contact or other means of varying its resistance. It is also called a **fixed resistance.**
Tapped resistor: A fixed resistor with three or more terminals so arranged that all or part of the resistance may be used. It is also called a **tapped resistance.**

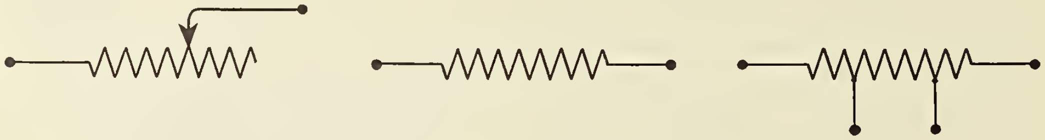


Figure 30 *shows the symbols generally used in diagrams of electrical circuits to represent resistors of various kinds. At the left is shown the symbol used for a variable resistor, such as a rheostat. The middle picture shows the symbol used for a fixed resistor, while at the right is shown the symbol used for a tapped resistor. The symbol for a fixed resistor is also used to represent the resistance of any electrical device in a circuit and, sometimes, to represent the total resistance of the conductors and devices connected to a source of electrical energy.*

brightness of the lamp will increase because more current is forced through the lamp.

A voltmeter measures the difference in electrical pressure or voltage between two points. In this way, it measures the voltage drop (the volts used) through the device across which it is connected.

The decrease in voltage caused by the opposition to current flow of the extra resistance in the circuit is equal to the voltage drop through the resistance. If you know how many amperes of current are flowing through the circuit and how many ohms of resistance are added by the rheostat, you can find the voltage drop without using a voltmeter. Using the Ohm's Law formula, $E = IR$ to do this, you multiply the current in amperes by the resistance in ohms. By now you can see that varying the resistance of a circuit varies the voltage available for driving current through a device connected in the circuit. In other words, a resistance causing a voltage drop at some point in a circuit reduces the current used by a device in that circuit. A rheostat (or any other resistance) connected in a circuit controls the voltage available at a device as well as the current flowing through it. In fact, the current in the whole circuit is actually controlled by varying the resistance.

The dimmers used to control theater lights are usually nothing more than large rheostats, one in each circuit. The speed control on small motors, such as those used in electric fans, windshield wipers, and mixing machines, is often a rheostat. Some rheostats, such as those used to control the speed of streetcar and factory motors, do not have a contact that slides along the wire. Instead, the movable contact slides across metal plates or disks, each of which is connected by a wire to some point along the resistance wire. Such an arrangement not only permits large currents to be handled, but also permits the movable knob or handle to be placed at a distance from the actual resistance wire.

A device used to reduce the current in a circuit by adding resistance to the circuit is often called a **resistor.** A rheostat, for example, is sometimes called a **variable resistor,** or a **variable resistance.**

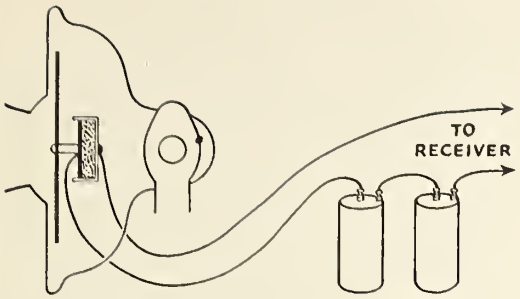
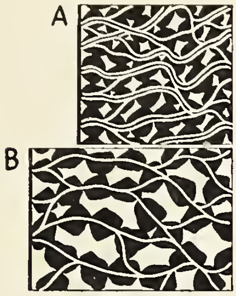


Figure 31 *shows another kind of variable resistance—the small cup, or "button," fastened to the diaphragm of a telephone transmitter. The cup contains granules of carbon so arranged that sound waves striking the diaphragm cause the resistance of the granules to vary, thus varying the current flowing through the circuit to a telephone receiver.*



At the left are two diagrams showing the carbon granules greatly enlarged. White lines represent the paths of the current. In diagram A the carbon granules are pushed together by pressure of a sound wave on the diaphragm, allowing more current to flow through the circuit. In diagram B less current is flowing because the diaphragm has moved back and there are fewer paths.

A coil of resistance wire without the movable contact that a rheostat has is often called a **fixed resistor,** or a **fixed resistance.** A fixed resistor with three or more terminals so arranged that all or part of the resistance may be used is often called a **tapped resistor,** or a **tapped resistance.**

Selecting resistors. Just which form of resistor you use in any particular case depends upon the kind of control you need. For instance, you have an electric fan that uses, let us say, 2 amperes at 110 volts. It has no speed control, and you want to add one that will reduce the current to 1 ampere. Using Ohm's Law, you can find the resistance of the motor, since you know the voltage and the amperage. Thus, $R = \frac{E}{I}$

Substituting the two values known:

$$R = \frac{110}{2} \text{ or } R = 55 \text{ ohms}$$

You know that if you double the resistance of a circuit, you cut the amperage in half when the voltage of the source remains constant. So you add a variable resistor having a maximum resistance of 60 ohms. After trying the fan at different settings of the rheostat for some time, you decide that the best speed is the one you get with about half of the rheostat's resistance in the circuit, though once in a while you prefer to use all the resistance in the circuit for a very slow speed. The rheostat is inconvenient when you move the fan, and you seldom use more than one or two settings. You can, then, do one of two things: Use a fixed resistor of 30 ohms resistance so that the fan always runs at the best speed for your purpose; or use a tapped resistor of 60 ohms resistance, with a connection at 30 ohms, which would give you the best speed and also the very slow speed by switching from one connection to the other.

Other resistors. Another way of controlling current by resistance is similar to that used in the *transmitter* of a telephone. In Figure 31 at the top of the page, the diaphragm is connected to a cup, or "button," containing very small granules of carbon, whose resistance varies according to the pressure of the diaphragm on them. As the pressure is increased, the resistance of the carbon granules decreases because the granules are packed more closely. Sound waves striking the diaphragm cause it to move in and out. The motion of the diaphragm varies the resistance of the granules. The variations in resistance cause variations in the current flowing through the transmitter. How these variations in current are used to produce sound waves in the receiver at the other end of the circuit will be explained in Chapter 6.

While most variable resistors work on the principle of changing the length of the circuit, there are two other types that you may be interested in knowing about. One of these, the *carbon rheostat* works on much the same principle as the telephone transmitter—that is, by varying the pressure on pieces of carbon. Instead of carbon granules, disks or plates of carbon are stacked together with their flat sides touching. An adjusting screw controls the pressure with which the flat sides are forced together. The greater the pressure, the better the contact between the pieces and the less the resistance. Another type of variable resistor sometimes used in laboratories and workshops is the *water rheostat.* Two strips of metal are put in a jar of water to which a small amount of salt has been added. As long as the metal strips do not touch each other, the current must flow through the salt solution, which offers considerable opposition to the flow of current and so increases the resistance of the circuit. In the water rheostat, the amount of resistance is controlled by the area of the metal strips actually in the solution, the distance separating the metal strips, and the amount of salt in the solution. If you wish, you can make a water rheostat (Experiment 12) and use it in place of the rheostat that is shown in Figure 29 to vary the brilliance of the small light bulb.

CHECKING WHAT YOU LEARNED

1. **a.** What is a rheostat? **b.** How is a rheostat connected in a circuit? Why?
2. **a.** Tell what happens in a circuit when you change the adjustment of a rheostat. **b.** Explain why this happens.
3. **a.** What is meant by a resistor? **b.** What different kinds of resistors are there? **c.** Describe each kind and tell why that particular kind is used in a circuit. **d.** What kind of resistor is a rheostat?
4. Tell what happens in a telephone transmitter when you talk into the mouthpiece.
5. Name two kinds of rheostats that are different from the wire kind and tell how each works.

USING WHAT YOU LEARNED

1. Why is *resistor* a better word than *resistance* to use for a device used to control the current in a circuit?
2. At a pressure of 6 volts, 1.5 amperes of current flow in a circuit before a rheostat is included. **a.** What resistance must the rheostat have in order to reduce the current to 1 ampere? **b.** What is the voltage drop through the rheostat?
3. A motor is designed to operate at a certain speed, using 2.5 amperes at 110 volts. **a.** In order to operate the motor at the proper voltage on an 115-volt circuit, how much resistance must be added to the circuit? **b.** How much more current will flow through the motor if the voltage is not reduced?
4. **a.** To reduce the current in a circuit by one half, a 7.5-ohm resistor must be added. What is the resistance of the circuit before adding the resistor? **b.** After adding it? **c.** How much will the voltage available at a device be reduced by including the resistor in the circuit?
5. **a.** A current of .4 ampere flows through a circuit that includes all of a 25-ohm rheostat. What is the voltage drop through the rheostat? **b.** If the rheostat reduces the current by one third, what is the voltage at the source? **c.** What is the resistance of the circuit without the rheostat?
6. Is there a potential difference between the terminals of any resistance connected in a circuit? How do you know?
7. How could you use a voltmeter and ammeter to find the resistance of a device in a circuit? Draw a diagram (using symbols) to illustrate your answer.
8. Draw a wiring diagram showing four dry cells connected to furnish current at 6 volts to a light bulb and include a variable resistor in the circuit. Connect a voltmeter in the circuit to measure the voltage drop across the resistor.
9. Plan an experiment to show that varying the E.M.F. and the current in a circuit will not change the resistance of the circuit (providing that the temperature of the conductors is not changed). Draw a wiring diagram to show how you would connect the circuit.

Heating element: The part of a heating device that changes electrical energy into heat energy. The wire in a heating element is usually made of nichrome or some other material that has a high resistance and yet will not melt or burn when red-hot.

Heating Effect of Current

As you have seen in the experiments in this chapter, a current meets with resistance when it flows through a circuit. This resistance to current flow, sometimes called *electrical friction*, results in heat, just as ordinary friction does.

As you know, we make good use of the fact that current produces heat when it flows through a circuit. Electric irons, toasters, stoves, and heaters are devices that change electrical energy into heat energy. Suppose we see how some of them work.

You know that each of these devices contains wire that becomes red-hot when it is connected to the house circuit. You have seen these red-hot coils or ribbons of wire in toasters and heaters. And if you have ever taken apart an electric iron, you probably discovered that it contained the same kind of wire as that which becomes red-hot in toasters and heaters. Why does this wire become red-hot, while the wires that lead to the device do not?

First you must realize that any conductor will become hot if the current flow is sufficiently large. As you did Experiments 9 and 10, you may have noticed that the smaller wire stretched between the nails became warm and then hot as you moved the end of the long wire toward the nail near the ammeter. A simple but striking way of demonstrating the heating effect of an electric current is shown in Experiment 13. This experiment shows that a great deal of heat is produced when the current from a dry cell is sent through a fine copper wire. The fine copper wire quickly becomes red-hot, then white-hot, and finally melts.

The current flow in this case was large enough to cause a short piece of fine copper wire to become so hot that it melted. This is not surprising when you learn that the heat produced in a conductor increases as the square of the current. That is, when the current doubles, the heat increases four times. Yet many strands of this same wire, twisted together so that each carries only a part of the current, will not become hot when they carry a current large enough to cause the coils or ribbons of wire in a heating device to become red-hot. Thus the size, or cross-sectional area, of a conductor must have something to do with whether or not it becomes hot when a certain current flows through it. Actually, every wire that carries a current is heated. But when the wires are large and are made of a good conducting material, so little heat is produced that it cannot be noticed. The heat escapes as fast as it is produced.

The coils and ribbons of wire that become red-hot in a heating device are really nothing more than a resistor so made that it can become very hot without the wire melting. It is not called a resistor, because it is not used to control the current flow in a circuit. Instead it is called a **heating element.** (In Experiment 14 you can examine the heating elements and other parts of various heating devices.)

Copper wire is unsuitable for use in heating elements. You have seen, in Experiment 13, how quickly the fine copper wire melted when a large current flowed through it. Furthermore, copper wire is such a good conductor that many, many feet of it would be needed to furnish enough resistance, or electrical friction, to change large amounts of electrical energy into heat energy. In fact, over 2000 feet of No. 20 copper wire would be needed for an electric iron using 5 amperes of current! What is needed, then, is wire that will become red-hot without melting or burning, and at the same time have a high resistance so that a reasonable length of fairly large wire will provide the necessary electrical friction.

Such wire has been developed for use in heating elements. One variety, nichrome, is an alloy, or mixture, of nickel and chromium. It does not melt or burn when red-hot; and having about 80 times the resistance of copper, a reasonable length of fairly large wire provides sufficient resistance to change large amounts of electrical energy into heat energy. The amount of electrical energy changed to heat energy in one second by a heating element (or any other resistance) can be measured. Heat is often measured in *calories*, and experiments in laboratories have shown that the number of calories of heat obtained per second is equal to .24 multiplied by the square of the current, multiplied by the resistance in ohms. This formula is written $H = .24\ I^2R$

Light from electrical energy. The ordinary electric light bulb is a heating device, too, as anyone knows who has ever tried to unscrew a lighted one. Of course, we do not want heat from it, but it gives light only because a wire inside is hot enough to glow. The bulb operates in the same way as heating devices like the toaster. Each light bulb contains a wire that becomes white-hot, or *incandescent*, when current flows through it. The wire must have enough resistance to become white-hot, and, above all, it must have a very high melting point so that it will not melt when white-hot. (If you wish to examine a light bulb, do Experiment 15 and look at Fig. 32.)

In the first successful electric incandescent lamp, Thomas Edison used a thread (*filament*) of carbon instead of a metallic wire. Because carbon burns rather easily, Edison sealed the filament in a glass bulb from which the air had been pumped. Pumping out the air produced a partial *vacuum* in the bulb. Since air could not get to the filament, the carbon could not burn. When the bulb "burned out," as people said, what happened was that some of the carbon had evaporated in the heat, weakening the filament until it snapped.

Today the filaments of our light bulbs are made of tungsten, which has a very high melting point. Very small tungsten wire (about .001 inch in diameter in a 25-watt bulb) is formed into a small, spring-like coil so that each turn of wire helps to keep other turns hot. The bulbs, after having the air pumped out, are filled with a gas (such as argon or nitrogen) that does not readily combine with other substances. Therefore, it does not change the tungsten, and its pressure helps keep the tungsten from evaporating as rapidly as it would in a vacuum. The old carbon filament could be heated to about 3500° F., while the tungsten filament in a modern gas-filled bulb can be heated to about 5100° F. Improvements like these give us about seven times as much light as could be produced with the same amount of current in a carbon-filament bulb. Even so, we receive only about five per cent of the electrical energy in the form of light, the other 95 per cent being changed to heat. Our light bulbs are thus much better "heaters" than "lighters."

Vapor lamps. Another kind of lamp you often see is a slender glass tube that glows with red, white, or bluish-green light. Since the glass tubes may be easily bent into different shapes, lamps of this kind are often used to make electric signs. This type of lamp is called a *neon lamp* because the first kind made, the red ones, actually contained neon gas. These tubular lamps have no filaments; instead, they contain a small amount of gas. A special electrical device sends current through the gas at a pressure of thousands of volts. The moving stream of electrons, striking molecules of gas, causes the electrons in the molecules to vibrate rapidly and give out light. Each different gas gives out its own peculiar color of light. Neon gives an orange-red light, mercury vapor a bluish-green light, and helium a white light. Other gases are used to produce still other colors.

Mercury vapor is also used in special kinds of lamps to change electrical energy into light. You may have seen these lamps in the form of a fairly large glass tube, 3 or 4 feet long, which glows with a peculiar bluish-green light. Because this light contains many ultra-violet rays (very short light rays that are invisible), the tube is sometimes made of quartz, which allows the ultra-violet rays to pass through. The lamp is then used for the treatment of certain diseases, for sterilizing purposes, or as a so-called "sun" lamp. Figure 33 shows the essential parts of a *mercury-vapor bulb* used in one type of sun lamp designed for home use. When the current is turned on, the

---

Measurement of heat: If the amount of heat in calories obtained over a period of time is desired, the formula is $H = .24\ I^2Rt$ (t stands for the number of seconds.)

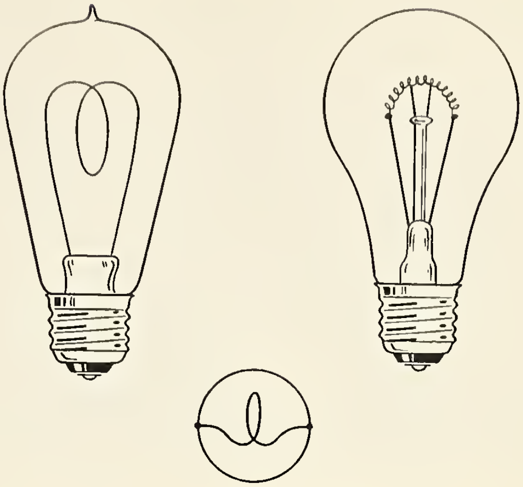


Figure 32 *shows two kinds of electric lamps in which light is produced when a flow of current causes a slender filament to become white-hot, or "incandescent." At the left is shown an older type of incandescent lamp having a carbon filament enclosed in a glass bulb from which most of the air has been removed. It is not very efficient. At the right is shown a modern type of incandescent lamp which has a filament of coiled tungsten wire enclosed in a glass bulb filled with a gas, such as nitrogen or argon. Underneath is shown the symbol often used for an incandescent lamp in diagrams of electrical circuits.*

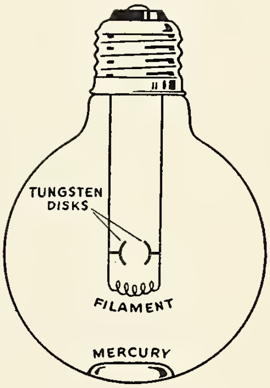


Figure 33 *shows a kind of lamp in which light is produced as an electric current flows through mercury vapor. When the current is turned on, the heat of the small filament changes some of the mercury to vapor. Then current flows through the vapor between the tungsten disks, filling the bulb with a peculiar bluish-green light. Because the resistance of the mercury vapor is less than that of the small filament, almost all the current flows between the disks, and the filament stops glowing. When the current is turned off, the vapor cools and changes back into a liquid. Lamps similar to this are sometimes used as "sun" lamps.*

small filament becomes hot enough to vaporize some of the liquid mercury in the bottom of the bulb. Then, because the mercury vapor offers less opposition to the flow of current than the small filament does, the current flows between the two tungsten disks, and the small filament stops glowing. When the current is turned off, the bulb becomes cool, and the mercury vapor changes back into liquid mercury. The fact that mercury is a liquid at ordinary temperatures makes it necessary for lamps of this kind to have a "starter," or some means of changing the mercury into a vapor so that the lamp will produce light.

Mercury-vapor lamps are much more efficient than filament-type lamps. That is, with the same current they give off more light with less heat than ordinary light bulbs do. But the peculiar bluish-green light makes the mercury-vapor lamp unsuitable for home use except for special purposes, such as a sun lamp. Rather recently, however, a way has been found to use the ultra-violet rays given off by the mercury-vapor lamp to make an efficient lamp for home and office use. While ultra-violet rays are themselves invisible, they cause certain mineral substances to glow, or *fluoresce.* The tubular lamps known as *fluorescent lamps* make use of this fact. The inside of the glass tube is coated with a mineral powder that glows when ultra-violet rays are given off by the flow of current through the mercury vapor contained in the tube. The color of the light given off by a fluorescent lamp depends on the kind of minerals used to

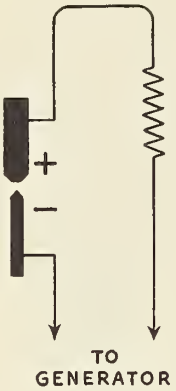
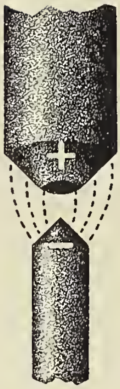


Figure 34. *The diagram at the left shows part of an arc-light circuit. When the carbon rods are touched together and then separated slightly, current flows across the gap, producing a very bright light. The resistor limits the current flow when the rods are touched together.*

The diagram at the right shows the curved path taken by the current. The positive carbon is larger because it is used up faster than the negative one. As current flows, the negative carbon becomes pointed, while the positive one becomes hollowed out slightly at the end.



coat the inside of the tube, and this makes possible an efficient vapor lamp that gives off a white light suitable for home use. Like other mercury-vapor lamps, the fluorescent lamp needs a device, or "starter," to change a small amount of mercury into vapor so that current will flow through the tube. This usually consists of a small filament or heater at each end of the tube and an automatic switch to turn the heaters off when current begins to flow through the mercury vapor.

The most efficient of all electric lamps is one using sodium vapor, which gives off a golden-yellow light that is unsuitable for home lighting but satisfactory for street lighting. As in fluorescent lamps, small filaments or heaters are used at opposite ends of the tube to produce the vapor needed for the current flow. But instead of a few seconds, as in the fluorescent lamps, many minutes are required to start sodium-vapor lamps.

Arc lamps. The *electric arc* shown in Figure 34 also changes electrical energy into heat and light. When two carbon rods, each connected to one wire of an electric circuit, are brought together so that their ends touch and are then separated a short distance, a bright, bluish light is given off between the ends of the carbons. This is called an *arc*. What happens is that when the tips of the carbon rods are brought together, a large current flows in the circuit. Because there is considerable opposition to the flow of this current at the point where the carbons touch, the ends become very hot, causing some of the carbon to change to carbon vapor. When the ends are then separated a fraction of an inch, the vapor provides a path for the current. Owing to the high resistance of this path, the current causes the vapor and the ends of the carbon rods to become white-hot, and a brilliant light is given off.

In an arc lamp the resistance of the carbon rods is low, and so some device is needed to control the amount of current that will flow in the circuit when the ends are brought together. A fixed resistor is generally used for this purpose.

Like the mercury-vapor lamp, an electric arc produces ultra-violet rays and, for this reason, is sometimes used in sun lamps. If you have ever used a sun lamp of this kind, you know that colored glasses are necessary to protect your eyes from the brilliance of the light and the ultra-violet rays. Never look at an arc light with unprotected eyes; the light can cause serious damage. You also know that after the current is turned on, it is necessary to "strike" the arc—that is, to bring the carbons together for an instant and then separate them. And you know that after the arc has been struck, the carbons need to be moved toward each other occasionally. If this is not done, the gap becomes wider as the ends of the rods change into vapor, and its resistance finally becomes so great that current will no longer flow. The arc then disappears.

Because the light produced by the electric arc is very bright, electric arcs are used in large motion-picture projectors, in some stage spotlights, and

On this page are shown a few of the interesting ways in which heat and light produced by an electric current are used. In the operating room at the upper left, the big incandescent lamp supplies ample illumination for the surgeons, while the slender vapor lamps supply ultra-violet light to rid the air of bacteria that might cause infection. The hooded worker at the upper right is using the intense heat produced by an electric arc to weld heavy steel rails. At the lower left a soldier is adjusting a large Army searchlight that uses an electric arc to produce an intensely bright beam, rated at 800,000,000 candle power and having an effective range of over five miles. And at the lower right is a small electrically heated furnace whose temperature can be controlled by means of a rheostat.

in large searchlights such as those used by the Army and Navy. In uses such as these the need for a source of powerful light is great enough to outweigh the many disadvantages of the electric arc, such as great heat, noisy operation, need for frequent adjustments, and replacement of carbons.

Electric furnaces and welding. Electric arcs are used in special furnaces to produce very high temperatures (up to 6800° F.) for making steel and for heating or melting other materials. In this kind of furnace two or three very large carbon rods reach down into the container that holds the steel or other material to be heated. The arc supplies an intense heat that will melt almost any material in a short time.

Electric arcs are also used for welding. One wire from the source of current is attached to the metal to be welded. The other wire goes to a metal rod, which is held by the welder in an insulated handle. The welder starts the arc by touching the end of the rod to the piece that is to be welded. When the metal glows, the rod is withdrawn slightly, and an arc forms across the gap between the welding rod and the object to be welded. The intense heat of the arc melts the rod and the metal along the joint that is to be welded. The melted metals then run together to form the weld. Welders must wear a hood with a dark glass window in order to protect their eyes from the effects of the ultra-violet rays thrown out by the arc.

In another kind of welding, the heat caused by passing a large current through the materials to be welded is sufficient to melt the materials and form the weld. Two sheets of iron, for example, are clamped between contact points of heavy copper, and a large current is sent through the circuit. The higher resistance of the iron causes the current to heat the iron between the contacts to the melting point, and the weld is formed. This way of joining sheets of metal is called *spot welding.*

CHECKING WHAT YOU LEARNED

1. **a.** What is a heating element? **b.** Explain why the heating element in a toaster or iron becomes much hotter than the wires used to connect the appliance to the source.
2. **a.** State three things that must be considered in selecting a good material for a heating element. **b.** What material is commonly used for heating elements?
3. A very small, short wire, such as you used in Experiment 13, will get very hot when connected in a house-wiring circuit. Why is it unsuitable for use in a heating device?
4. **a.** State two things that determine the amount of heat produced in one second by a conductor. **b.** Tell what effect increasing each one has on the amount of heat produced, when the other is not changed.
5. What change of energy takes place in a heating element? In the filament of an ordinary electric light bulb?
6. **a.** Name the main parts of an electric light bulb and tell what each part does. **b.** Draw a diagram of a light bulb and label its parts.
7. **a.** What material was first used to produce light in an incandescent lamp? **b.** What material is used now? Why?
8. What is the main disadvantage of the light bulbs we commonly use?
9. List several other kinds of electric lamps and tell briefly how each kind works.
10. **a.** How is an electric arc produced? **b.** What other device usually is needed in a circuit with an arc? Why? **c.** Name three important uses of electric arcs.

USING WHAT YOU LEARNED

1. A wire that is supposed to get red-hot fails to do so when connected in a circuit. **a.** What two changes might be made in the wire in order to make it heat properly? **b.** Explain why each change would work.
2. At 110 volts a toaster uses 5 amperes. Another toaster has a resistance of 27.5 ohms. Which one will produce more heat when operated at the same voltage? Why?
3. A modern electric iron has a resistance of 10 ohms, while an older model has twice this resistance. **a.** Which iron uses more current when operated at 110 volts? **b.** Which one supplies more heat in one second? **c.** How much more compared with the other iron? Explain your answer.
4. An electric stove for use in a 220-volt circuit has a resistance of 7⅓ ohms when all the heating elements are turned on. **a.** How much current flows through the stove? **b.** If the

stove is connected to a 110-volt circuit, how much current will flow through it? **c.** In which circuit will it produce more heat? **d.** How much more than the other? Why?

5. Must carbon rods be used for electric arcs? Give reasons for your answer.
6. Is the resistance of the vapor in an arc high or low? Give your reasons.
7. **a.** An incandescent bulb with a tungsten filament has a resistance of 200 ohms when hot. If used at a pressure of 110 volts, how much current flows through the filament? **b.** When the current is turned on, the cold filament instantly gets hot. As a result of the increased temperature, its resistance becomes 20 times as great as when it was cold. Explain why it is a good thing that an increase in resistance takes place.
8. One foot of No. 24 nichrome wire has a resistance of 1.63 ohms. To make a heating element for a toaster that will use 5 amperes of current at 110 volts, how many feet of this wire are needed?
9. An arc lamp is operated at 110 volts. In order to keep the starting current down to 15 amperes, the voltage available at the carbon rods must be reduced to 50 volts. **a.** How much voltage drop must there be through the resistor included in the circuit? **b.** What is the resistance of the resistor?
10. Why do the various kinds of vapor lamps produce less heat than an incandescent lamp that gives out an equal amount of light?

Safeguarding the Circuit

You have seen some of the practical uses of resistance in conductors, both to control the current in circuits and to change electrical energy into heat and light. Now you will see how the heating effect of current is used to safeguard circuits.

Wire sizes and insulation. Electric circuits are usually designed to carry a certain amount of current at a certain voltage. In the ordinary house-wiring circuits, for example, the E.M.F. is 110 volts, and the material used for the conductors is copper. Hence, the only practical way to vary the resistance of the different circuits is by varying the size, or cross section, of the wires. The wiring in the walls is probably no smaller than No. 14, though longer circuits, or those used to carry a large current for electric irons, toasters, and so forth, are probably No. 12. The small, flexible cord used to connect a floor lamp or an electric clock probably has No. 16 or No. 18 wires in it, which are heavy enough to carry the small current required by these devices. A toaster or iron, on the other hand, has a cord with wires of much larger cross section, because these devices need much more current to work properly. The small, flexible cord of a floor lamp or clock will not carry enough current to operate an iron efficiently. Furthermore, it would probably become dangerously hot. Thus you can see that a wire must have a low resistance if it is to carry a large current efficiently and safely. Circuits in which large currents flow are called *high-amperage circuits.* A circuit of high amperage is connected with wires that can carry a large number of amperes.

Perhaps you are wondering why the No. 18 insulated copper wire you used in the experiments is not satisfactory for connecting an electric clock or a lamp to the house-wiring circuit. One No. 18 insulated copper wire will carry about the same current as another of the same length. Of course, the solid wire is stiffer than the flexible lamp cord ordinarily used to connect such devices, and its stiffness would make it unhandy to use. Aside from that, however, why is this wire unsuitable? If you examine the insulation on the two different No. 18 wires, you may be able to guess the real reason for using one instead of the other to connect an electric clock or lamp. The wire you used in the experiments is insulated with cotton threads dipped in paraffin. The wire used to connect an electric clock or lamp is first insulated with threads and then covered with rubber; it may have even another insulating covering over the rubber. You can see that this wire is much better insulated than the one you used in the experiments. The voltage of the house-wiring circuit is 110 volts, while the circuit in the experiments had only the voltage furnished by one dry cell (about 1.5 volts) or two dry cells (3 volts). For safety's sake, wires used in *high-voltage circuits* must be well insulated.

The amperage of the circuit must be considered in selecting a conductor of the proper size or cross-sectional area, while the voltage of the circuit determines the amount and kind of insulation needed to keep the conductors from touch-

Overload: The condition existing when the conductors in a circuit are carrying more current than they were designed to carry.

Fuse: A safety device that melts and automatically opens a circuit when an overload occurs. It consists of a wire that has a low melting point. The two common kinds are plug fuses and cartridge fuses.

Circuit breaker: A safety device that can be closed again after it has automatically opened a circuit as a result of an overload. There are two main kinds of circuit breakers: heat-operated (thermostatic) and magnet-operated (electromagnetic). This second kind is discussed in Chapter 6.

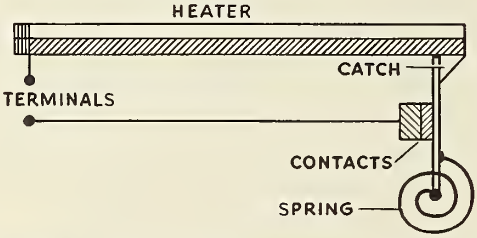
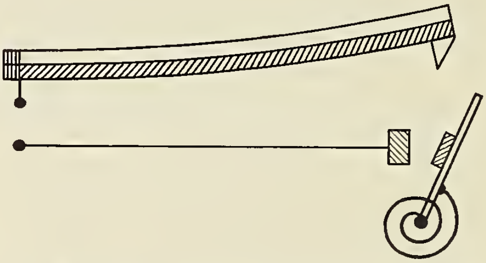
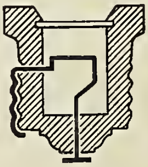


Figure 35. *The diagram above shows one kind of circuit breaker with the contacts closed. The device is connected into one wire of a circuit like a switch or fuse, so that all the current in the circuit can flow in at one terminal, flow through the heater strip, movable arm, and contacts, and flow out at the other terminal without interruption so long as contacts are held together.*



The diagram above shows the contacts open after the circuit breaker has "tripped." When the current becomes too large, the heater strip becomes hot and expands. The heater is made of two metals, one of which expands more than the other, causing the heater strip to curve and release the catch holding the movable arm. The spring then parts the contacts, opening the circuit.

At the left is shown the top of a plug fuse. Through the window you can see the thin strip of easily melted metal. At the right is shown the path of the current through a fuse. The circuit is opened when a large current melts the thin strip.



ing each other or other conductors. When more current is used than the circuit was designed to carry, a condition exists that we call an **overload.**

Overloads are dangerous in many circuits. You have seen what happens when too much current passes through a conductor, such as the fine copper wire in Experiment 13. The wire became red-hot, white-hot, and then melted. You can imagine what happens when the conductors in a house-wiring circuit become red-hot.

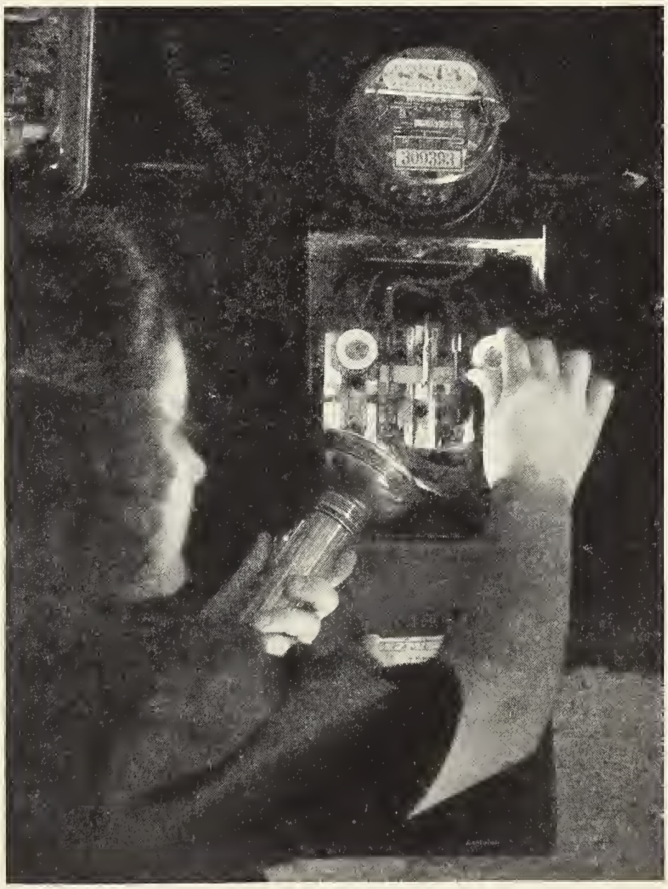
Fuses and circuit breakers. Safety regulations require the use of devices to prevent fires and other serious damage when circuits are overloaded. Whether the overload is caused by adding too many devices to the circuit or by some defect in the insulation, allowing one conductor to touch the other, makes no difference. In either case the wires are likely to become dangerously hot, and you already know that doubling the current through a conductor produces four times as much heat. If, however, there is a fuse or a circuit breaker in the circuit, the overload causes the device to open the circuit automatically. When a fuse opens a circuit, we say that it "blows." When

One kind of modern circuit breaker used for safeguarding house-wiring circuits is shown at the right. Mounted in the wall at a convenient place in the house is a box containing a combined switch and circuit breaker for each branch circuit. When an overload occurs, the circuit breaker trips, shutting off the current automatically. Once the overload has been corrected, merely moving the switch lever resets the circuit breaker and turns on the current. Circuit breakers of this type are both convenient and safe because there is nothing to replace and because there are no exposed connections to cause a shock.

The man at the lower left doesn't realize that using a penny for a fuse can cause thousands of dollars' damage by fire. The girl at the lower right is much smarter. She has turned off the main switch and is replacing the blown fuse with a new one of the same rating.

DON'T DO THIS

DO THIS



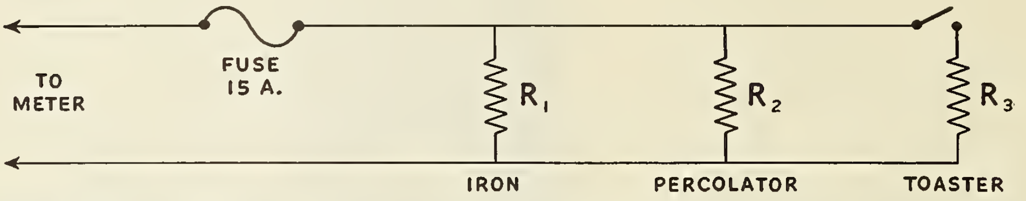


Figure 36 *shows a diagram of part of a house-wiring circuit. The three electrical appliances are represented by the resistors* R_1, R_2, R_3, *since they permit various amounts of current to flow in the circuit. Notice how the fuse is connected into one wire of this circuit so that, when the wire melts, the flow of current is stopped. The large wires at the meter are often considered the source of electrical energy in house-wiring circuits.*

a circuit breaker is used, we say that it "trips." Both devices safeguard a circuit by automatically shutting off the current when too many amperes of current flow in the circuit, thus keeping the conductors from becoming too hot.

A fuse is nothing more than a short piece of wire that has a low melting point. It is connected in the circuit in such a way that all of the current flowing in the circuit must flow through the fuse. When more amperes flow than the fuse is intended to carry, the increased current causes the fuse wire to melt before the other conductors in the circuit become dangerously hot. Once the fuse has "blown," or melted, it is necessary to replace the fuse with a new one before current will again flow in the circuit. Of course, if the condition causing the overload still exists, the new fuse will promptly blow, too.

When fuses are properly used, they provide an inexpensive means of safeguarding the circuit. But several cautions need to be noted. A fuse of larger rating than the one intended to protect a circuit may not "blow" so quickly, but neither will it safeguard the circuit so well. Consequently, it is dangerous to replace a blown fuse with one of larger rating. Safety regulations usually require 15-ampere fuses in house-wiring circuits using No. 14 wire, and 20-ampere fuses for the special circuit of No. 12 wire, which is designed to carry current for electrical appliances. To use larger fuses is dangerous. Even more dangerous is the so-called "emergency" repair of a blown fuse by removing the fuse, dropping a penny in the socket, and replacing the blown fuse. Since the penny is capable of carrying several hundred times the current that will melt ordinary house wiring, you can see that the "fuse" is no longer a safety device; instead it has become a "danger" device. With a penny in place of the fuse, a sufficiently large overload will cause the house wiring to become dangerously hot and possibly to melt; an expensive rewiring job is inevitable even if the overheated wires do not cause a serious fire.

The circuit breaker is an automatic switch that shuts off the current when too many amperes flow in the circuit. It is connected in a circuit in the same way as a fuse. Figure 35 shows how one type of circuit breaker works. You can see that when the switch is ON, the contacts are held together by a catch fastened to one end of a "heater," through which the current flows. This heater is a strip made of two kinds of metal, riveted or welded together. It is really a kind of *thermostat*. When too large a current flows, the heater strip becomes hot, and the two metals expand but not at the same rate. Since the lower part of the strip expands more than the upper part, the heater strip curves upward, releasing the catch and allowing the spring to open the contacts. After an overload has tripped the circuit breaker, the current remains off until the switch is closed, or "reset," by means of a small lever. If the conditions causing the overload still exist, the circuit breaker trips again within a few seconds. Circuit breakers are more expensive than fuses, but once installed they provide greater protection, since they cannot be tampered with.

Series connection: The method of connecting parts of a circuit so that the current flows through one part after another in consecutive order. When the various parts of a circuit are connected in an end-to-end arrangement, we say that these parts are **in series.** Removing or disconnecting any one of the parts connected in series interrupts the flow of current through the rest of the circuit.

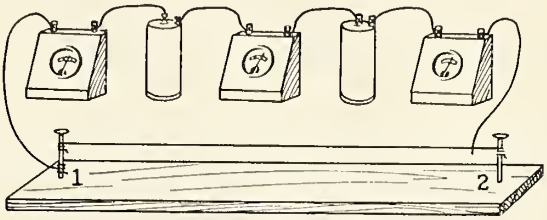


Figure 37 *shows an important fact about a series connection. If three ammeters are connected at various points in the circuit as shown, they will all indicate the same number of amperes when a current flows through the circuit. As one wire slides along the wire between nails 1 and 2, the needles of the three ammeters will move together, thus indicating that in a series connection the same current flows through all parts of the circuit.*

Now that we have seen how these safety devices safeguard the circuit, let us see what conditions cause them to shut off the current. Probably the commonest form of overload is that resulting from connecting too many devices to one circuit. Suppose we have three electrical appliances: a large flatiron, a small percolator, and a toaster that turns on when a lever is pushed down. Whenever these three devices are connected to the same circuit, the 15-ampere fuse blows; yet individually each device works perfectly. Every morning the percolator and toaster are on at the same time, and often the iron and percolator are on at the same time. But if the iron and percolator are connected when the lever on the toaster is pushed down, the fuse blows. What causes the overload to occur at some times and not at others?

Figure 36 shows a diagram of this circuit with the iron and percolator connected but with the toaster switch in the OFF position. We know that when the toaster is connected to this circuit, the 15-ampere fuse blows. Let us see why. Let us suppose that the iron draws 9 amperes, the percolator 3 amperes, and the toaster 5 amperes when these devices are connected in a 110-volt circuit.

If we add the amperes used by each device, we find that I (current in the circuit) =

$I_1 + I_2 + I_3$ or $9 + 3 + 5$ or 17 amperes

It is now clear to us why the 15-ampere fuse blew when all three devices were connected to the circuit at one time. You can also see why the fuse did not blow when the percolator and toaster were both turned on; only 8 amperes were being used. Even when the percolator and the iron were both in use, only 12 amperes of current flowed.

The fact that connecting more devices in a circuit draws more current requires explanation. In the experiments performed so far we have seen that resistance increased as we added more devices. In the experiments the devices were connected **in series.**

Series and parallel connections. If you will look at Figure 37 carefully, you will see what is meant by a **series connection.** Each part of the circuit has two terminals or ends; when these parts are connected end to end so that the same current flows through all parts of the circuit, they are connected in series. For example, the ammeter in Figure 23 is connected between the center post of one dry cell and one of the nails. If you wished, you could connect the center post of the cell directly to this nail and put the ammeter at any other place in the circuit—between the two dry cells, between the added cell and the long wire, between the long wire and the nail farther from the cells, or between the nearer nail and the dry cell, where it is shown in Figure 23. In every one of

Parallel connection: The method of connecting parts of a circuit so that different currents may flow at various points in the circuit. The parts connected in this way are said to be **in parallel** or **in multiple.** Removing or disconnecting any one of the parts connected in parallel does not interrupt the flow of current through the rest of the circuit.

these places it would indicate the same amount of current flowing in the circuit. One other fact will help you understand a series connection. Any break in the end-to-end arrangement causes the current to stop flowing. For instance, when the end of the wire is not touching either nail or the bare wire stretched between the nails, the ammeter shows that no current flows in the circuit. When the end of the wire touches nail 1, the bare wire is not part of the circuit; when it touches nail 2, all the bare wire is in series with the other parts of the circuit. Fuses and circuit breakers are always in series with the other parts of the circuit.

Devices connected as the iron, the percolator, and the toaster are in Figure 36 are said to be **in parallel** or **in multiple.** The method of connecting parts of a circuit in this way is usually called a **parallel connection.** Two things distinguish a parallel connection from a series connection. In a parallel connection different amounts of current may flow at various points in the circuit, while in a series connection the same amount of current flows in all parts of the circuit. Furthermore, in a parallel connection any one of the parts in parallel may be removed or disconnected without interrupting the flow of current through the rest of the circuit; in a series connection the removing or disconnecting of any part opens the circuit and causes the current to stop flowing.

You know that when two or more resistors in a circuit are connected in series, the current flowing through the circuit is less than it would be with any one of the resistors left out, for with a constant E.M.F. at the source the current in a circuit decreases as the resistance increases. And you have just seen that when two or more resistors in a circuit are connected in parallel, the current flowing through the whole circuit is greater than it would be with any one of the resistors left out; for the more paths there are for the current to follow, the less opposition there is for the E.M.F. to overcome in the circuit as a whole. And you know that the current in a circuit increases as the resistance decreases.

When the resistance in a circuit is greatly reduced, a dangerously large current may flow. This type of overload we usually call a **short circuit,** since it results from a shortening of the path through which the current is supposed to flow. A fuse is a protection against the dangerous results of short circuits. In house-wiring circuits, where conductors are mainly in the walls and ceilings, fuses and circuit breakers are very important.

Look again at the circuit diagram in Figure 36. Suppose that somewhere between the fuse and the iron a screwdriver comes into contact with the two wires leading to the devices. There is a sudden flash, and the fuse blows. What has happened? We know that the 15-ampere fuse in this circuit would not carry the 17 amperes we found were required by the three devices. Have we in some way decreased the resistance of the circuit still more, so that even more current flowed through the fuse?

If you stop to think for a moment about what caused the fuse to blow, you will see that the screwdriver was actually connected in parallel with the other devices in the circuit. And you know that in a parallel connection, the more paths provided for the current, the greater will be the flow of current as the resistance of the circuit decreases. We can see by looking at the screwdriver that it probably has a very low resistance. The length is short, the cross-sectional area is large, and the material (steel) is a fair conductor. Let us say that the part of the screwdriver in the circuit has a resistance of 0.0008 ohm. Knowing

Short circuit: A very large overload caused by shortening the path through which the current is intended to flow in a circuit.

the E.M.F. in volts and the resistance in ohms, we can find the current in amperes by using the Ohm's Law formula $I = \frac{E}{R}$

Substituting the two values known:

$$I = \frac{110}{.0008} \text{ or } I = 137{,}500 \text{ amperes}$$

Actually the fuse "blew" long before any such large current flowed in the circuit. But the fact remains that a path for a dangerously large current was provided by the screwdriver with its low resistance.

CHECKING WHAT YOU LEARNED

1. **a.** Why are fuses used in wiring systems? **b.** What causes a fuse to blow? **c.** What happens to the fuse when it blows?
2. Why must care be used in selecting wires of the correct size and with proper insulation for use in a circuit?
3. **a.** What is an overload? A short circuit? **b.** Tell how each may be caused in a circuit.
4. **a.** Explain how a heat-operated circuit breaker safeguards a circuit. **b.** What advantage do circuit breakers have over fuses? **c.** Why are they not more commonly used?
5. **a.** How are the wires arranged when several devices are connected in parallel? Draw a diagram to illustrate your answer, using symbols. **b.** How are devices connected in series? Draw another diagram to show this arrangement.
6. In what two ways do series and parallel connections differ?

USING WHAT YOU LEARNED

1. **a.** Fuses that screw into sockets have numbers on them—5, 10, 15, etc. What do these numbers mean? **b.** What determines the size fuse to use in a circuit?
2. **a.** Are fuses connected in series or in parallel with the devices in a circuit? Why? **b.** What would happen if the other connection were used?
3. **a.** Tell why it is dangerous to put a penny behind a blown fuse. **b.** Explain why it is also dangerous to use too large a fuse in a circuit.
4. One type of Christmas tree lights has the bulbs connected in series. **a.** What is the advantage of this arrangement? **b.** What is the disadvantage?
5. Give at least two reasons for providing a special appliance circuit to operate electric irons, kitchen stoves, large motors, and other devices using large currents.
6. Draw a diagram showing how the wires, switches, and fuses would be connected to furnish current to two 15-ampere lighting circuits and one 30-ampere appliance circuit in a house.
7. As long as an ammeter is properly connected in a circuit, the place where it is connected in the circuit makes no difference in its reading. Explain why this is true.

THINKING OVER WHAT YOU LEARNED

1. On a sheet of paper write down the main topics of the chapter, leaving a space after each topic. Then in complete sentences state the big ideas or principles you learned in studying each topic.
2. Show in some way that you understand the meaning of the following terms. You may use a definition or a sentence to do this. **a.** fuse, **b.** voltmeter, **c.** parallel connection, **d.** resistance, **e.** overload, **f.** heating element, **g.** electric arc, **h.** circuit breaker, **i.** resistor, **j.** series connection, **k.** filament, **l.** short circuit, **m.** fluorescent, **n.** voltage drop, **o.** incandescent, **p.** rheostat, **q.** ammeter.

Experiment 9: **Effect of Material, Cross Section, and Length on Resistance**

THINGS NEEDED: Two nails. Hammer. Board about 10½ feet long and 4 inches wide. No. 18 insulated copper wire. No. 30 bare or insulated copper wire. No. 30 bare iron wire. No. 18 bare iron wire. Dry cell. Ammeter reading up to 30 amperes. (See Fig. 22.)

WHAT TO DO: **a.** At each end of the board drive a nail. Stretch a piece of No. 30 copper wire between the two nails, twisting the ends around the nails securely. With a short piece of insulated copper wire, No. 18 or larger, connect one nail to the negative terminal (−) of the ammeter. Connect another short piece of the same size wire from the positive terminal (+) of the ammeter to the center post of the dry cell. Now connect a 10-foot length of insulated wire (No. 18) to the outside post of the dry cell. Touch the end of the long wire from the dry cell to nail 2. Read the ammeter. (NOTE: Keep the circuit closed only long enough to take the readings.) Now repeat the same experiment, using No. 30 iron wire stretched between the two nails. How does the ammeter reading compare with the one you got with No. 30 copper wire? What conclusion can you make?

b. Now substitute a piece of No. 18 iron wire for the No. 30 iron wire stretched between the two nails. Touch the end of the long wire to the nail and note the ammeter reading. How does the ammeter reading compare with the one you got with the No. 30 iron wire? What do your results show?

c. Still using the No. 30 bare iron wire, touch the end of the long wire from the cell to the middle of the stretched wire. Read the meter. How does the ammeter reading compare with the one you got with the wire twice as long? What do your results show?

Experiment 10: **Effect of E.M.F. on the Current through a Resistance**

THINGS NEEDED: Board with nails, connected as in Experiment 9, Part **a**. Another dry cell. A yard stick. (See Fig. 23.)

WHAT TO DO: **a.** Fasten a piece of No. 30 bare iron wire between the nails on the board as you did in Part **a** of Experiment 9. Touch the end of the long wire to the bare iron wire at a point 2 feet from the nail near the ammeter. Note and record the ammeter reading. Then touch the end of the long wire to a point 4 feet from the ammeter. Again note and record the ammeter reading. Repeat at the 6-foot point.

b. Now connect another dry cell in the circuit as shown in Figure 23. (This is a connection in series, as explained later in the chapter.) You now have twice the E.M.F. available at the source of electrical energy. Repeat Part **a** of this experiment. Note and record the ammeter readings when the long wire is touched at the 2-foot, 4-foot, and 6-foot points. How do these readings compare with the readings taken when 1 dry cell was used? What conclusions can you make about the current in a circuit when the E.M.F. is increased without changing the resistance?

Experiment 11: **Using a Rheostat to Control Current**

THINGS NEEDED: Ammeter. Voltmeter. Two dry cells and insulated wires from Experiment 10, Part **b**. Rheostat. Flashlight bulb (3-volt) and socket. No. 18 insulated copper wire. (See Figs. 27, 28.)

WHAT TO DO: **a.** Connect the apparatus as shown in Figure 27, page 52. (Be sure that the rheostat is in the OFF position while you are making these connections.) Now slide the movable contact toward the terminal of the rheostat that is connected to the ammeter. Move the sliding contact slowly until the ammeter shows about 5 amperes of current. Then move the contact back to the OFF position. What happens to the current when you move the sliding contact back and forth? Why?

b. Now substitute the 3-volt flashlight bulb and socket for the ammeter. Slide the movable contact from one end of the rheostat to the other. What change takes place in the brightness of the bulb? What is happening to the current? Why?

c. Measure the voltage available at the source of electrical energy. To do this connect a voltmeter to the two dry cells, as follows: Connect the center post of the first cell to the outside post of the second cell. Connect the center post of the second cell to the + terminal of the voltmeter. Connect a wire from the outside post of the first cell to the — terminal of the voltmeter. Read the voltmeter. The reading indicates the voltage available from the two dry cells in series. Now connect the two cells, a rheostat, flashlight bulb, and the voltmeter as shown in the upper part of Figure 29. (Be sure that the rheostat is set in the OFF position when making connections.) Now slide the movable contact from one end of the rheostat to the other and back again. What is the reading when the bulb is brightest? When the bulb is very dim?

d. Now add an ammeter to the circuit as shown in the lower part of Figure 29. (Be sure the rheostat is set in the OFF position when making connections.) Now slide the movable contact of the rheostat back and forth. Notice what happens to the current when the voltmeter reading is high and when it is low. What does the voltmeter connected across the rheostat indicate? What effect on the voltage did you get from varying the resistance of your circuit? How did varying the resistance of the circuit affect the current?

Experiment 12: **Making and Using a Water Rheostat**

THINGS NEEDED: Same as for Experiment 11, Part **d**, except that the following are substituted for the rheostat: Two similar strips of metal such as iron, copper, or brass (old dry-cell carbons may be used); glass jar; salt; water.

WHAT TO DO: Pour water in the glass jar until it is two-thirds full. Put in 2 tablespoonfuls of salt and stir until dissolved. To each wire which runs to the rheostat in Experiment 11 (see Fig. 29), connect one metal strip. Be careful not to let the metal strips touch each other. Hold one strip in each hand and lower the free ends into the salt solution in the jar. Watch the effect on the ammeter. Move the strips closer together and farther apart. Also add more salt to the solution. In each case notice what happens.

Experiment 13: **Heating Effect of Current**

THINGS NEEDED: Board. Two nails. Hammer. Short strand of fine copper wire from a lamp cord. No. 18 insulated copper wire. Dry cell.

WHAT TO DO: Drive two nails about 2 inches apart on the board. Separate the strands in a short piece of flexible lamp cord. Take several inches of a single strand of fine wire and stretch between the nails. Now connect a dry cell to the ends of the fine wire, using No. 18 insulated copper wire. What happens?

Experiment 14: **Heating Devices**

THINGS NEEDED: Various types of heating devices (toaster, iron, heater, etc.) Screwdriver.

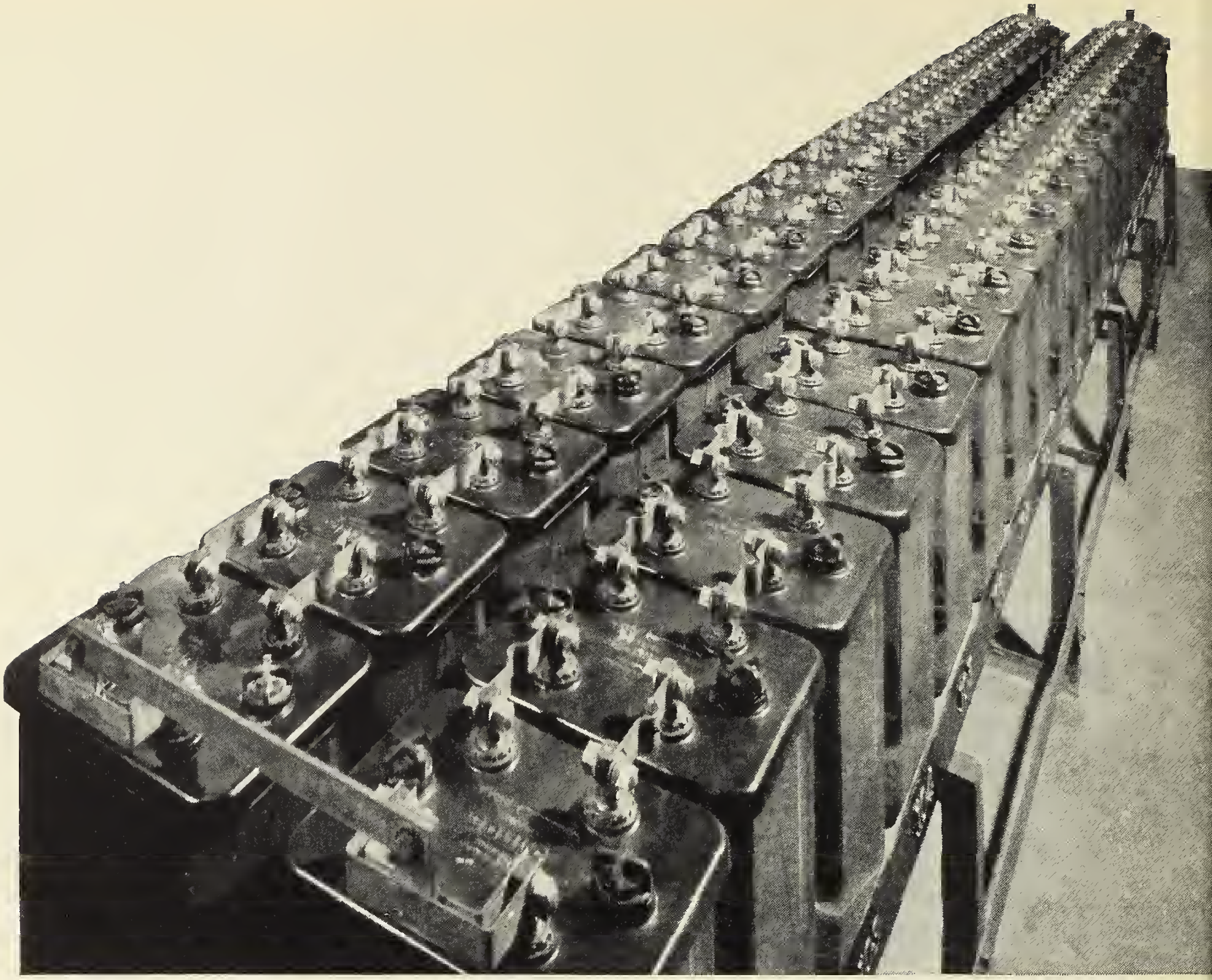
WHAT TO DO: Examine as many heating devices as are available. Find out how the heating element is arranged in the space provided for it. What insulating materials are used in the device?

Experiment 15: **Incandescent Bulb**

THINGS NEEDED: "Burned-out" light bulb. Pliers. Knife. Heavy cloth.

WHAT TO DO: **a.** With a pair of pliers and a knife remove the base (part that screws into the socket) from a "burned-out" light bulb. Find the wires that connect the base with the filament. How are they insulated from each other? Where is the tube used to remove air from the bulb?

b. Wrap the bulb in a heavy cloth and break the glass. Examine a piece of the filament. Is it straight or coiled? What happened to the filament when the bulb "burned" out?



4. E.M.F. by Chemical Action

FINDING OUT WHAT YOU KNOW

1. In what two ways is electrical energy commonly produced?
   Which of these ways is cheaper? Why is the other used at all?

2. List the things you would need to make a simple electrical cell that would send current through a circuit.
   How would you arrange the parts so that the cell would work?

3. Make a diagram to show how you would connect a cell to operate a small light bulb.
   Put a switch in the circuit to turn the bulb on or off.

4. Explain why the name *dry cell* is misleading.

5. What determines the voltage of a cell?
   The amperage of a cell?

6. How would you connect cells to increase the E.M.F. in a circuit?
   To increase the current that can be furnished without changing the E.M.F.?
   To increase both the E.M.F. and the current that can be furnished?

7. What is the main difference between a storage cell and a dry cell?

8. How is an automobile storage battery tested?

UP TO THIS POINT in the book you have been reading about electrical energy and how it behaves. You have learned that an electric current is a stream of electrons moving through a conductor. Now it is time for you to find out what happens in order to keep electrons moving around a circuit. In Chapter 2 you learned that electrons move from one charged object through a path to another object as long as there is a difference of potential between the two objects. When the difference of potential no longer exists, the electromotive force disappears, and electrons are no longer driven from one object to the other. In order to keep electrons moving from one object to another, we must have something that will maintain a potential difference between them and thus keep up a continuous electromotive force. In everyday life there are two kinds of electron "pumps" used to do this—cells (often called "batteries") and generators. Whenever it is practical to do so, we use generators because they produce large quantities of electrical energy much more cheaply than do cells. However, generators are often heavy machines, and they must be kept turning all the time we need current. When we cannot get small amounts of electrical energy conveniently from generators, we use cells. You have probably seen flashlight "batteries" and similar cells many times. In this chapter you are going to learn how cells produce E.M.F. and thus current by chemical action.

You have already been warned against getting into the habit of thinking that cells and generators *make* electrical energy. There are just as many

Cell: A cell consists of two different electrodes in an electrolyte.

Electrode: Either of the two plates or terminals of an electrical cell, battery, or other source of electrical energy. Because electrodes must conduct an electric current, they are usually made of metal. The active (negative) electrode in a cell is always made of a metal or metallic compound. However, carbon (a non-metal) is used for the inactive (positive) electrode in dry cells.

Electrolyte: A solution of a chemical compound that will conduct an electric current. The electrolyte in a cell must have a chemical action with one of the electrodes. It may be a solution of an acid, a base (alkali), or a salt (a compound formed when an acid and a base act chemically on each other).

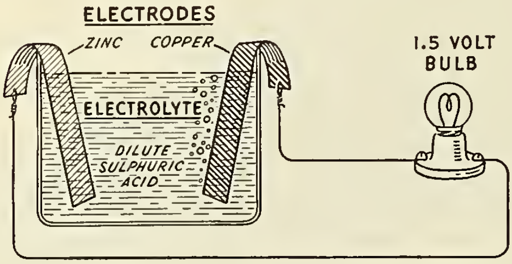


Figure 38 *shows a simple cell connected to a small flashlight bulb. The electrodes are strips of copper and zinc, and the electrolyte is a dilute solution of sulphuric acid and water. When the electrodes are put in the electrolyte, current flows through the light bulb, and bubbles start to form on the copper strip.*

electrons in a circuit before the current is turned on as afterward. The difference between a closed circuit and an open circuit is that in a closed circuit, the electrons can move around the complete path, while in an open circuit the path is broken. A cell or turning generator, in working order, always provides the potential difference between parts of a circuit; but the circuit must be closed before the E.M.F. resulting from the potential difference can drive the electrons around the circuit. Because generators are mechanical devices, it is not hard to see that they act somewhat like pumps. Cells, on the other hand, furnish electromotive force by the chemical action of the materials they contain. Because cells are not mechanical devices, it may not be so easy to see how they, too, act somewhat like pumps. Economy and convenience really determine whether we use a cell or a generator in a circuit.

The Simple Cell

The very simplest kind of electrical **cell** consists of two pieces of different metals in a solution. The pieces of metals, called **electrodes**, must be different. The solution, or **electrolyte**, must conduct an electric current and have a chemical action with one of the electrodes. In Experiment 16 (page 108) you can make and operate a simple cell that will show all the main facts about producing E.M.F. by chemical action. To make such a cell, you need a strip of zinc, a strip of copper, and a jar of dilute sulphuric acid.

In order to show that a simple cell will produce an E.M.F. and thus a current, you connect the wire from each metal strip to the terminals of a small bell (or buzzer) or to the terminals of a socket holding a 1.5-volt flashlight bulb. The bell or buzzer should give a weak sound, or the bulb should glow. A better way to show that the cell causes a current to flow is to use a simple instrument called a *galvanometer* that will tell whether or not there is a current in the wires. In Experiment 16 you can make a galvanometer from a compass and a coil of wire. When the coil of the galvanometer is connected to the cell, the compass needle instantly swings to the right or left. (If the connections between the coil and the cell are reversed, the needle will swing in the opposite direction.) The cell produces a current

Direct current: An electric current that always flows in the same direction. Often abbreviated **D.C.**

Direction of current flow: The current in a circuit is said to flow from positive to negative. (Actually, the electrons move in the opposite direction, as you know.)

Direction of electron movement: The free electrons in a conductor move from where there is a surplus of them to where there is a shortage or absence of them. In a circuit outside a cell or generator the electrons move from negative to positive.

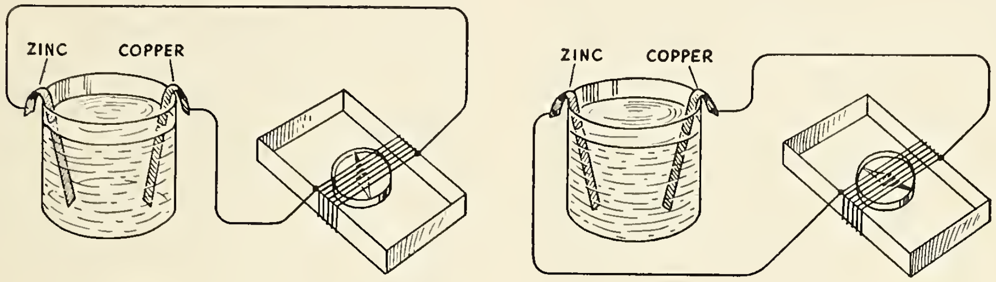
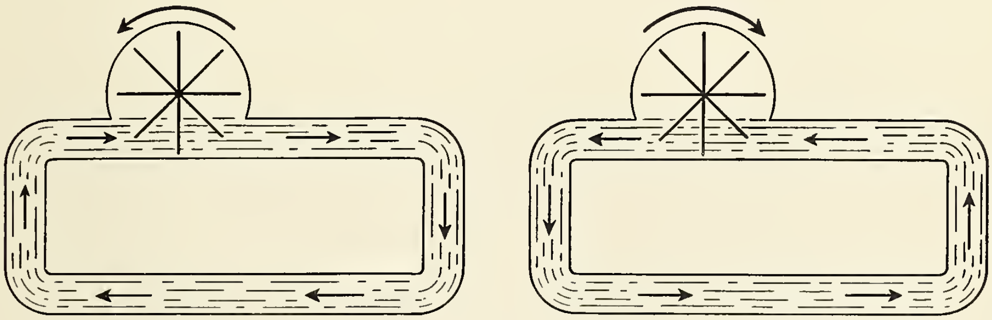


Figure 39. *The pictures above show a simple cell connected in two ways to a coil of wire in which is placed a small compass. When current flows through the wire in one direction, the black end of the needle swings to the left. When the current flow is reversed, the needle swings to the right. The diagrams below show a similar situation, in which the direction of flow determines which way the paddle wheel turns.*



that always flows in the same direction. Such a current is called a **direct current.**

A galvanometer shows not only the presence and strength of an electric current but also its direction in a wire. In Chapter 6 you will learn a rule for telling the direction of current flow in a wire by using a compass. If a voltmeter is available, the E.M.F. resulting from the potential difference between the electrodes in the cell can be measured. This simple cell has an E.M.F. of about 1 volt, as the voltmeter reading will show.

If you wish, you can try other pairs of metals, such as iron, tin, lead, and aluminum, in place of the copper and zinc electrodes. You can also try two copper strips or two zinc strips. You will find that any pair of *different* metals will produce enough current to move the galvanometer needle but that zinc and copper will produce more current than most other pairs of metals. If you care to try other electrolytes, you can use water solutions of salt, vinegar, or sal ammoniac (ammonium chloride). All of these will work, but none of them will work so well as dilute sulphuric acid. If you try a solution of sugar or denatured alcohol in distilled water, you will find that no current is produced, no matter what pair of metals is used. Not all solutions of substances that will dissolve in water will also conduct an electric current. You can see that a simple cell must contain the following things to produce an E.M.F. and thus make a current flow:

1. Two different electrodes.
2. An electrolyte.

Polarization. If you did Experiment 16, you can understand why a simple cell has little practical value. It produces only a weak current because there is only a small E.M.F. to make the current flow through the circuit. If we had no better sources of electrical energy than simple cells, we could not make much use of electric current. You can see another reason why this is true if you observe what happens to the compass needle of the galvanometer when the cell is left connected in a closed circuit for a time, as in Experiment 16. First notice how far the needle swings to right or left just as the circuit is closed. Look at the needle for about two minutes or until no further change is observed in its position. The needle will gradually swing back until it indicates that very little current is flowing.

While the cell is in use, a gas (hydrogen) is given off at the copper electrode. You can see the bubbles rising from the copper. However, not all the bubbles escape into the air. Some of them stick to the copper until finally the copper electrode is completely covered. This means that the cell now has a hydrogen electrode instead of copper. The E.M.F. of the cell decreases, and the current decreases, too. The collection of gas on an electrode is called *polarization*. You can *depolarize* the cell, that is, start it working properly again, by removing the copper electrode and wiping off the hydrogen bubbles. When you put the copper back in the electrolyte, the E.M.F. and current will be as strong as they were at first. But the cell will soon become *polarized* again if the circuit is left closed.

Chemical action and current flow. Now that you know what a simple cell is and what it does, you are ready to find out how it changes chemical energy into electrical energy. In a cell, such as the one in Experiment 16, the sulphuric acid acts

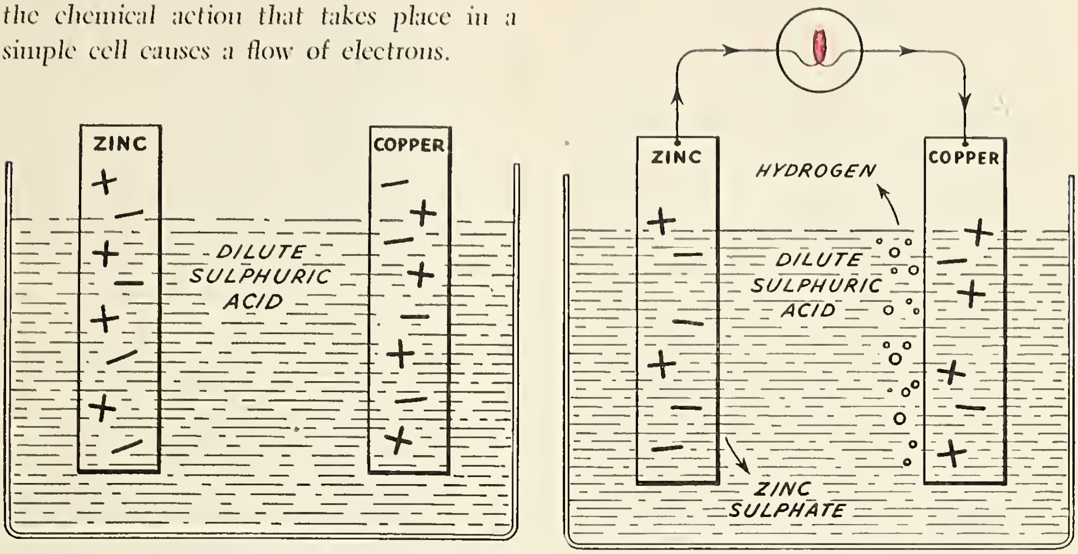
---

Direction of current flow: Up to the time the electron theory was developed to explain the observed facts about electricity, all scientists and experimenters arbitrarily assumed that a direct current flowed from positive to negative, because they thought it made no difference which way it was said to flow. Now we know the electrons move from negative to positive. Unfortunately, however, the old assumption about the direction of current flow was followed in many books on electricity and used in several practical rules you will learn later in this book. Whenever you see a reference to direction of current flow in this book, you will know that we mean a flow of current from positive to negative. But when the movement of electrons is mentioned in this book, you will know that a movement from negative (surplus of electrons) to positive (shortage of electrons) is meant.

Local action: Because the metals used for the electrodes of cells almost always contain impurities, tiny simple cells are usually formed on the electrodes when they are in an electrolyte. When this happens, **local action** is said to be taking place. For example, the zinc electrode in a cell is likely to contain tiny bits of carbon, iron, lead, or other impurities. Each particle of impurity on the surface of the electrode forms a simple cell with the zinc and the electrolyte. Whether the terminals of the cell are connected to a closed circuit or not, local action goes on all the time, using up the zinc electrode.

Amalgamation: One way of preventing local action is to put mercury on the electrode. The mercury and metal together form a mixture called an **amalgam** on the surface of the electrode. The amalgam covers the impurities so that they are not in contact with the electrolyte. In this way, amalgamation prevents local action when the cell is not connected in a closed circuit.

Figure 40. *These two diagrams show how the chemical action that takes place in a simple cell causes a flow of electrons.*



At the instant the electrodes are put into the electrolyte, neither one has a surplus or a shortage of electrons. When the acid begins to act on the zinc, potential difference is established between the electrodes.

The formation of zinc sulphate and hydrogen results in a surplus of electrons on the zinc and a shortage of them on the copper. Because of the difference in potential, electrons flow from the zinc to the copper.

on the zinc. As a result, both the zinc and the acid are changed chemically. The products of the chemical action are zinc sulphate and hydrogen. The zinc sulphate dissolves in the electrolyte, and the hydrogen is set free as a gas at the copper electrode. When the zinc is acted on and eaten away by the acid, a great many electrons are left on the zinc that still remains. Since the zinc has a surplus of electrons, it is negatively charged. The electrons on the zinc repel one another, because they have like charges.

If a path to the copper electrode is provided, some of the electrons will be repelled through the path to the copper, which is positively charged. When you touched the wires from the zinc and copper strips to the terminals of the galvanometer, a current flowed through the circuit. The stream of electrons moving from one electrode to the other was an electric current. In order to complete the circuit within the cell, electrically charged particles called *ions* must move between the electrodes in the electrolyte. Curiously enough, the ions move in both directions in the *internal circuit* within the cell, although the electrons in the *external circuit* outside the cell move only from the negatively charged zinc to the positively charged copper.

The electromotive force that drives the electrons through the wires from the zinc to the copper is the result of a potential difference between the electrodes. The zinc has a surplus of electrons and thus is negatively charged, while the copper has a shortage of electrons and thus is positively charged. As you know, a current will flow as long as there is a potential difference between two objects connected by a path through which electrons can move. The cell maintains the potential difference between the electrodes until the zinc is entirely eaten away by the acid or until the hydrogen bubbles completely cover the copper and polarize the cell. When all the zinc is eaten away, there is no surplus of electrons. The potential difference between the electrodes no longer exists, the electromotive force disappears, and the current stops flowing. If the cell becomes polarized, a hydrogen electrode is substituted for the copper. The potential difference and the electromotive force decrease. Since hydrogen is such a poor conductor as to be almost an insulator, very little (if any) current will flow when the electrode is covered with hydrogen.

The electrical energy produced by the cell comes from the chemical energy stored in the zinc and sulphuric acid. When the sulphuric acid acts on the zinc, the chemical energy is changed into electrical energy. Thus the cell is simply a device for changing chemical energy into electrical energy. (You will read more about changing energy from one form to another in Chapter 8.) Since the zinc is eaten away by the acid, you can say that the cells "burn" zinc as a fuel. Cells are not a very economical source of electrical energy, because zinc is not a cheap fuel from which to get energy.

Voltage and amperage. Did you know that a small flashlight cell has the same E.M.F. (about 1.5 volts) as the larger No. 6 cell used in bell and buzzer circuits? It is a curious fact that the size of a cell has no effect on its E.M.F. By doing Experiment 17 you can easily see that this is true. Make a simple cell just as you did in Experiment 16, but use electrodes that are only half as big as the one used before. When you connect this cell, it will show an E.M.F. of about 1 volt just as it did with the larger electrodes. If you try another pair of electrodes twice as big as those used in Experiment 16, the voltmeter reading will still show about 1 volt.

The voltage will not be changed by using more or less electrolyte or by moving the electrodes closer together or farther apart. Evidently, the voltage of a simple cell does not depend on the

---

Ionization or dissociation: Some materials, when they dissolve, break up into electrically charged particles called **ions.** An ion is formed when an atom (or group of atoms) gains or loses electrons and thus becomes either negatively or positively charged. A material that forms ions when it dissolves is said to **ionize,** or **dissociate,** in solution. Any chemical compound, such as an acid, base, or chemical salt, that will ionize in solution can be used to make an electrolyte; for a solution of such a compound will conduct an electric current. Chemical compounds, such as sugar and alcohol, that do not ionize in solution cannot be used to make electrolytes.

Chemical changes in a simple cell: In a simple cell the zinc (Zn) and sulphuric acid (H_2SO_4) containing stored chemical energy are changed into zinc sulphate ($ZnSO_4$) and hydrogen (H_2), thus releasing electrical energy.
The following equation shows the chemical action: $\mathbf{Zn + H_2SO_4 \rightarrow ZnSO_4 + H_2\uparrow}$

In a simple cell the sulphuric acid breaks up into hydrogen ions having one positive charge each and sulphate ions having two negative charges each. The zinc is acted on by the sulphuric acid and goes into solution as ions with two positive charges each. Since the zinc electrode was neutral to begin with, the loss of positive charges results in a surplus of negative charges on the zinc. Each zinc ion replaces two hydrogen ions in the electrolyte. The positively charged zinc ions and the positively charged hydrogen ions repel one another. The hydrogen ions go to the copper electrode. Here each hydrogen ion removes one electron from the copper. The positive charge on the hydrogen ion is neutralized by the negative charge on the electron. The result is an atom of hydrogen set free as a gas at the copper electrode. Since the copper is losing electrons, it has a shortage of electrons and becomes positively charged. If a wire is connected between the zinc and copper electrodes, the electrons on negatively charged zinc will repel one another through the wire to the positively charged copper, which attracts them. The potential difference maintained between the electrodes thus results in an electromotive force that drives electrons from the zinc to the copper. The stream of electrons is an electric current. To keep the current flowing, zinc must continue to go into solution and hydrogen must come out of solution as a gas. In other words, an E.M.F. is produced only so long as chemical energy is changed to electrical energy in the cell.

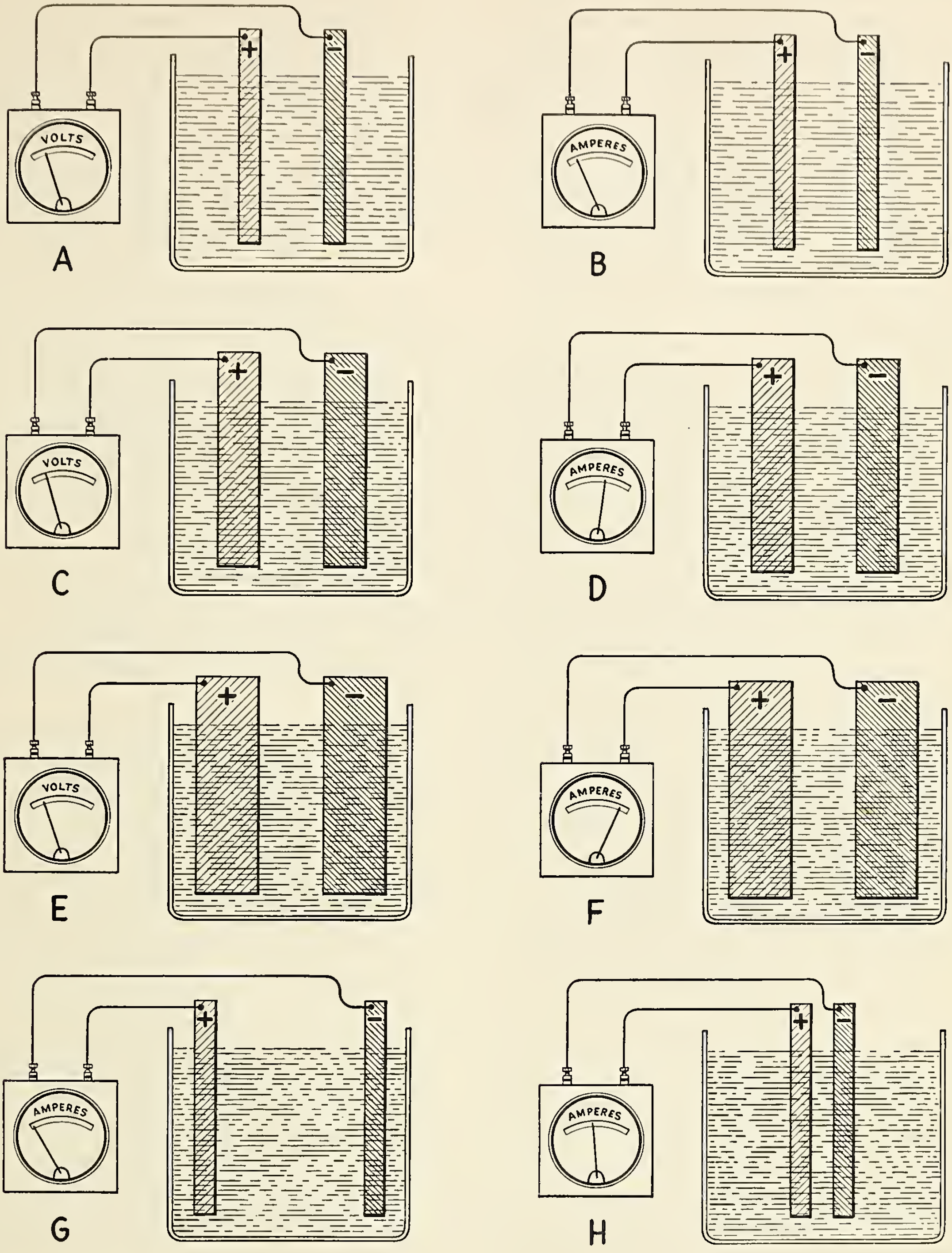


Figure 41 *shows the effect of electrode size and separation on the voltage and amperage of a simple cell. Diagrams A, C, and E show that the voltage does not change as the electrodes are increased in size. Diagrams B, D, and F show that the amperage increases as the electrodes are increased in size, while diagrams G and H show that the amperage increases as the distance between the electrodes is decreased.*

size of the electrodes, the amount of electrolyte in contact with them, or the distance between the electrodes. Many experiments and tests show that this is true, not only for simple cells but for all kinds of cells. Copper and zinc in dilute sulphuric acid always form a cell whose E.M.F. is about 1 volt. Other pairs of electrodes in various electrolytes produce a certain voltage for each combination. The voltage of any cell, that is, the E.M.F. resulting from the potential difference between the electrodes, depends solely on the materials used to make the cell—the electrodes and the electrolyte.

However, the amount of current that a cell will furnish does depend on the size of the electrodes in contact with the electrolyte and also on the distance between them. The second part of Experiment 17 demonstrates these facts about a cell. If you use a galvanometer or ammeter to measure the current from a simple cell when electrodes half as big as those used in Experiment 16 are put in the electrolyte, you will find that the meter shows less current than before. If you next use the pair of large electrodes, the meter will show more current than it showed in Experiment 16. If you use less electrolyte, the current will decrease. If you use more, the current will increase. Another way to vary the amperage of a cell is to move the electrodes closer together or farther apart. If you do this, you will see that a larger current flows when the electrodes are close together.

Increasing the size of the electrodes exposes more surface to the chemical action of the electrolyte. This reduces the **internal resistance** of the cell. You may be surprised to learn that a cell offers resistance to the flow of electric current just as any conductor does. Little current will flow unless the materials used to make the cell are good conductors of electricity. The electrodes and electrolyte must all conduct a current. You remember that the current decreased when the simple cell became polarized. Hydrogen, a very poor conductor, covered the copper, which is a very good conductor. As a result, the internal resistance of the cell increased so much that very little current flowed. If you tried to use a solution of sugar or denatured alcohol as an electrolyte, you found that no current flowed. One reason for this is that sugar and alcohol solutions are nonconductors; they have a very high resistance to the flow of electric current in the cell.

By now you have probably guessed why adding more electrolyte or moving the electrodes closer together increases the current from a cell. With more electrolyte in contact with the electrodes or with less electrolyte between the electrodes the internal resistance of the cell decreases. From Ohm's Law you know that anything done to reduce the resistance of a conductor will increase the current that can flow through it. Making the conductor larger (increasing the size of the electrodes in contact with the electrolyte or adding more electrolyte) or making the conductor shorter (moving the electrodes closer together) will of course decrease the internal resistance. You can also see that using a solution of low resistance as the electrolyte will decrease the internal resistance of the cell and thus increase its amperage. The internal resistance of a source of electrical energy and the **external resistance** in all the other parts of a circuit together determine the amount of current that can flow around the circuit. The following things are true about any cell:

1. The voltage of a cell depends solely on the materials used for the electrodes and electrolyte.
2. The amperage of a cell depends on its internal resistance and voltage. Anything done to lower the internal resistance will increase the current that the cell will furnish.

CHECKING WHAT YOU LEARNED

1. **a.** Tell what you need in order to make a simple cell. **b.** How would you arrange the different parts so that the cell would work?
2. **a.** Why must every complete circuit contain a source of electrical energy? **b.** Explain in detail how a simple cell supplies electrical energy when it is connected in a closed circuit.
3. When will a current stop flowing in a closed circuit connected to a simple cell? Explain.
4. **a.** What kind of current does a cell furnish? How do you know? **b.** How does direction of current flow differ from that of electron movement?
5. **a.** State two reasons why a simple cell is such a poor and expensive source of electrical energy. **b.** If cells are poor and expensive sources of electrical energy, why do we use them at all?
6. **a.** What energy change takes place in a simple cell? **b.** What materials supply the energy?

Internal resistance: The resistance to current flow inside a source of electrical energy, such as a cell, battery, or generator. The resistance of the **internal circuit** within the source of electrical energy must be taken into account in determining the total resistance of a circuit.

External resistance: The resistance to current flow in all parts of a circuit except the source of electrical energy. The resistance of the **external circuit** outside the source of electrical energy must be added to the internal resistance in order to find the total resistance of a circuit.

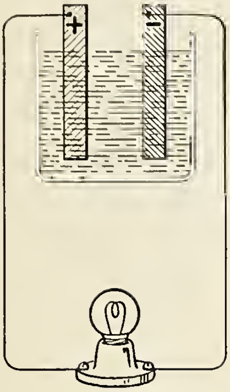
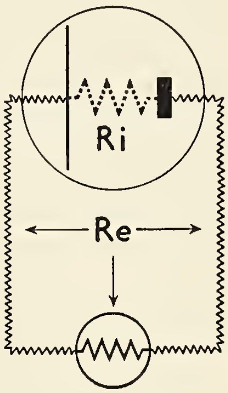


Figure 42 *shows that the resistance of a circuit such as that shown at the left is divided into two parts, the internal resistance of the cell and the external resistance of the circuit to which the cell is connected. In the diagram at the right the internal resistance (Ri) is shown by the dotted zigzag line between the electrodes of the cell, while the external resistance (Re) of the device and the connecting wires are shown by solid zigzag lines.*



7. What determines the E.M.F. of a cell? The current that a cell will supply?
8. You may think of the resistance of a circuit as being made up of two main parts. Name each part and tell where it is located.

USING WHAT YOU LEARNED

1. In any cell, which is the positive electrode? The negative? Give reasons for your answer.
2. An iron nail and a strip cut from an aluminum pan were put in a jar of strong salt water. Was a current produced when the nail and aluminum were connected by a wire? Why?
3. **a.** Which of these statements is correct? *No current flows in a circuit unless an electromotive force is present. No electromotive force is present in a circuit unless a current flows.* **b.** Explain why one statement is correct and the other is not.
4. **a.** How much current will flow through a wire whose resistance is 1 ohm if the pressure is 1 volt? **b.** A cell that supplies a pressure of 1 volt is found to have an internal resistance of 2 ohms. What is the largest current it will provide? **c.** If the wire mentioned in **a** is connected between the terminals of this cell, how much current will flow in the circuit? **d.** Why is the current in the circuit less than the wire will carry or the cell will provide?

The Dry Cell

You have seen that while a simple cell will produce an E.M.F. and thus a current in a circuit, it will not provide electrical energy in large amounts. Let us see how a much better cell, the so-called **dry cell**, works. Compared with a "wet" cell, a dry cell is fairly convenient to carry, because it contains no liquid that spills out when the cell is tipped over.

Beginning with the very first experiment in Chapter 1, we have been using dry cells as a handy source of electrical energy. You have seen that a dry cell, or a battery of two dry cells, will produce an E.M.F. that drives a current around a circuit, but you probably have not thought much about how this type of cell works. It appears to be very different from the simple cell used in the last two experiments. The very first thing for you to learn about a dry cell is that it is not dry at all! When it becomes really dry, the cell is useless. In fact, the only place where a usable dry cell is dry is on the outside. The inside must be kept moist; otherwise the cell will not work.

Structure and materials. In order to see how a dry cell is made, you should do Experiment 18. When the paper or cardboard covering is removed from a worn-out cell, you will see that the sides and bottom of the cell are made of zinc. This zinc "can" may be riddled with holes where the chemical in the electrolyte has eaten it away. You may also find white crystals (zinc chloride) on the outside of the can and around the holes. If a slit is cut through the zinc down one side and around the bottom, the zinc can may be unrolled and the cell taken apart, layer by layer. First there is a layer of blotting paper (or something much like it). When the cell was made, this paper was soaked in a water solution of sal ammoniac (ammonium chloride) and zinc chloride. The sal ammoniac solution is the electrolyte that acts on the zinc can, which of course is the active (or negative) electrode.

Inside the paper lining of the cell there is a pasty mass. When the cell is new, this mass is quite moist because it contains water to keep the blotting paper damp. A new No. 6 dry cell contains about three tablespoonfuls of water. The pasty mass is made of a water solution of sal ammoniac, zinc chloride, manganese dioxide, carbon grains, and usually a "filler" of sawdust. In the center of the cell there is a long carbon rod, which may be either smooth or grooved. This rod is of course the inactive (or positive) electrode of the cell. Because the electrolyte does not act on it, the rod does not have to be made of metal. Carbon, as you know, is a fair conductor of current. It is much cheaper to use than a copper rod of the same size would be. With zinc and sal ammoniac, carbon makes a cell whose E.M.F. is 1.5 volts. If the top of the cell is removed, there may be a layer of sand above the paper lining. Above this may be a layer of pitch and then there is a layer of sealing wax. The purpose of the pitch and sealing wax is to keep the water from evaporating from the cell.

By now you can see that a dry cell has all the essential parts needed to produce an E.M.F. by chemical action: two electrodes of different material (zinc and carbon) in an electrolyte (solution of sal ammoniac). Although different materials are used, the dry cell and the simple cell both work on the same principle. In either cell, chemical energy stored in the active electrode and in the electrolyte is changed into electrical energy. You have noticed, however, that a dry cell contains several materials not found in a simple cell. Perhaps you are wondering why these materials are added. They are put in simply to make the dry cell a better source of electrical energy than a simple cell is.

The pasty mass contains sawdust and carbon grains. The sawdust keeps the mass from packing down and also holds water. The carbon grains reduce the internal resistance of the cell, thus increasing the current that the cell can furnish. But what about the manganese dioxide and zinc chloride? You saw that a simple cell soon becomes polarized if left connected in a closed circuit. A dry cell will also become polarized if used for very long in a closed circuit. The zinc chloride and manganese dioxide are used to depolarize the cell. For that reason, they are called *depolarizers.* When the ammonium chloride (sal ammoniac) in the electrolyte acts on the zinc electrode, zinc chloride, ammonia, and hydrogen are formed.

Chemical changes in a dry cell: In a dry cell the zinc (Zn) and ammonium chloride (NH_4Cl) containing stored chemical energy are changed into zinc chloride ($ZnCl_2$), ammonia gas (NH_3), and hydrogen (H_2).

The following equation shows this chemical action: $Zn + 2NH_4Cl \rightarrow ZnCl_2 + 2NH_3\uparrow + H_2\uparrow$

Chemists are not agreed as to exactly what happens when the depolarizers act on the ammonia and hydrogen. However, they do know that the zinc chloride acts on the ammonia to form more ammonium chloride and that the manganese dioxide (MnO_2) acts on the hydrogen to form more water.

Dry cell: An improved type of cell that contains a moist, pasty electrolyte mixture sealed in a watertight container. The electrodes are carbon and zinc, which form the container.

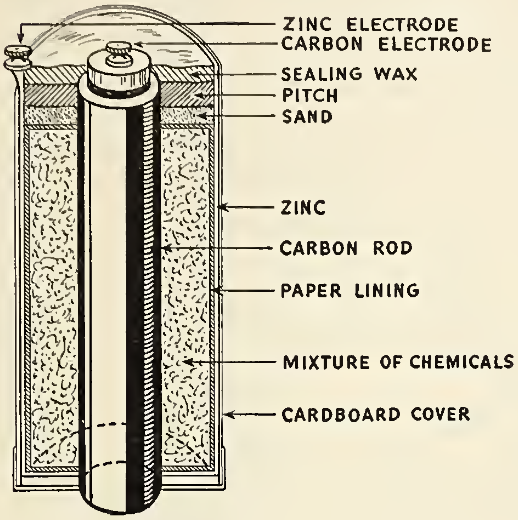


Figure 43 *shows a cut-away view of a dry cell. You can see that the center post is connected to the carbon rod, while the outside post is connected to the zinc can, which has a paper lining soaked with electrolyte. Between this lining and the carbon rod is a pasty mixture of chemicals and sawdust. The layers of pitch and sealing wax keep the pasty mixture from drying out, while around the cell is a cardboard cover. The carbon rod is the positive electrode, and the zinc can is the negative electrode.*

(You may smell ammonia if you cut open the dry cell in Experiment 18.) The zinc chloride dissolves in the electrolyte, while the hydrogen and ammonia collect on the carbon rod as bubbles of gas. Here the depolarizers slowly go to work. The manganese dioxide combines with the hydrogen to form water, while the zinc chloride acts on the ammonia to form more ammonium chloride, or sal ammoniac. You can see that a dry cell is a very cleverly designed device. Action of the electrolyte on the zinc provides more zinc chloride to act on the ammonia. When the zinc chloride acts on the ammonia, more sal ammoniac is formed to replace some that was used up. The manganese dioxide acts on the hydrogen to form more water, thus helping keep the pasty mass and paper lining moist.

The only material whose use we have not explained is the sand in the first layer at the top of the cell. Not all dry cells have this layer of sand; some have just a space between the pasty mass and paper lining and the layer of pitch or sealing wax. The purpose of the sand (or space) is to make room for the hydrogen and ammonia that are formed. When a large current is being used in the circuit, the gases are formed faster than the depolarizers can act on them. The gases are under considerable pressure, and they will burst the zinc can unless there is some place for them to go. The sand, space, and sawdust help absorb these gases until the depolarizers can act on them. Sometimes, however, such large currents are "drawn" from a dry cell that a great deal of gas is formed. Maybe you have seen a cell after this has happened; its sides are bulged out and possibly split.

Economical use. You have probably noticed that the light from a flashlight using dry cells is bright when first turned on, but if left on for very long it becomes dim. Then if you shut off the light, the cells regain their strength. For when you turn the light on again, it seems to be as bright as it was at first. From what you have learned about cells, you may have guessed the reason for this. While the cells in the flashlight are supplying current, hydrogen and ammonia are being formed at the carbon electrode. Even when the current is not too large, the depolarizers act rather slowly. The gases collect as bubbles faster than they can be removed by chemical action. The gas bubbles increase the internal resistance of the dry cells just as they did in Experiment 16.

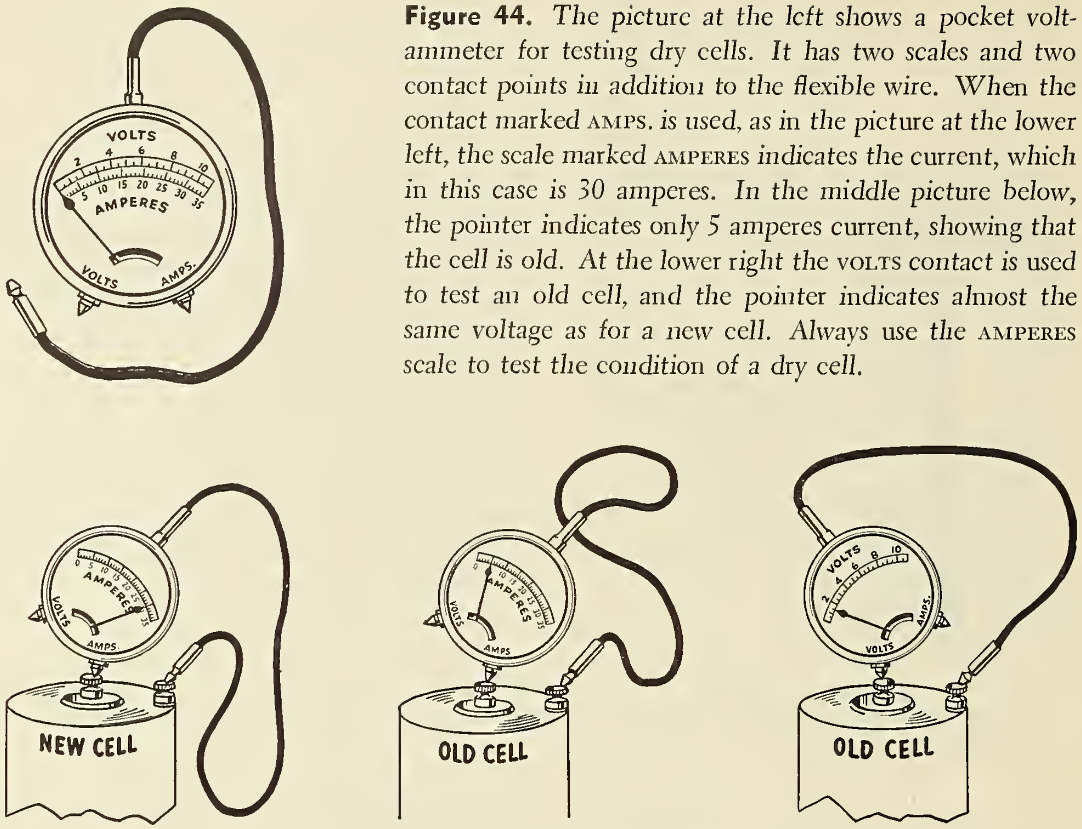


Figure 44. *The picture at the left shows a pocket volt-ammeter for testing dry cells. It has two scales and two contact points in addition to the flexible wire. When the contact marked* AMPS. *is used, as in the picture at the lower left, the scale marked* AMPERES *indicates the current, which in this case is 30 amperes. In the middle picture below, the pointer indicates only 5 amperes current, showing that the cell is old. At the lower right the* VOLTS *contact is used to test an old cell, and the pointer indicates almost the same voltage as for a new cell. Always use the* AMPERES *scale to test the condition of a dry cell.*

An increase in resistance, as you well know, reduces the current flowing through the circuit, which includes the flashlight bulb. With less current flowing through it, the filament of the bulb produces less heat and therefore less light. When the light is turned off for a time, the dry cells can "recuperate." The depolarizers act on the gas bubbles and remove them from the carbon. After this has happened, the light will be as bright as when it was first turned on. Perhaps you can see now why it is called a *flash*light, for the best way to use it is by flashing the light on and off. You can also see why dry cells are satisfactory for operating doorbells and buzzers, which use current only when a button is pushed.

A dry cell wears out even if it is never used to furnish current. In spite of great pains taken in manufacturing dry cells, a certain amount of chemical action (called *local action*) takes place in every cell even when it is not connected in a circuit. In time this chemical action will eat holes in the zinc electrode. When this happens, the water in the electrolyte evaporates, and the cell becomes useless. Keeping dry cells in a cool, dry place will prolong their life when they are not in use; but a cell is usually worthless after 12 to 15 months, whether used or not. Even after a dry cell becomes dry, it can sometimes be "revived." If you punch holes in the zinc can of a "dead" cell and then stand the cell in water (salt water will work even better), the cell will produce a current again. The water moistens the electrolyte in the blotting paper and pasty mass, and the cell can be used for a time. Of course, if the zinc is eaten away and the sal ammoniac and other chemicals are used up, nothing you do will revive the cell.

Testing. As long as there are zinc and sal ammoniac solution, the cell will furnish current. But as the materials are used up, the internal resistance of the cell increases. As a result, more of the E.M.F. is used to drive the current through

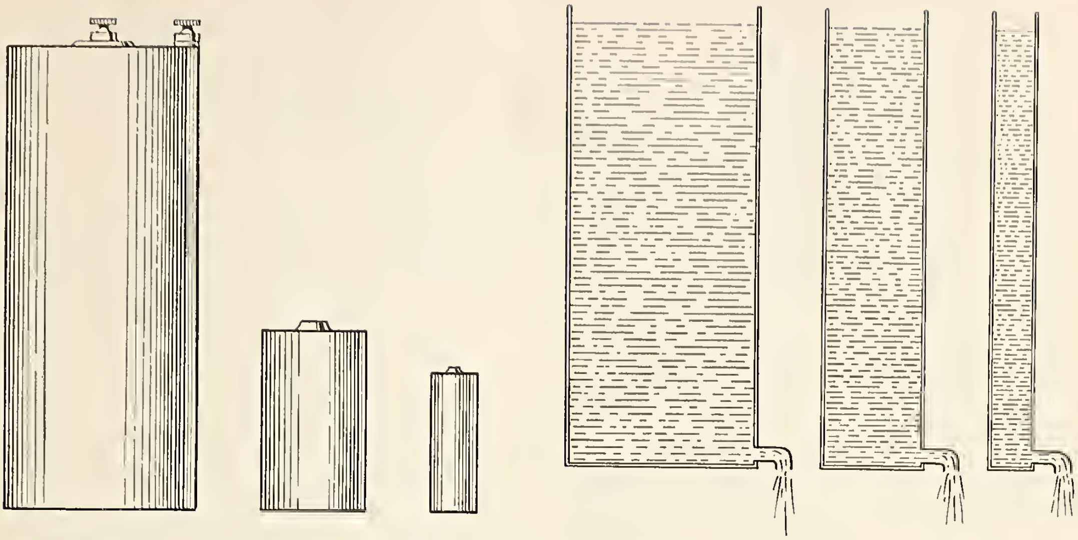


Figure 45. *At the left are shown three dry cells, each able to supply current at 1.5 volts pressure. With equal current flow the smallest will wear out first. At the right are three tanks of the same cross-sectional area as the cells. All three tanks produce the same pressure, but with equal flow the smallest tank will become empty first.*

the cell, and less E.M.F. is available to drive the current through the external circuit. As long as there are any active materials left in the cell, it will continue to show nearly the same voltage (about 1.5 volts) although the current it will furnish in a circuit may be very small. If you do Experiment 19, you can see that this is true.

If you use a pocket volt-ammeter to measure the voltage of a new dry cell and then that of an old dry cell of the same size, you will find that the voltage is about the same for each cell—close to 1.5 volts. As you have learned, the materials used to make a cell determine its voltage. Zinc, carbon, and sal ammoniac solution make a cell with a potential difference between the electrodes of about 1.5 volts. If you measure the amperage of a new No. 6 cell and also that of an old No. 6 cell, the new cell may give an ammeter reading of about 30 amperes, though the reading may be as low as 25 or as high as 35 amperes. The amperage of the old cell will be very much lower. If it is less than 5 amperes, the cell should be thrown away.

From Ohm's Law you can easily figure out what difference there is between the internal resistance of a new cell and that of an old cell. If a new cell shows 30 amperes at 1.5 volts, its internal resistance is $R = \frac{1.5}{30}$ or **.05 ohm.** If the old cell shows 5 amperes at 1.5 volts, its internal resistance is $R = \frac{1.5}{5}$ or **.3 ohm.** In other words, the old cell has an internal resistance six times as great as that of the new cell. You can see that testing a dry cell with a voltmeter tells you little if anything about its actual condition. A new cell that shows less than 1.45 volts is defective. Always test dry cells with an ammeter. Make the test quickly because the ammeter short-circuits the cell. If it is left across the posts of the cell very long, the cell will probably be ruined. You have already learned what will happen when large currents are drawn from dry cells. For most efficient use, no current larger than .25 ampere should be drawn from a No. 6 dry cell except for very short periods of time.

The small, round or rectangular dry cells used in flashlights are made of the same materials as the larger No. 6 dry cell used in the experiments. As you would expect, each of these cells produces the same voltage (about 1.5 volts). The combination of zinc and carbon electrodes in an electrolyte of sal ammoniac and water will always make a cell that furnishes current at a pressure of about 1.5 volts. If you did Experiment 17, you will remember that the size of the electrodes made no difference in the reading you obtained with a voltmeter. But you will recall that the reading you obtained with an ammeter varied with the size of the electrodes and their distance from each other. Similarly, we might expect the amperage of a dry cell, which indicates the amount of electrical energy the cell is supplying, to depend on the size of the electrodes in contact with the electrolyte and the distance between the electrodes.

If you test an ordinary flashlight cell with the pocket meter, you may find that the ammeter reading is about half as high as for a large No. 6 cell, that is, the reading may show about 15 amperes or less. If you test one of the very small, slender cells used in pencil-type flashlights, the reading may show only about 1 ampere. The reason for this, of course, is that the smaller cells have a higher internal resistance than the large cell. They are suitable only when a very small current is needed. Not only does a small cell furnish a smaller current, but in the long run it produces less electrical energy than a larger cell does. Obviously, a larger cell contains more stored chemical energy in its larger electrodes and greater amount of electrolyte in contact with them. As a result, a larger cell will provide more electrical energy.

CHECKING WHAT YOU LEARNED

1. Is a dry cell really dry? Explain your answer.
2. Why is a dry cell a better source of electrical energy than a simple cell? Give as many reasons as you can. Include any reasons you can think of that are not given in the text.
3. What substances produce an E.M.F. by chemical action in a dry cell? Tell what is produced in this chemical action.
4. **a.** What is meant by a depolarizer? **b.** Name the depolarizers used in a dry cell and tell what each one does.
5. List any substances not mentioned in questions 3 and 4 that are also found in a dry cell. After each one state the reason for using it.
6. Tell how you would test a dry cell.
7. What is the main difference between an old dry cell and a new one of the same size? Give the reason (or reasons) for this difference.
8. What determines the voltage of a dry cell? The amperage? The total amount of electrical energy it will provide?

USING WHAT YOU LEARNED

1. Where is the positive terminal of a dry cell? The negative? How do you know?
2. Using what you learned about the chemical action in a simple cell, tell how a dry cell produces an E.M.F. and thus a current by chemical action. Be sure to mention what happens to the electrons.
3. **a.** A manufacturer of dry cells says that its cells have a "shelf life" of from one year to fifteen months. What do you think this means? **b.** Most manufacturers stamp an "expiration date" on the dry cells they make. How can you use this in buying dry cells?
4. Is a dry cell an example of "perpetual motion"? Explain.
5. **a.** A dry cell whose pressure is 1.5 volts has an internal resistance of .075 ohm. If tested with an ammeter, how much current will it show? **b.** Is the cell satisfactory for use? Explain.
6. A dealer guarantees that all the No. 6 dry cells he sells will furnish at least 30 amperes. A man buys a cell and connects it in a closed circuit using a current of 5 amperes. In a short time the cell goes "dead." Has the man any reason to complain about the short life of the cell? Why?
7. When tested, a dry cell shows 3.75 amperes at 1.5 volts. **a.** What is its internal resistance? **b.** The cell is connected in a circuit requiring .25 ampere at 1.5 volts to operate properly. If the external resistance of the circuit is 11.6 ohms, will the cell be satisfactory? Explain.

Connecting Cells in Circuits

As you know, all ordinary dry cells supply current at a pressure of about 1.5 volts, no matter what their size or shape. But many times we need more pressure than a single cell will provide in order to drive enough current through a circuit to make a device work as it should. Devices are usually rated in volts; they are designed to work at a cer-

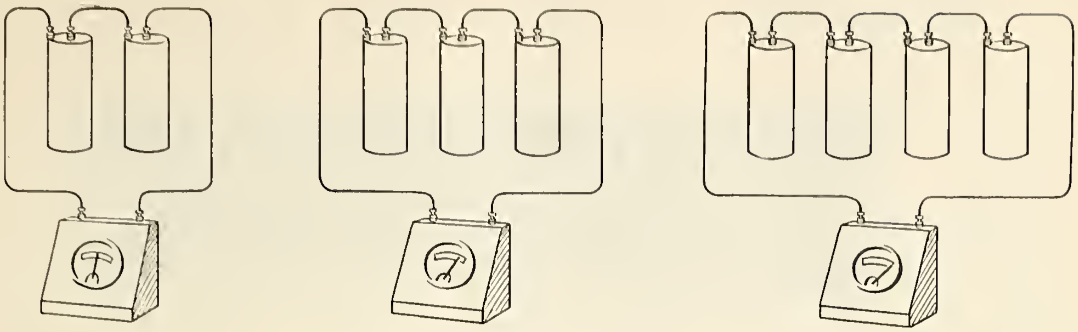
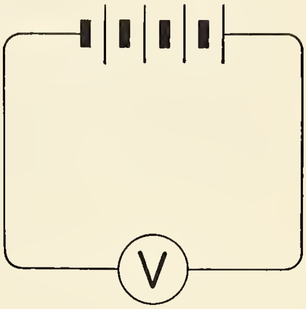


Figure 46 *shows how cells are connected in series to obtain increased voltages. Connecting two dry cells in series gives double the voltage of one cell, or 3 volts. Connecting three in series gives 4.5 volts, and connecting four in series gives 6 volts. In the diagram at the lower right, four pairs of long and short lines indicate that four cells in series are connected to the voltmeter, just as shown in the drawing at the upper right.*



tain pressure in the circuit. For example, flashlight bulbs may be rated as 1.5-, 3-, 4.5-, and 6-volt lamps. If a lamp is rated at 6 volts, an E.M.F. of 6 volts is required to force enough current through the filament to heat it to a temperature at which it will give off a bright light. One dry cell will not supply enough current to heat a 6-volt bulb properly, because it lacks sufficient E.M.F. In Experiment 11 the bulb became dim when the voltage available at the socket was reduced by increasing the resistance of the external circuit with a rheostat. Reducing the available voltage reduced the current through the filament of the bulb. The same thing will happen when there is not enough E.M.F. at the source of electrical energy. No matter what is done to decrease the resistance of the external circuit, a single dry cell will not supply current at a pressure of more than 1.5 volts. In order to get more E.M.F. in the circuit, we must connect two or more cells *in series.* In Experiments 10 and 11 two cells were connected in series to furnish current at a pressure of about 3 volts. When cells are connected in series, the E.M.F. of each cell is added to that of the others. You can see that this is true by doing the first part of Experiment 20, measuring the voltage of cells in series.

Cells in series. When you measure the voltage of two dry cells in series, the voltmeter reading should show about 3 volts—twice the voltage of one dry cell. If you connect another cell in series with the first two, the voltmeter reading should show about 4.5 volts (1.5 + 1.5 + 1.5), or three times the voltage of one cell. If you add a fourth cell in series with the other three cells, the voltmeter reading will show about 6 volts (1.5 + 1.5 + 1.5 + 1.5), or four times the voltage of one dry cell. You can keep on adding dry cells in series indefinitely. Each time you add another cell, you will find that the voltage increases by about 1.5 volts. The total voltage (at any time that the cells are not connected in a closed circuit) will equal the sum of the voltages of the individual cells. Since each cell has the same voltage, all you have to do to find the total voltage is to multiply the voltage of one cell by the number of cells connected in series. For handy use, we can put these statements in formulas: $E = E_1 + E_2 + E_3. \ldots$ This means that *E*, the total E.M.F., is equal to

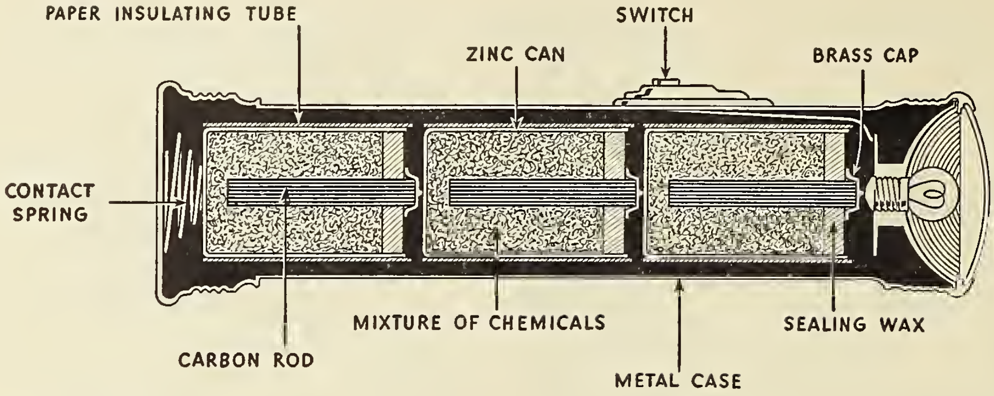


Figure 47 *shows a cut-away view of a three-cell flashlight. Notice that the three dry cells are connected in series, the carbon rod of one cell making direct contact with the zinc can of the next cell. The contact spring is important. In addition to completing the circuit, it holds the cells in contact with one another and with the lamp.*

the sum of all the *E*'s of the cells in series. If all the cells have the same voltage, then E = the E of one cell × the number of cells in series. You can see that these formulas apply equally well to any source of E.M.F. other than a dry cell.

In order to fix this important idea firmly in your mind, look at Figure 50. You see four pumps connected end to end, so that the stream of water flowing in the circuit of piping must flow through one pump after another. The pressure that each pump can exert on the water must be added to the pressures exerted by the other pumps to get the total pressure on the stream of water. The same amount of water flows through each pump in the circuit. As the water flows through the pumps, one after another, it gets a "kick" from each one. Each kick makes the water move faster. The faster the water flows, the greater the rate of flow in the circuit. You can see that the pumps in series are like the cells connected in the same way. Each cell gives the current a kick and thus increases the rate of flow in the circuit.

The series connection is by far the commonest way of connecting cells. An ordinary flashlight battery of two or more cells is a good example of a series connection. Figure 47 shows a three-cell battery in a flashlight. You can see that the center terminal of the first cell touches the center terminal of the bulb. The center terminal of the second cell touches the zinc can of the first cell, and the center terminal of the third cell touches the zinc can of the second. Behind the third cell is a metal spring attached to the screw cap. This pushes all the cells forward, making a good connection between the bulb and the cells. The metal spring is connected through a switch attached to a flat metal strip to the outer terminal of the bulb. Thus the flashlight not only has three cells connected in series but also a spring, switch, metal strip, and bulb in series with the cells. The battery of three cells furnishes current to the bulb at a pressure of 4.5 volts, or three times the pressure of one cell.

Another good example of a battery of cells connected in series is the so-called *B-battery* used in radio sets that do not work off the house-wiring circuit. In one part of the radio set a pressure of 90 or more volts is sometimes needed. Of course 90 volts could be supplied by connecting 60 large dry cells in series; but the cells would take up a great deal of space besides being very heavy. Since very little current is needed in this part of the radio set, there is no point in using 60 big cells. Much smaller batteries are provided by connecting 60 tiny cylindrical cells in series by soldering wires from one cell to the next. Then the

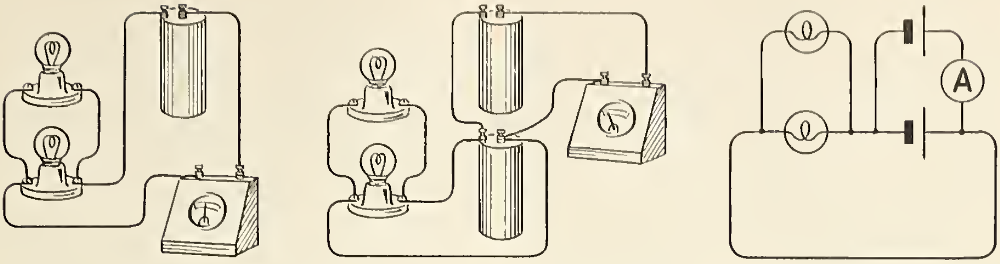


Figure 48 *shows why cells are connected in parallel. In the picture at the left, the ammeter indicates that the two lamps require about twice as much current as one dry cell can supply economically. However, when another dry cell is connected in parallel, each cell supplies half the current, as shown in the middle picture. At the right is a diagram of the circuit used in the middle picture. Notice that the ammeter is connected so that it measures only the current supplied by the additional cell.*

connected cells are put in a rectangular box and covered with sealing wax to protect the cells.

A much better B-battery is made up of many cells consisting of alternate layers of zinc, blotting paper soaked in sal ammoniac and zinc chloride, a cake of carbon grains and manganese dioxide, and carbon. You can see that each of these cells is a complete dry cell, which will furnish current at a pressure of 1.5 volts. Piling the cells up in layers gets rid of the soldered wire connection between cells; it also saves a great deal of space. A *layer-built* battery, as this type is called, will last much longer than a battery made of cylindrical cells, if the two batteries are the same size. You can see why this is true, for there is very little waste space in the layer-built battery. Practically all the space inside the battery box is taken up by cells. The larger cells have less internal resistance and will furnish more current than the smaller cylindrical cells of the other type B-battery.

Cells in parallel. Now let us find out how to connect dry cells so that we can draw larger currents without using up the individual cells too fast. For most efficient use, you know that no more than .25 ampere should be drawn from a single No. 6 dry cell except for very short periods of time. But suppose we need more than .25 ampere at a pressure of 1.5 volts or a little less. In some battery-operated radio sets the tubes require current at a pressure of 1.5 volts (sometimes 1.1 volts) to heat their filaments. Each tube in the set may require .25 ampere in order to heat the filament properly. Of course we could use one dry cell to furnish the current at a pressure of 1.5 volts for all the tubes, but this would mean that the cell would have to supply a current of .25 ampere *times* the number of tubes in the radio set. Let us say that the radio set has four tubes. Four times .25 ampere equals 1 ampere, the current that must be furnished as long as the set is turned on. Many experiments and tests have shown that when more than .25 ampere of current is drawn from a No. 6 dry cell in a closed circuit, the total amount of electrical energy that can be obtained decreases rapidly. In fact, when a current of 1 ampere is supplied for more than a short time, the cell will furnish only about one fourth as much useful electrical energy as when it supplies only .25 ampere for a long time. Dry cells, as you know, are rather expensive sources of electrical energy. It costs anywhere from 7 to 30 times as much to get electrical energy from a dry cell as from a generator. Drawing large currents from a dry cell for long periods of time uses up the cell rapidly and makes it even more expensive to use.

In order to prolong the life of the dry cell, you might suggest providing a separate cell to supply current for each tube in the radio set. In this way, the current drawn from any one cell would be kept down to .25 ampere. Your suggestion would solve the problem, but it would be unhandy to use in actual practice. However, what is done to solve the problem amounts to the same thing as your suggestion. First, all of the filaments in the tubes are connected in parallel, just as the heating appliances in Chapter 3 were connected in parallel in the house-wiring circuit. Then a battery of cells called an *A-battery* is connected *in parallel,* too. Since each tube requires .25 ampere at 1.5 volts, the battery must include one cell for each tube in the set. The battery of cells in parallel is connected to the filaments of the tubes in parallel. Obviously, the cells in the battery cannot be connected in series, because doing this would increase the E.M.F. in the circuit. So much current would flow that the filaments in the tubes would burn out. No more than 1.5 volts are needed to furnish current to the tubes. Therefore, the cells must be connected in such a way that a larger current can be drawn from the battery without increasing the E.M.F. in the circuit. From Chapter 3 you recall that when devices are connected in parallel in a circuit, part of the current flows through each device. When cells are connected in parallel, the same thing happens: Each cell furnishes part of the current in the circuit. If you do the second part of Experiment 20, you will see that this is true.

Now look carefully at Figure 48. You can see that the ammeter measures only the current supplied to the circuit by the second cell. Current supplied by the first cell does not flow through the meter. You already know how much current the first cell furnished to the circuit when one bulb was used and also how much current it supplied when two bulbs were used. The ammeter reading shows that the second cell is supplying the same amount of current as the first cell supplied to one bulb. Thus you can see that each cell in parallel furnishes part (in this case, half) of the total current used in the circuit. If you add additional sockets and bulbs in parallel, you will find that each added bulb draws as much more current as each of the bulbs connected in the circuit drew before the last bulb was added. Then if you add a dry cell to supply current for each added bulb, you can show that the added cell will furnish the extra current needed. When you measure the voltage of the battery of cells connected in parallel, you find that it is about 1.5 volts, the E.M.F. of a single dry cell, no matter how many cells are connected in the battery. When cells are connected in parallel, their E.M.F. is no greater than that of a single cell. Adding cells in parallel amounts to the same thing as increasing the size of one cell. You know that increasing the size of a cell has no effect on the E.M.F. of the cell but that it does increase the amount of current the cell will supply. The total current furnished by a battery of cells in parallel is equal to the sum of the currents supplied by the separate cells. This can be shown in a formula: $I = I_1 + I_2 + I_3 \ldots$ If all the cells will furnish the same current, then I = the I of one cell × the number of cells.

In order to get a clear idea of what connecting cells in parallel means, look at Figure 50. You see four pumps connected side by side. The pumps are the same size, and the pressure exerted by all four pumps working together is the same as the pressure of any one of them working alone. Water flowing through the circuit of piping gets a kick from only one pump, because only part of the water flows through each pump. However, each pump can handle the same amount of water as any other one can. The four pumps working together will furnish the sum of the amounts of water supplied by the separate pumps, or four times as much water as any one pump can supply at one time. You can see that pumps in parallel are like the cells connected in the same way. Each cell furnishes part of the current and thus increases the total current that can be supplied to the circuit without increasing the pressure in the circuit.

Cells in series-parallel. Now you know what to do when you need more E.M.F. or more current than a single cell will provide. If you need to increase the voltage in a circuit, you connect more cells in series. On the other hand, if you need more current (at the same pressure) than one cell will economically supply, you connect more cells in parallel. Perhaps you are wondering what to do if you need more E.M.F. *and* more current in a circuit. What kind of connection do you make in a situation like this? If you stop and think a minute, you can probably answer the question yourself. You make both a series and a parallel connection of cells. Such an arrangement of cells is called a **series-parallel connection.** If you do the last part of Experiment 20, you will see how cells are connected in this way.

Series-parallel connection: A method of connecting devices (usually cells) in a circuit so that groups in series are also in parallel with other groups in series. The devices connected in this way are said to be in **series-parallel.** Part of the total current in the circuit flows through each parallel connection, but the same amount flows through each group connected in series.

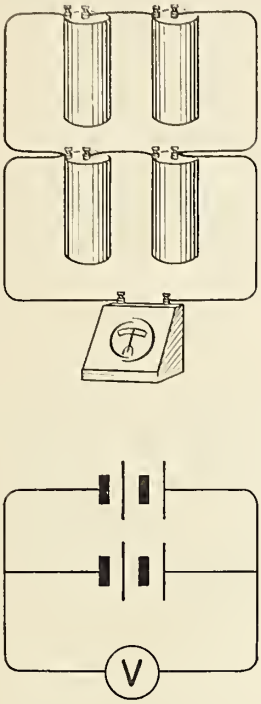
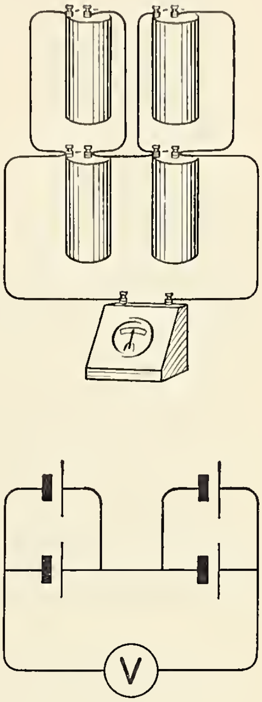


Figure 49 *shows two ways of connecting four cells in series-parallel. At the left, two cells in series are connected in parallel with two other cells in series. This is the usual way of connecting cells in series-parallel when all the cells are located at one point in the circuit. At the right, two cells in parallel are connected in series with two other cells in parallel. This way is seldom used unless the cells are at more than one point in the circuit. Either way gives the same voltage and amperage.*



If you measured the voltage of the series-parallel connection, it should be about 3 volts, which is what you would expect from two dry cells connected in series. You can use this connection of cells to supply .5 ampere of current at a pressure of 3 volts. By adding more cells in series or in parallel, you can make up any combination of E.M.F. and economical current use you need in a circuit.

In the last part of Experiment 20 you could have connected two sets of cells in parallel and then connected these sets in series. This connection would also furnish current at 3 volts. Figure 49 shows four cells connected in this other way. The other connection was used in the experiment because the cells connected in that way produce the same pressure with the same economical current use but require one less wire to connect the cells. You can see this by looking at the pictures. When the two sets of cells are far apart, as in a telephone circuit, it is better to use this second connection of cells, because only one long wire needs to be used in connecting in series the two sets of cells in parallel. No matter which one of these two connections is used, the total voltage is equal to the sum of the E.M.F.'s of the cells in one series connection. And the total amount of current that can be economically drawn from the cells is equal to the sum of the amounts of current supplied by the cells in each parallel connection. If you remember these two facts, you will never have any trouble in finding the voltage or amperage of any battery using a number of cells in series-parallel. No matter how complicated the connections may look, these two facts can be applied to find the voltage and amperage.

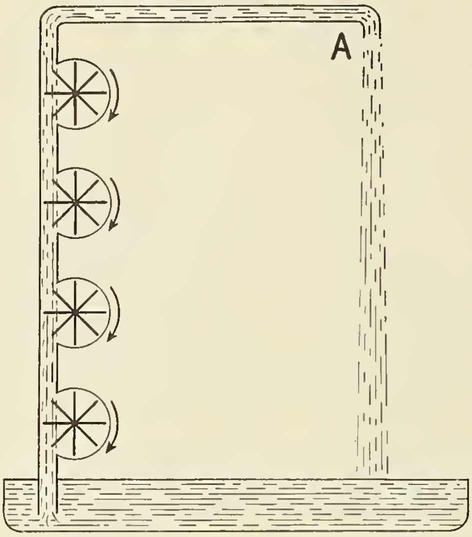
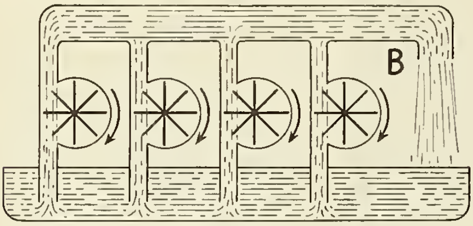
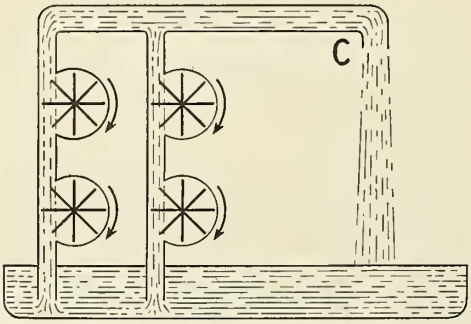


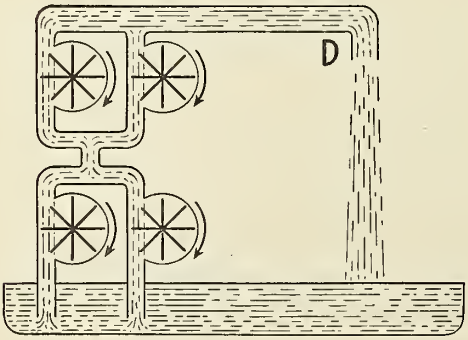
Figure 50 *shows various arrangements of pumps that correspond to various ways of connecting cells in circuits. Let us suppose that each pump is capable of lifting water 1.5 feet through a pipe of 1 inch cross-sectional area. By connecting the four pumps in an end-to-end (or* SERIES*) arrangement, we can lift the water four times as far as with one pump. At point A, which is 6 feet above the water level of the tank, the flow is the same as it would be with one pump.*



By connecting the four pumps in a side-by-side (or PARALLEL*) arrangement, we can lift four times as much water as with one pump. At point B, which is 1.5 feet above the water level of the tank, the flow is four times as large as at point A above.*



*By connecting two of the pumps in an end-to-end arrangement, we can lift the water twice as far as with one pump. And by connecting two more pumps in parallel with these (*SERIES-PARALLEL*), we can double the flow. At point C, which is 3 feet above the water level of the tank, the flow is twice as large with one set of pumps.*



*By connecting two of the pumps in a side-by-side arrangement, we can lift twice as much water as with one pump. And by connecting two more pumps in series with these (*SERIES-PARALLEL*), we can double the distance the water is lifted. At point D, which is 3 feet above the water level of the tank, the flow is the same as at point C.*

Open-circuit voltage: The electromotive force available at the terminals of a cell, battery, or generator not connected in a closed circuit. Also called **E.M.F. on open circuit.**

Closed-circuit voltage: The electromotive force available at the terminals of a cell, battery, or generator connected in a closed circuit. It is equal to the open-circuit voltage less the voltage drop due to overcoming the internal resistance. Also called **effective E.M.F.** or **effective voltage.**

In order to be sure that you understand series-parallel connections, look at Figure 50. The two bottom pictures show different connections using four pumps. You can see that an extra pipe is needed to make the second set of connections. Either arrangement of pumps will provide the same rate of flow of water at the same pressure as the other. When cells are connected in series-parallel, there is an increase in the E.M.F. and also in the amount of current that can be economically supplied to a circuit.

In actual practice, you will not meet with many situations in which cells must be connected only in parallel to furnish current. Usually more than one cell is needed to supply enough pressure in the circuit. In order to increase the E.M.F. and thus the current in a circuit, you will often have to connect cells in series. A parallel connection of devices using current is much commoner than parallel connection of cells, as you will see in working with different types of electrical circuits.

At times you will also have to connect cells in series-parallel to furnish current more economically and at a higher pressure than one cell will provide. Everything that you have learned about connecting dry cells in circuits applies equally well to any other kind of cell or, for that matter, to any source of electrical energy.

Voltage drop through cells. You have measured the voltage of cells in series, cells in parallel, and cells in series-parallel. You also know how much current each connection of cells can economically supply when used for more than a short time in a closed circuit. Now you are ready to find out just why various connections of cells are needed to furnish enough current at the proper pressure in different circuits. Like any other conductor in a circuit, a cell (or any source of electrical energy) offers opposition to the flow of current. This opposition, as you know, is called internal resistance. Whenever a current is forced through a resistance of any kind, there is a loss of E.M.F., or voltage drop, through the resistance, because some of the E.M.F. is used up in overcoming the opposition to current flow. In Experiment 11 you measured the voltage drop through a rheostat when a current was flowing through it. From the voltage drop and the current in amperes you know how to calculate the resistance in ohms of the rheostat, or any part of it. To do this, you use the Ohm's Law formula: $R = \frac{E}{I}$, in which *E* is the voltage drop and *I* is the amount of current flowing in the circuit. Since a cell offers resistance to the flow of current, it should be possible to measure the voltage drop through the cell when it is furnishing current to a circuit. If you know the voltage drop and the amount of current flowing, you should be able to calculate the internal resistance of a cell or any battery. The first part of Experiment 21 shows you how to do this.

When you took the voltmeter reading with the switch open, you noticed that it showed about 1.5 volts, the E.M.F. of one dry cell. When a voltmeter is used in this way, it measures what is called the **open-circuit voltage**, or **E.M.F. on open circuit**, of a source of electrical energy. After the switch was closed, the voltmeter showed a lower reading. Some of the E.M.F. was used in driving the current through the cell. The voltmeter showed how much voltage was left after this voltage drop through the cell. In other words, the meter showed the **closed-circuit voltage**, or **effective E.M.F.**, of the source of electrical energy connected in a closed circuit. You can see that the

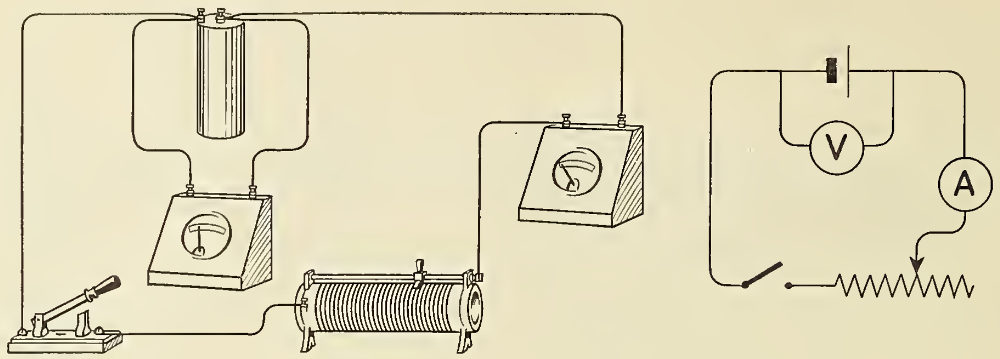


Figure 51. *When the switch is open in this circuit, the voltmeter shows the voltage of the dry cell when it is not supplying current. When the switch is closed, the voltmeter shows less voltage at the terminals of the cell while it is supplying current. The difference in the two readings is the drop in voltage caused by the internal resistance of the cell. At the right is shown a diagram of the circuit at the left.*

voltage drop through the cell is equal to the open-circuit voltage less the closed-circuit voltage. Suppose the voltmeter showed a closed-circuit voltage of 1 volt when a current of 2 amperes was flowing in the circuit. In this case, the voltage drop through the cell would be 1.5 volts minus 1 volt, or .5 volt. From this voltage drop and the current we can calculate the internal resistance of the cell: $R = \frac{E}{I} = \frac{.5}{2}$ or .25 ohm. The cell we are assuming must be an old cell, because a new cell has an internal resistance of about .05 ohm—one fifth as much. A great deal of the E.M.F. is lost in driving a current through the high internal resistance of the old cell. As a result, the closed-circuit voltage has been reduced to two thirds of the open-circuit voltage.

Since every cell or other source of electrical energy has some internal resistance, there is always a voltage drop through the source when it is furnishing current in a closed circuit. The closed-circuit voltage is always less than the open-circuit voltage. How much less depends on the internal resistance and the amount of current flowing. The higher the internal resistance or the larger the current, the greater the voltage drop will be. You can see that this is true from the Ohm's Law formula: $E = IR$. Any increase in either I or R will cause an increase in E, the voltage drop. If both I and R increase, the voltage drop will increase still more. As the voltage drop increases, the closed-circuit voltage decreases; for there is only a certain amount of open-circuit voltage to begin with. When a great deal of this E.M.F. is used up in merely driving the current through the cell, little is left to force current through the external circuit.

If the voltage drop through one dry cell is .5 volt when a current of 2 amperes is flowing, the terminal voltage is reduced to 1 volt. From the closed-circuit voltage and the number of amperes of current flowing in the circuit we can calculate the external resistance of the circuit by using the Ohm's Law formula: $R = \frac{E}{I} = \frac{1}{2}$ or .5 ohm. Now we can find the total resistance of the circuit by adding the internal resistance and the external resistance: .25 ohm + .5 ohm = .75 ohm. If we multiply the current flowing through the circuit by the total resistance, we get the E.M.F. acting in the circuit: $E = IR = 2 \times .75 = 1.5$ volts, the open-circuit voltage of the dry cell. Of course we knew this all the time, because the dry cell supplies current at a pressure of 1.5 volts. However, we wanted to show that all of the E.M.F. is used up when it drives a current around a circuit. Part of it is used to overcome the internal resistance, and all the rest is used in forcing the current through the external circuit. A potential difference must be maintained between the electrodes of a cell (or other source of E.M.F.) in order to keep on furnishing an E.M.F. to drive the current around the circuit. Chemical action in the cell maintains the potential difference that results in a continuous E.M.F. only so long as the stored energy in the cell is being changed to electrical energy. When the circuit is open or when all the stored chemical energy has been used up, the cell will not furnish current because the E.M.F. can no longer act in the circuit.

Increasing current. Now just what does all this have to do with connecting cells in circuits? The external circuit is always in series with the internal circuit of the source of E.M.F., no matter whether the source is a cell, battery, or generator. No more current can be driven through the external circuit than can be forced through the internal circuit of the source of E.M.F. If we want to increase the current flowing through the entire circuit, there are only two things we can do: Increase the E.M.F. at the source or reduce the resistance of the circuit. If we are using dry cells, we can increase the E.M.F. and thus the current by adding cells in series. Of course adding one or more cells in series increases the internal resistance of the source. You remember that the resistance of devices in series is equal to the sum of the individual resistances. The increase in internal resistance and the increased current caused by the greater E.M.F. of the cells in series result in a greater voltage drop through the cells in series than through one cell alone. Even so, the closed-circuit voltage is increased because the open-circuit voltage has been increased, too. If you do the second part of Experiment 21, you will see that this is true.

If we do not wish to increase the E.M.F. in a circuit, we can increase the current by reducing the resistance. From Chapter 3 you recall that when three heating appliances were connected in parallel, their combined resistance was less than that of any one of them. Connecting them all in parallel reduced the external resistance of the circuit and thus the total resistance of the circuit. So much current flowed that the fuse became hot and melted. In a similar way, we can reduce the resistance of a circuit by reducing the internal resistance of the source of electrical energy. When cells are connected in parallel, more paths are provided. Connecting cells in parallel has the same effect as increasing the size of one cell. As you know, a large dry cell has a lower internal resistance than a smaller one. Because of their lowered internal resistance, cells in parallel will furnish more current (at the same pressure) than will one cell alone. Two identical cells in parallel have an internal resistance equal to one *half* that of one cell; three identical cells in parallel have an internal resistance equal to one *third* that of one cell; and so on for any number of identical cells in parallel. Cells in parallel have the same E.M.F. as a single cell, but the internal resistance of such a battery is lower. Therefore, there will be less voltage drop through the battery of cells than through one cell. As a result, the closed-circuit voltage increases and more of the E.M.F. is available to drive current through the external resistance. If

---

Calculating the current in a circuit: For all ordinary purposes the current in a circuit can be calculated from the Ohm's Law formula: $I=\frac{E}{R}$ in which E is the open-circuit voltage of the source of E.M.F. and R is the total resistance of the circuit. For very precise work, however, it is sometimes necessary to take into account the internal resistance (R_i) of the source and also the external resistance (R_e). The following formulas show how to do this for various connections of identical cells. In the formulas E stands for the open-circuit voltage of one cell.

Cells in series: $I=\dfrac{E\times\text{number of cells}}{R_e+(R_i\times\text{number of cells})}$

Cells in parallel: $I=\dfrac{E}{R_e+\dfrac{R_i}{\text{number of cells}}}$

Cells in series-parallel:

$$I=\frac{E\times\text{number of series groups in parallel}\times\text{number of cells in series in each parallel group}}{(R_e\times\text{number of series groups in parallel})+(R_i\times\text{number of cells in series in each parallel group})}$$

you do the third part of Experiment 21, you can see this for yourself.

In selecting the best connection of cells for a circuit, both the resistance of the circuit and the amount of current needed must be considered. If the external resistance is high and the current needed is not large, the cells should be connected in series to provide more E.M.F. to drive the current through the circuit. On the other hand, if the external resistance is low and a large current is needed, the cells should be connected in parallel to furnish the current economically. But if a large current must be sent through a fairly high external resistance, the cells should be connected in series-parallel to provide for economical current use at a greater E.M.F.

Suppose you need a current of 1 ampere at a pressure of 6 volts in a circuit. You connect four dry cells in series to get the pressure of 6 volts. Then you connect three more sets of four cells in series. These sets are connected in parallel with the first set of four cells in series. Each set will then furnish .25 ampere of current to the circuit, or a total of 1 ampere, at 6 volts. Cells in series-parallel form a battery with the advantages of both series and parallel connections.

CHECKING WHAT YOU LEARNED

1. **a.** Name the three main ways of connecting cells in a circuit. After each one tell why it is used. **b.** Draw a diagram of a battery of four dry cells connected in each way. On each diagram indicate the E.M.F. of the battery and the largest amount of current it will supply economically when used in a closed circuit for more than a short time.
2. **a.** What is meant by open-circuit voltage? Closed-circuit voltage? **b.** Which one is greater? Why?
3. How many dry cells does a 45-volt B-battery contain? How do you know?
4. **a.** In what two ways can the current in a circuit be increased? Why? **b.** Tell how cells are connected to supply current in each of these ways.

USING WHAT YOU LEARNED

1. **a.** A current of 2.5 amperes flows in a circuit containing one dry cell whose internal resistance is .08 ohm. What is the voltage drop through the cell? The closed-circuit voltage? **b.** Find the external resistance of the circuit and also the total resistance.
2. **a.** A 6-volt lamp requires 1 ampere for proper brilliance. How many dry cells will be needed to supply the current economically at this pressure? **b.** Draw a diagram to show how you would connect the battery of cells in a circuit with the lamp.
3. In connecting cells in parallel, why must you be careful not to connect the center post of one cell to the outside post of another and then connect the other two posts?
4. **a.** Explain what happens in a circuit if one cell goes "dead" in a battery connected in series? **b.** In a battery connected in parallel?
5. The internal resistance of each of four dry cells in series is .1 ohm. **a.** Find the voltage drop through the battery and also the closed-circuit voltage when a current of 2 amperes is flowing in the circuit. **b.** What is the external resistance of the circuit? The total resistance?
6. Six dry cells, each having an internal resistance of .2 ohm, are connected to furnish .5 ampere at 4.5 volts. **a.** Draw a diagram showing how the cells are connected in the battery. **b.** Calculate the voltage drop, the closed-circuit voltage, and the internal resistance of the battery. **c.** Calculate the external resistance of the circuit and also the total resistance.

The Storage Battery

You know that a cell will furnish an E.M.F. and thus a current in a circuit only so long as chemical energy stored in the cell can be changed to electrical energy. When all the stored chemical energy is used up, the cell will no longer supply current to a circuit. If there is no practical way of *charging* the cell again, that is, restoring its chemical energy, the worn-out cell is thrown away and replaced with a new one. Cells, such as a dry cell or a simple cell, that cannot be recharged are called **primary cells** to distinguish them from cells that can be recharged, which are known as **secondary cells.** The storage batteries you are going to read about in this part of the chapter are made up of secondary cells, usually connected in series to provide current at a higher pressure than one

Primary cell: An electrical cell, such as a simple cell or dry cell, that cannot be recharged after all its stored chemical energy has been changed to electrical energy.
Secondary cell: An electrical cell, such as a storage cell, that can be recharged by sending a current through the cell and thus changing electrical energy into chemical energy, which is stored in the cell to be changed back to electrical energy as needed.

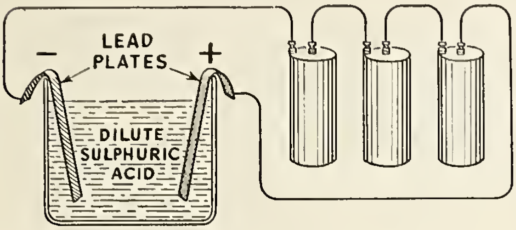


Figure 52 *shows a simple storage cell made by putting two strips of lead into a solution of dilute sulphuric acid. Three dry cells in series are connected to the strips to form the plates and charge the cell.*

cell will furnish. A secondary cell works on the same principle that a primary cell does: Chemical energy stored in electrodes and the electrolyte is changed to electrical energy by chemical action. But when the chemical energy has been used up, the secondary cell can be recharged by sending a current through it. In this way, electrical energy is changed into chemical energy, which is stored in the materials of the cell. After recharging, a secondary cell will again furnish an E.M.F. and thus a current. Right now is the time for you to understand clearly that a storage cell does *not* store electrical energy; it stores chemical energy just as any cell does and then changes the chemical energy into electrical energy as needed. When the chemical energy has all been changed to electrical energy, it can be restored only by sending a current through the cell. Since you have learned that dry cells are not really dry, you should not be surprised to learn that storage batteries do not really store electrical energy.

Lead-acid cell. There are two main types of storage cells in use, but the commoner by far is the lead-acid cell. The storage battery in an automobile is made up of three lead-acid cells connected in series. Trucks and airplanes often use a storage battery of six cells in series. You can easily see how a lead-acid cell is made and how it works by doing Experiment 22. (See Figs. 52 and 53.)

When you put two clean lead plates into a glass jar about two-thirds full of dilute sulphuric acid and then connect the plates to an ammeter or bell, you soon discover that no current is produced. That is what you might expect; since in order to produce a current, a cell must have two different electrodes in an electrolyte. Both electrodes are the same, and so no current flows in the circuit. However, if you connect a battery of three dry cells in series to the lead plates, you will soon see that a chemical action is taking place. Bubbles of gas (hydrogen) are formed at the lead plate attached to the negative terminal of the battery, and this lead plate appears even cleaner and fresher than before. At the other plate fewer gas bubbles (oxygen) are formed, and the plate gradually changes from lead gray to dark brown. This brownish material is a kind of lead "rust" called lead peroxide. It is formed because the current produces oxygen at the plate connected to the positive terminal of the battery. If you disconnect the dry cells at the end of a few minutes and then connect the electrodes to a bell, the bell will ring for some time. An ammeter connected to the cell will show that it produces a current of possibly 3 amperes. If you test the cell with a voltmeter, it will show an open-circuit voltage of about 2 volts. A charged lead-acid cell always shows this pressure.

When one of the plates was changed to lead peroxide, your cell had all that was needed to form a cell: two different electrodes (lead and lead peroxide) in an electrolyte (water solution of sulphuric acid). The cell then produced a current in the same way that any cell does—by changing

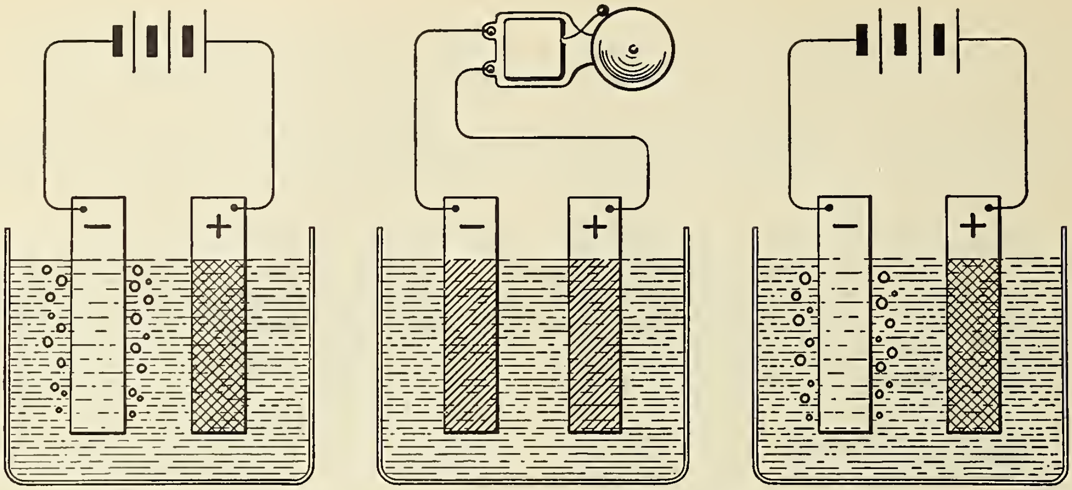
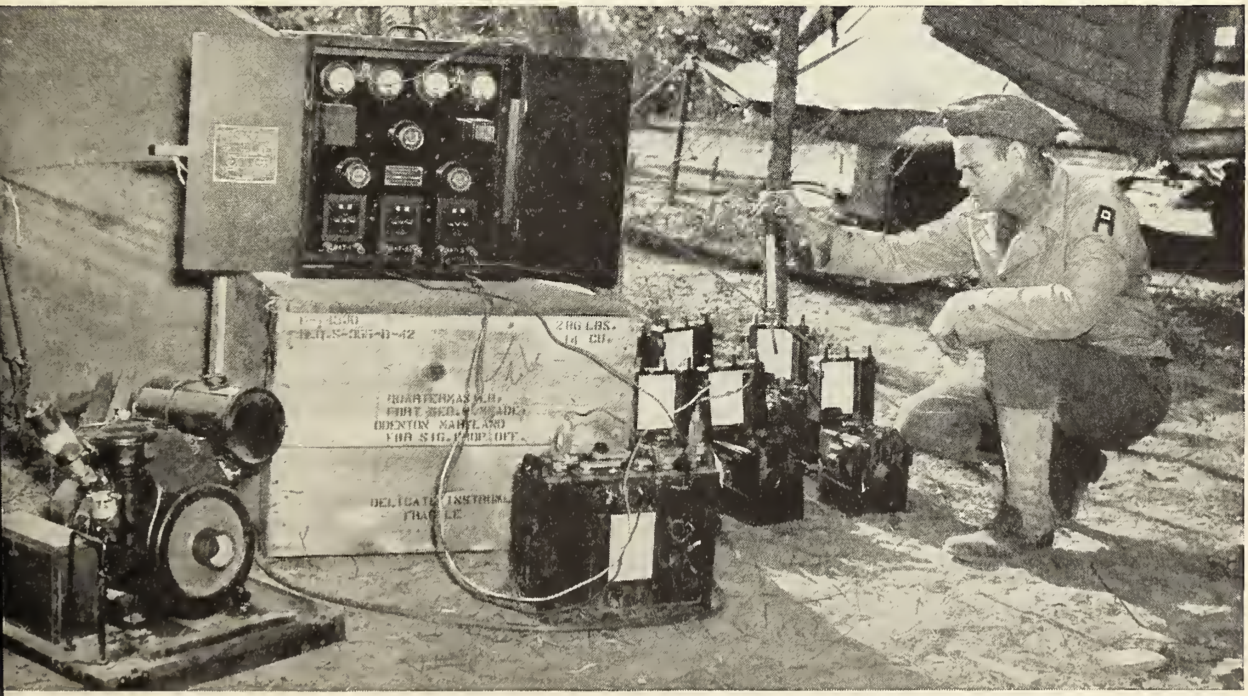


Figure 53. *At the left is shown a simple storage cell while the plates are being formed. Hydrogen bubbles rise from the negative plate, which becomes a clear gray as the positive plate becomes coated with brown lead peroxide. The middle diagram shows the cell discharging. The formation of lead sulphate causes the lead plate to become a dull gray and the lead peroxide plate to become light brown. At the right the cell is being charged. The negative plate becomes a clear gray and the positive plate becomes dark brown again as the lead sulphate is removed.*

stored chemical energy into electrical energy. If you left the storage cell connected to the bell for a time, the ringing gradually became weaker until it stopped entirely. The dark-brown plate is now a lighter brown, and the lead plate is a dull gray. Evidently, the cell has become *discharged,* for it will not provide enough E.M.F. to force a current through the bell circuit. If you connect the cell to an ammeter, the needle will show that very little (if any) current is flowing. The chemical energy stored in the materials of the cell has been largely or entirely changed to electrical energy. If any chemical energy is left, it is not sufficient to furnish an E.M.F. that will overcome the internal resistance of the cell and make a current flow. By connecting the discharged cell to the battery of dry cells once more, you can charge the cell again. After a time the brown plate will become dark, and then the cell will produce a current.

Chemical action. Now that you know what a storage cell is and what it does, you are ready to find out what chemical changes take place to produce electrical energy. When you connected a battery to the lead plates and sent a current through the cell, the water in the electrolyte was broken down into the chemical elements that make it up by a process called *electrolysis.* From Chapter 2 you recall that water is composed of hydrogen and oxygen. The hydrogen in the form of electrically charged ions goes to the lead plate connected to the negative terminal of the battery of dry cells. Here it escapes from the electrolyte as bubbles of gas. The oxygen, also in the form of ions, goes to the lead plate connected to the positive terminal of the battery. Here some of it escapes as bubbles of gas, but most of it combines with the lead to form a brownish compound, lead peroxide. Changing one lead plate to lead peroxide and the other to pure lead is known as *forming* the plates. The cell now contains two different electrodes in an electrolyte; it will produce a current, as you have seen. When the cell is discharged, the sulphuric acid acts on *both* electrodes and changes them to lead sulphate. In the simple cell and the dry cell, you recall that only one electrode was changed chemically by the electrolyte. When lead sulphate is formed by

The Army finds many uses for storage batteries and dry cells of various kinds. At the upper left, for example, is the familiar automobile storage battery on the running board of an Army truck. A voltmeter is being used to check the charge in one of the cells of the battery. At the upper right is shown a Signal Corps soldier operating a small, battery-powered radio designed for two-way communication. Although intended primarily for use by soldiers on horseback, the radio works equally well when used by soldiers on foot or in vehicles. The picture below shows how the special storage batteries used for telephones and other means of communication are charged while troops are in the field. A portable generator driven by a small gasoline engine supplies current to charge the batteries. In this picture a hydrometer is being used to test the charge.



this chemical action, water is also formed. As a result, the sulphuric acid becomes even more dilute. When both electrodes are covered with lead sulphate, the cell no longer has two different electrodes in an electrolyte and chemical energy is no longer changed to electrical energy. Now if the battery is charged by sending a current through it, one plate will be changed back to lead peroxide and the other to lead. Another product of the chemical action is sulphuric acid, which is formed from the water and lead sulphate. The cell is now recharged. It will furnish a current because once more the electrodes in the electrolyte are different from each other.

Commercial storage batteries. From Experiment 22 do not get the idea that it is very simple to make a reliable storage battery. If you charge your storage cell and let it stand for a while, you will find that it loses its charge as a result of local action within the cell. The storage batteries used in automobiles, trucks, tanks, airplanes, submarines, and torpedo boats are much more carefully constructed than the cell you made. Even so, a commercial storage battery is not so efficient as you might think, because it does not give out as much electrical energy while discharging as it requires when being charged. A good battery will give back from 75 to 85 per cent of the electrical energy used in charging it. The other 15 to 25 per cent is used to make the chemical action take place and to produce heat and gases (hydrogen and oxygen).

Well-made storage batteries are designed to furnish large currents. In order to do this, the internal resistance of each cell must be made as low as possible. Large plates are used to increase the amount of surface exposed to the electrolyte. In each cell of a lead-acid battery, there are two different sets of plates—the positive (lead peroxide) set and the negative (lead) set. All the plates in each set are connected together by a strip of lead at the top. Then the two sets are fitted together, as shown in Figure 54. Increasing the number of plates in each set increases the amount of surface exposed to the electrolyte, and thus helps make it possible for the cell to furnish large currents. There is always one more plate in the negative set than in the positive set, because in each cell the outside plate at either end is a negative plate.

Another way in which the current of a cell is increased by lowering the internal resistance is a result of putting the sets of electrodes close together. In order to keep the electrodes from touching, thin strips of wood, rubber, or plastic called *separators*, are put between the electrodes. The separators have holes or grooves in them, so that the electrolyte can touch each plate. Using a large surface exposed to the electrolyte and a small space between electrodes means that a storage cell will provide much larger currents than a simple cell or even a dry cell. For example, to run the motor that starts an automobile, a current of 200 amperes is needed for a short time. Each cell of a lead-acid battery furnishes current at a pressure of about 2 volts, as you know. The three cells connected in series by lead strips thus supply current at a pressure of 6 volts. It would take four dry cells just to provide this pressure. Without unduly using up the dry cells, we could probably draw a current of 2 amperes at 6 volts for a short time. In order to provide 200 amperes at 6 volts, we would then need 400 dry cells in series-parallel to start the car! You can well imagine how a large battery of dry cells like this would look. It

---

Chemical changes in a storage cell: When the two lead (Pb) plates are put in the dilute sulphuric acid (H_2SO_4 and H_2O) and a current is sent through the cell, the following chemical action takes place: $Pb + 2H_2O \rightarrow PbO_2 + 2H_2 \uparrow$

Only one of the lead plates is changed to lead peroxide (PbO_2), and the sulphuric acid serves only to make the water a conductor of current. When the lead peroxide plate is formed, the cell is charged and will furnish current. As the cell discharges, the following chemical action takes place: $Pb + PbO_2 + 2H_2SO_4 \rightarrow 2PbSO_4 + 2H_2O$

During discharge both plates are changed to lead sulphate ($PbSO_4$), and water is also formed. When the cell is recharged by sending a current through it, the chemical action is reversed:

$$2PbSO_4 + 2H_2O \rightarrow Pb + PbO_2 + 2H_2SO_4$$

Ampere-hour: The amount of electrical energy furnished by a current of 1 ampere flowing for 1 hour. Storage batteries are rated by the number of ampere-hours they will supply during a discharge period of 8, or sometimes 10, hours.

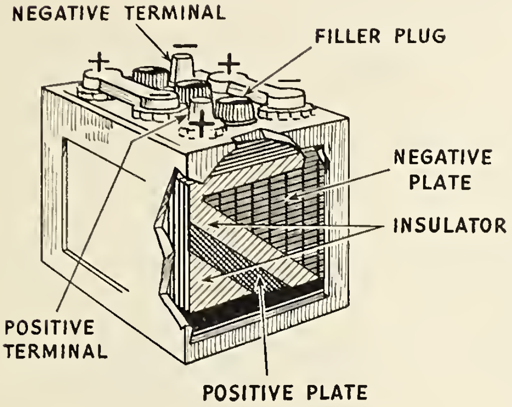


Figure 54 *shows a cut-away view of an automobile storage battery, which usually consists of three storage cells in series. Each cell consists of a number of negative and positive plates separated by insulators, and thick strips of lead join these plates to the terminals of the cells. The filler plug is removed whenever it is necessary to add distilled water to the cell or whenever it is necessary to measure the density of the electrolyte.*

would take up all the space in the back seat. Since dry cells cost about 50 cents apiece, this bulky battery would cost about 200 dollars. You can buy a good storage battery for about 10 to 15 dollars. Storage batteries not only furnish large currents, but they take up only a little space and are fairly inexpensive. In a pinch, you can use the storage battery of a car to move the car by means of the starter motor. However, this may damage the battery and should never be done except in an emergency. Ordinary 6-volt storage batteries are not designed for this kind of use.

To furnish large currents and withstand abuse, a storage cell must be sturdily built. The plates are composed of rigid frameworks, or *grids*, made of an alloy of lead and another metal called antimony. The active material of each plate is held in place by the grid. Into the positive grids brown lead peroxide is pressed, while very pure "spongy" lead is forced into the negative grids. (When storage cells were first made, the positive plates were formed from lead just as they were in Experiment 22. It is much cheaper and quicker to prepare the lead peroxide outside the cell.) The metal strips at the top of each set of grids are melted, or "burned," together to form a good connection between all the plates of a set. The two sets of plates are fitted together with their separators and hung in a case of plastic, rubber, or glass. The electrolyte consisting of dilute sulphuric acid is then poured in, and the cell is ready to furnish current. As already mentioned, three or six storage cells are usually connected in series to furnish current at a pressure of 6 or 12 volts.

Rating storage batteries. Each cell of a storage battery contains an odd number of plates. As you know, the more plates a cell contains the larger the current it will supply. Storage batteries are sold as 11-plate batteries, 13-plate batteries, and so on. Actually, a battery contains as many plates as there are in each cell *times* the number of cells. For example, a 17-plate battery of three cells contains 51 plates. A much better way of rating storage batteries is by the number of **ampere-hours** of electrical energy they furnish. An ampere-hour is the amount of electrical energy furnished by a current of 1 ampere when it is used for 1 hour. If a storage battery is rated at 100 ampere-hours, this does not mean that it will supply a current of 100 amperes for 1 hour. Such a large drain of current

Hydrometer: An instrument for measuring the specific gravity of liquids. The electrolyte in storage cells is tested with a hydrometer to determine the amount of charge in each cell.

Specific gravity: The weight of a liquid (or solid) substance compared with the weight of an equal volume of water. The electrolyte of a fully charged storage cell will show a specific gravity of 1.300 (or a little less). The electrolyte of a fully discharged storage cell will show a specific gravity of 1.150.

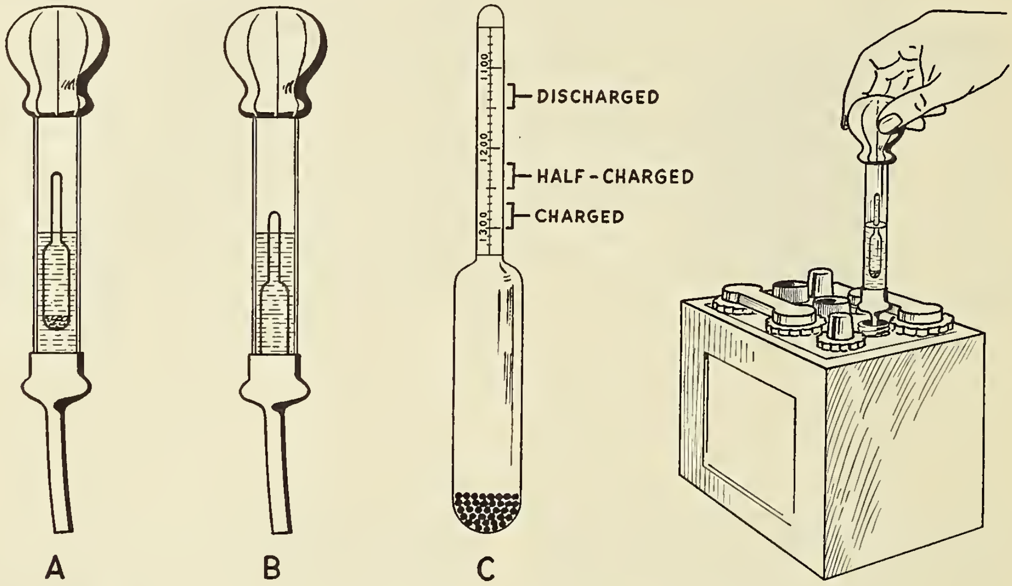


Figure 55. *The picture at the right shows how a hydrometer is used to test the charge of a storage cell by measuring the specific gravity of the electrolyte. The position of the float in electrolyte drawn from a fully charged cell is shown at A, and from a discharged cell at B. A close-up of the float is shown at C. Notice particularly the scale used to indicate the specific gravity of the electrolyte and the ranges of specific gravity for cells that are charged, half-charged, and discharged.*

for so short a time would ruin the battery. Instead, the rating means that the battery will furnish 100 ampere-hours of electrical energy during a discharge period of 8, or sometimes 10, hours. For example, a 100-ampere-hour automobile battery will furnish a steady current of 12.5 amperes for 8 hours (12.5 amperes × 8 hours = 100 ampere-hours). The 8-hour discharge period is used in rating storage batteries for Army as well as civilian use. On the other hand, the Navy rates batteries on a 10-hour discharge period. Thus a 100-ampere-hour storage battery for Navy use must furnish a steady current of 10 amperes for 10 hours.

Testing. Since storage batteries furnish such large currents, you can readily see that a pocket meter would quickly burn out if used to measure the current in the same way as for a dry cell. You know that a voltmeter reading does not tell very much about the condition of a dry cell. The same thing is true for a storage cell. When the cell is fully charged, it should have an open-circuit voltage of about 2.2 volts. When it is discharged, the open-circuit voltage will be about 1.8 volts. A change of .4 volt for each cell will result in a total change of 1.2 volts for a battery of three cells in series. A sensitive meter will show this change, but a much better way to test a storage cell, or battery of cells, for the condition of its charge is with an instrument called a **hydrometer.**

By means of a hydrometer you can find out how much the sulphuric-acid solution of the electrolyte has been diluted with water. You remember that when a storage cell discharges, water is added to the solution and sulphuric acid is removed. When a storage cell is charged, water is removed from the solution and sulphuric acid is added. The electrolyte in a discharged cell thus contains more water and less acid than in the same cell when fully charged.

Pure concentrated sulphuric acid weighs 1.835 times as much as an equal volume of pure water. Scientists say that concentrated sulphuric acid has a **specific gravity** of 1.835. (*Gravity* is an old word for "weight," and *specific* means "compared with a standard." *Specific gravity* thus means "weight compared with a standard." The standard used is an equal volume of water.) When the concentrated sulphuric acid is diluted with water to make the electrolyte, its specific gravity is reduced to about 1.300. If this electrolyte is poured into a new cell of a commercial battery, the cell will be fully charged and able to furnish current. As the cell discharges, more water is added and some sulphuric acid is removed so that the specific gravity of the electrolyte is further reduced. In a fully discharged cell the electrolyte has a specific gravity of about 1.150. Since the specific gravity of water is 1.000, you can see that the electrolyte in a discharged battery must contain more water than sulphuric acid.

By using a hydrometer you can test the specific gravity of the electrolyte in each cell, and thus you can tell how much charge the battery has. The usual type of hydrometer used for this purpose consists of a glass tube with a rubber bulb at one end and a rubber tube at the other end. Inside the glass tube is a float, also made of glass. On the float there is a scale reading from 1100 at the top to 1300 at the bottom. In all the scale numbers the decimal point has been left out; for example, 1100 really means 1.100 and 1300 really means 1.300. A fully charged cell will show a hydrometer reading of somewhat less than 1300, usually 1280 or 1290. When halfway discharged, the cell will give a hydrometer reading of 1250. The reading should never be allowed to get below 1175. In the winter, especially, the reading should be kept above 1225. Although the storage cell is not completely discharged at this point, it is not advisable to discharge a cell entirely. The reason for this is that a complete discharge changes so much of both electrodes to lead sulphate (a non-conductor) that it is difficult to change them back to lead peroxide and lead.

To use a hydrometer, remove the filler plug from a cell. Insert the rubber tube of the hydrometer into the cell and squeeze the rubber bulb. Release the bulb, drawing some electrolyte into the glass tube. Take the reading and then return the electrolyte to the cell. After each use, a hydrometer should be flushed out with clean water.

To recharge a storage battery, a current from another source of electrical energy must be sent through the cell. The positive terminal of this source must be connected to the positive terminal of the discharged battery, and the negative terminal of the source must be connected to the negative terminal of the battery. In other words, the charging current must be sent through the battery in the opposite direction to the current that is produced by the battery. The source of electrical energy, a generator or a *rectifier,* must supply a direct current. A well-made storage battery can be discharged and recharged as many as 500 times before finally wearing out.

If you do not know which terminal of a commercial storage battery is positive and which is negative, you can easily find out. Put some faucet water in a glass tumbler or small jar. (If you add a little salt or acid, the water will conduct a current better.) Then attach insulated wires to the terminals of the battery. Dip the bare ends into the water but do not let the ends touch. Bubbles

---

Rectifier: A device for changing the alternating current ordinarily supplied to a house-wiring or similar circuit to direct current. Rectifiers will be discussed again in Chapters 11 and 12. They are used not only to charge storage batteries but also to supply current to radio sets operated from the house-wiring circuit.

of gas (hydrogen) will appear at the bare end of the wire connected to the negative terminal of the battery. Another way to find out which terminal is which is to connect a voltmeter to the terminals of the battery. If the voltmeter shows a reading, the positive terminal of the battery is connected to the positive terminal of the voltmeter and the negative terminal is connected to the negative terminal of the meter. If no reading is indicated, you have connected the voltmeter backwards. This second method will work only with voltmeters whose terminals are marked. If the meter terminals are not marked, the meter may be connected in either way.

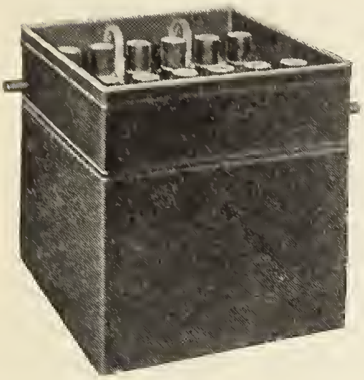
Care. With good care a storage battery will last from one and a half to two years or even longer. One of the most important things to do is to check the level of the electrolyte in each cell at least once every two weeks. Check the level oftener in hot weather or when much driving is done. Some of the water in the electrolyte evaporates, and some is decomposed when the battery is charged or discharged. This water must be replaced with distilled water so that the plates are covered by at least ⅜ inch of electrolyte. Be sure to use distilled water, or if this is not available, clean rain water. Never use well water or ordinary faucet water, which usually contains minerals that will be deposited on the plates by electrolysis and thus set up local action that will ruin the cells of the battery. Be sure to keep the battery dry. Wipe off any water spilled on top when filling the cells, and make sure that the battery case does not leak. Also wipe off any sulphuric acid spilled in testing the cells.

Another thing to do in order to prolong the life of the battery is to remove any corrosion at the terminals and cover them with vaseline. Also remove the corrosion from the ends of the wires connected to the battery and smear vaseline over them. The corrosion is a result of the action of sulphuric acid that creeps up from the cells. The filler plugs on the cells should be kept clean, too. Otherwise the gases formed in the cell cannot escape. Incidentally, these gases (hydrogen and oxygen) are very explosive. Never bring a lighted match, cigarette, cigar, or flame near a battery that is being charged. Some gas is produced while the battery is discharging, but much more is produced when the battery is charging.

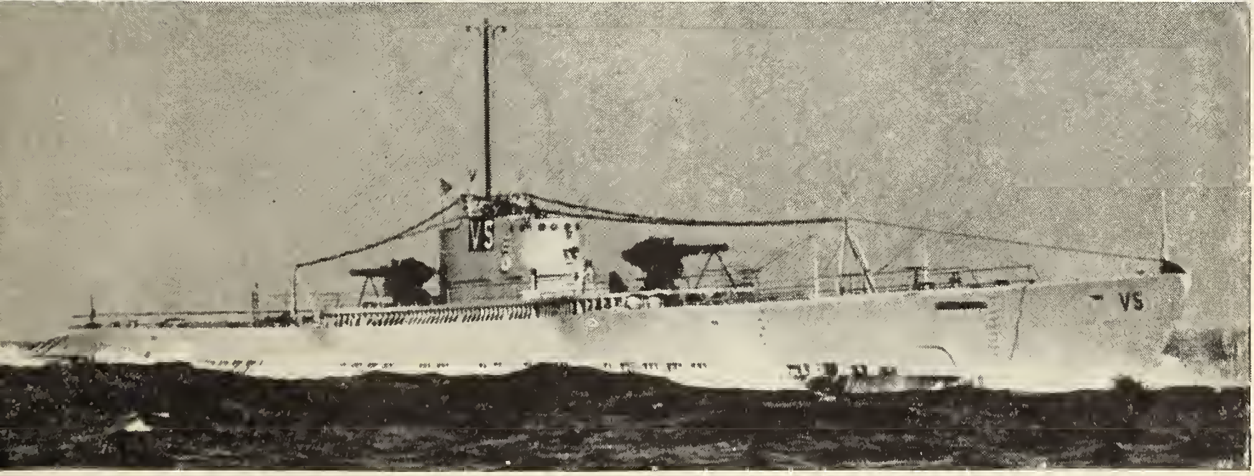
A few more rules should be observed in caring for a storage battery. Never add more sulphuric acid to the cells. Do not wait until the battery is fully discharged before charging it. You already know why this is necessary. Always keep a battery fully charged when cold weather sets in. If the electrolyte becomes too dilute, it will freeze more readily than the more concentrated electrolyte in a fully charged battery. Whenever a battery is not used for a time, it loses its charge. Check it regularly with a hydrometer and recharge it as necessary. Also add water to keep the plates covered. With proper care a storage battery is a reliable and comparatively cheap source of electrical energy.

Sometimes an automobile battery runs down. This may happen if the car is not driven often enough to recharge the battery from the generator, if the car is driven mostly at night with the lights on, or in the winter time when a car is hard to start, the starter motor may be run longer than usual. As you know, the starter motor may use up to 200 amperes of current. If this large drain is continued for any length of time, the battery must be recharged. Storage batteries are not designed to supply such large currents for more than a few seconds at one time. If the storage cells are charged or discharged too rapidly, the plates may buckle, ruining the battery. Although storage batteries are fairly rugged, care must be taken not to drop or jar the batteries, thus cracking the case or breaking the separators. If the separators become clogged in any way, the current from the cell will be reduced. Using distilled water to fill the cells and avoiding excessive charge or discharge will usually prevent clogging. A certain amount of *sulphation* (forming of lead sulphate on the plates) is normal during discharge, but excessive sulphation caused by too rapid charge or discharge will clog the separators or buckle the plates. When this happens, the battery must usually be replaced.

Uses. In an automobile a storage battery is used to furnish current for several purposes. When the motor is not running, the battery supplies current to operate the lights and horn, and also a radio, lighter, and motor-driven heater if the car is equipped with these devices. See Figure 7 in Chapter 1. When you wish to start the motor, the battery furnishes current for the starter motor



The big 30-ton flying boat above shows one of the ways in which the Navy uses storage batteries. Modern aircraft requires specially designed batteries, such as the 24-volt shielded type shown at the left. Special batteries are also needed to withstand the terrific pounding the PT boats take at high speeds, and to supply the great amount of electric current used by modern submarines.



and the spark plugs. Then when the motor is running, a generator attached to the car motor sends current through the battery to recharge it so that the battery will always be ready for use. This generator also supplies current for the devices that are operated by the battery when the car motor is not running.

On the instrument panel, or dash, of an automobile there is an ammeter that shows whether the battery is being charged or discharged. When the switch is turned on to start the car, the needle of the ammeter will swing far to the left, or discharge side. (However, the current for the starting motor does not go through the ammeter.) When the car is running with no lights in use, the ammeter needle should swing to the right, or charge, side. It may show that from 10 to 15 amperes of current are being sent by the generator through the battery in order to charge it. When the battery is fully charged, an automatic regulator reduces the current from the generator to the battery. This prevents the battery from becoming overcharged. An automatic "cut-out" also prevents the battery current from going through the generator, at low speeds or when the car is stopped.

Storage batteries have important uses in addition to their wide use in automobiles and trucks. Some trucks are even driven by electric motors that get their current from storage batteries. Telephone exchanges and small power plants have storage batteries to supply current when the generators are not running or when extra current is needed. Country homes sometimes get electric current from storage batteries charged by a generator run by a gasoline engine. The Army and Navy make a wide use of storage batteries not only in airplanes but for signaling and other communication work. Every tank, "jeep," truck, or other gasoline-driven motor vehicle must have a storage battery in its ignition system. The Navy also uses storage batteries in small gasoline-driven boats and submarines. When a submarine is under water, it cannot be driven by the same engines used on the surface. Instead, electric motors supplied with current by storage batteries are used to propel it. The storage batteries are recharged by a generator driven by the regular engines which require quantities of air for operation. For this reason, a submarine must come to the surface in order to recharge its batteries.

Edison cell. Although the lead-acid battery is by far the commonest kind of storage battery, there are other kinds in use. One kind is made up of *Edison cells.* An Edison cell has electrodes of nickel oxide and iron in an electrolyte of potassium hydroxide (caustic potash) and water. This combination of electrodes and electrolyte provides about half as much E.M.F. as the combination used in a lead-acid cell. Just as in a lead-acid cell, there are sets of nickel oxide (positive) plates and sets of iron (negative) plates; each set is connected together to increase the current that can be drawn from the cell. Even so, the internal resistance of an Edison cell is higher than that of a lead-acid cell of the same size. For this reason, batteries of Edison cells cannot furnish large enough currents to start automobiles. However, they are used to drive electric trucks.

When fully charged, an Edison cell furnishes current at 1.2 volts. When discharged, the cell shows an open-circuit voltage of .9 volts. The specific gravity of the cell does not vary during discharge or charge. For this reason, a hydrometer cannot be used to test an Edison cell. A voltmeter must always be used to find out the condition of the cell. Even though an Edison cell furnishes current at about half the pressure of a lead-acid cell, it has certain advantages. An Edison cell can stand for a long time without losing its charge. If it is connected improperly to a generator or rectifier, it will not be ruined as a lead-acid cell would be. For another thing, an Edison cell weighs about half as much per volt as a lead-acid cell. In other words, four Edison cells weigh only a little more than one lead-acid cell. Edison cells are extremely rugged; they can stand jarring and other abuse that would surely damage a lead-acid cell beyond repair. The Navy uses batteries of Edison cells in its high-speed torpedo boats, the so-called PT boats, that must pound through rough seas at very high speeds. Another use of Edison cells is in some airplanes, where they are suitable because of light weight and resistance to vibration. But in the last few years the lead-acid cell has been so greatly improved that it has replaced the Edison cell for most purposes. Some batteries of Edison cells are still used in the Army, but these are gradually being replaced with lead-acid batteries. Edison cells are considerably more expensive to make than lead-acid cells, even though their life and general sturdiness are greater. They are not so efficient as lead-acid cells, since they give back only about 60 to 65 per cent of the electrical energy required to charge them.

CHECKING WHAT YOU LEARNED

1. **a.** How is a secondary cell like a primary cell? **b.** How is it different from a primary cell?
2. Tell what energy changes take place when a storage cell is discharged and when it is charged.
3. **a.** Explain why a discharged storage cell will not furnish current to a circuit. **b.** Why will the recharged cell furnish current again?
4. Tell how a lead-acid storage battery is tested to find how much charge its cells contain.
5. In what two ways are storage batteries rated? Explain what each rating means.
6. Name some uses of storage batteries. You may include uses not given in the text.
7. List at least six rules to be observed in taking care of a storage battery.
8. **a.** How does an Edison cell differ from a lead-acid cell? **b.** How is an Edison cell tested for the condition of its charge? **c.** Give some advantages of the Edison cell and also some disadvantages.

USING WHAT YOU LEARNED

1. **a.** Would you need more lead-acid cells or more dry cells to provide current at 12 volts? Tell how you know. **b.** Allowing for economical current use, how many dry cells would you need to provide a current of 10 amperes at 12 volts? **c.** How many storage cells would be needed to furnish the same current at the same pressure? Explain your answers.
2. **a.** What kind of current must be used in charging a storage battery? Why? **b.** If this current is not available, from the wiring circuit, what must be used to supply it? **c.** Tell how the terminals of a storage battery are connected when the battery is being charged.
3. Explain why a simple cell, a dry cell, a lead-acid cell, and an Edison cell are, in one sense, all "storage" cells.
4. A storage battery should not ordinarily be charged at a faster rate than the discharge rate used in calculating its electrical energy in ampere-hours. **a.** What is the largest charging current that should be sent through a 120-ampere-hour automobile battery? Explain your answer. **b.** If the hydrometer reading of each cell in the battery is 1250, how long should this current be sent through the battery to bring it up to full charge? Tell how you know.
5. If the terminals of a storage battery are not marked, how can you identify them? There are at least two ways in which this can be done. Tell how each one works.
6. Why should a lead-acid cell never be completely discharged?

THINKING OVER WHAT YOU LEARNED

1. Write down the four topics of this chapter and after each topic state the big ideas or principles you learned. Use complete sentences in stating each idea or principle. Be sure to give only the big ideas or principles.
2. By using either a definition or a sentence, show that you understand the meaning of each of the following terms: **a.** electrode, **b.** depolarizer, **c.** hydrometer, **d.** grid, **e.** ampere-hour, **f.** direct current, **g.** internal resistance, **h.** sulphation, **i.** electrolyte, **j.** separator, **k.** series-parallel, **l.** polarization, **m.** external resistance, **n.** specific gravity, **o.** open-circuit voltage, **p.** charge, **q.** closed-circuit voltage, **r.** discharge.

Experiment 16: **Making and Using a Simple Cell**

THINGS NEEDED: Glass tumbler or small jar. Concentrated sulphuric acid. Glass stirring rod. Hammer. Small nail. Zinc strip 1 inch wide and 5 inches long. Copper strip of the same size. No. 18 insulated copper wire. Small bell (or buzzer) or flashlight bulb (1.5-volt) and socket. Shallow cardboard box. Magnetic compass. Voltmeter reading to at least 1.5 volts. Paper towel.

WHAT TO DO: **a.** (See Fig. 38.) Fill the glass tumbler or small jar about three-fourths full of dilute sulphuric acid. (To dilute the acid, pour 1 part of concentrated acid slowly into 10 parts of water, stirring with a glass rod as you do so. **Do not pour water into the acid. Be careful not to spill the acid on the table or your clothing. It is very corrosive.**) With a hammer and small nail punch a hole near one end of the zinc strip. Do the same thing to the copper strip. Fasten the bare end of a piece of No. 18 insulated copper wire about 12 inches long to each strip by putting the wire through the hole and then twisting the wire about itself. Bend the strips at the ends where the wires are attached. Now put the strips in the tumbler or jar containing the acid solution, and see that the strips do not touch. Touch the ends of the wires to the terminals of a small bell (or buzzer) or to the terminals of a socket containing a 1.5-volt flashlight bulb. What happens?

b. (See Fig. 39.) Wind a coil of five turns of No. 18 insulated copper wire around the middle of a shallow cardboard box. Fasten the wire so that the ends will not unwind. Leave long ends to connect to the simple cell. Then set the compass inside the coil and turn the box until the compass needle and turns of wire point in the same direction. Now connect each wire from your *galvanometer* that you have just made to one of the metal strips in the simple cell. What happens to the compass needle? Reverse the connections from the coil to the cell. Now what happens? Lift the zinc strip out of the acid solution and watch the compass needle. Replace the zinc strip and lift the copper strip out of the solution. Again observe the compass needle. What conclusion can you make about the cell you have made? If a voltmeter reading to at least 6 volts is available, connect the two wires from the cell to the terminals of the meter. Attach the wire from the copper strip to the positive terminal and the wire from the zinc strip to the negative terminal. What is the voltage of the cell?

c. (See Fig. 39.) Connect the electrodes of the simple cell to the galvanometer without placing them in the electrolyte. Lower the electrodes into the solution as you watch the compass needle. Continue to watch the needle for about two minutes. Does the current change? (If you notice no change, repeat, using the bare end of the copper wire in place of the copper strip.) Did you see any bubbles (of hydrogen) rising from the copper strip? Examine the copper strip now. What is clinging to its surface? Remove the copper strip from the acid. Rinse it off in water and then wipe it with a paper towel. Then replace the strip in the acid. Again notice the position of the compass needle. What has happened?

d. (*Optional*) Try other pairs of metals as the electrodes. Use such metals as iron, tin, lead, and aluminum. Then try using two copper strips or two zinc strips. Also try various solutions as the electrolyte. Use a water solution of salt, vinegar, or sal ammoniac (ammonium chloride). Try a solution of sugar or denatured alcohol in distilled water.

Experiment 17: **Voltage and Amperage of a Simple Cell**

THINGS NEEDED: Simple cell and galvanometer from Experiment 16. Strip of zinc one half as big as the strip used in Experiment 16 and another twice as big. Two copper strips of the same size as the two zinc strips. Voltmeter reading to at least 6 volts. Ammeter reading to at least 10 amperes. No. 18 insulated copper wire.

WHAT TO DO: **a.** (See Fig. 41.) Make a simple cell using copper and zinc strips half as big as those used in Experiment 16. Connect the copper strip to the positive terminal of the voltmeter and the zinc strip to the negative terminal. How does the voltmeter reading compare with the reading in Experiment 16? Now use a pair of copper and zinc strips twice as big as the ones used in Experiment 16. Again measure the voltage of the cell.

Also measure the voltage with more or less electrolyte in the glass tumbler or small jar. Try moving the electrodes closer together and farther apart. What conclusions can you make about the voltage of a simple cell?

b. (See Fig. 41.) Using the pair of small copper and zinc strips, measure the current furnished by the cell with a galvanometer or ammeter. (Connect the copper strip to the positive terminal of the ammeter and the zinc strip to the negative terminal.) Repeat, using the copper and zinc strips used in Experiment 16. Then use the pair of large copper and zinc strips. What effect does increasing the size of the electrodes have on the current? Try using more or less electrolyte. Also try moving the electrodes closer together. What conclusions can you make about the amperage of a simple cell?

Experiment 18: **Examining a Dry Cell**

THINGS NEEDED: Worn-out dry cell (No. 6 or flashlight size). Hammer. Dull chisel or old screwdriver. Sheet of paper.

WHAT TO DO: (See Fig. 43.) First remove the paper or cardboard covering from the worn-out cell. The metal can is made of zinc. Is it smooth and whole? Or does it have holes eaten out by the chemicals? Do you see any fine white crystals of zinc chloride on the outside of the zinc can? Now lay the cell on a sheet of paper. With a hammer and a dull chisel or an old screwdriver cut a slit through the zinc can down one side and across the bottom. Unroll the zinc can and take the cell apart, layer by layer. Compare the different layers you find with those shown in Figure 43. What takes the place of the copper in this cell?

Experiment 19: **Testing Dry Cells**

THINGS NEEDED: New No. 6 dry cell. Old No. 6 dry cell. Pocket volt-ammeter for testing dry cells. (See Fig. 44.)

WHAT TO DO: With the pocket volt-ammeter first test the voltage and then the amperage of a new dry cell. To measure the voltage touch the pointed terminal labeled *volts* to the center post of the cell and then touch the terminal at the end of the wire attached to the top of the meter to the outside post of the cell. Read the number of volts on the top scale. To measure the amperage, touch the pointed terminal labeled *amperes* to the center post of the cell and then touch the contact on the wire to the outside post. Quickly read the number of amperes on the lower scale, and then disconnect the ammeter from the cell. **This reading should be taken as quickly as possible because the ammeter short-circuits the cell.** Next test the voltage and amperage of an old dry cell. Compare the readings for the two cells. Then calculate the internal resistance of each cell from the readings you made, using Ohm's Law.

Experiment 20: **Series, Parallel, and Series-Parallel Connection of Cells**

THINGS NEEDED: Four No. 6 dry cells. Voltmeter reading to at least 6 volts. Ammeter reading to at least 5 amperes. No. 18 insulated copper wire. Two 1.5-volt bulbs and sockets.

WHAT TO DO: **a.** (See Fig. 46.) With a piece of wire connect the center post of one dry cell to the outside post of another. Fasten a short wire to each terminal of a voltmeter. Now connect the positive terminal of the voltmeter to the center post not attached to the outside post of the other cell. Connect the negative terminal of the voltmeter to the outside post of the other cell. Now measure the voltage of the two cells in series. Add another cell in series and measure the voltage again. Then add a fourth cell in series with the other three. Again take the voltmeter reading. What conclusion can you make about the voltage of cells connected in series?

b. (See Fig. 48.) With a short piece of wire connect the positive terminal of an ammeter to the center post of a dry cell. Connect the negative terminal of the meter to one terminal of a socket containing a 1.5-volt bulb. (Unscrew the bulb except when you are taking meter readings.) Now attach a wire from the other terminal of the socket to the outside post of the cell. Screw in the bulb so that it lights up and notice the ammeter reading. Then unscrew the bulb again and add another socket and bulb in parallel with the first socket and bulb. Screw in both bulbs and take the ammeter reading again. How does it compare with the first reading? Then unscrew both bulbs and disconnect the ammeter. Connect a wire directly from the center post of the dry cell to the unconnected terminal of the first socket. Next connect a second dry cell in parallel with the first cell. Attach a wire from the outside post of the first cell to the outside post of the second cell. Connect the ammeter between the center posts of the two cells. (Be sure to connect the positive terminal of the ammeter to the center post of the second cell.) Now screw the bulbs into the sockets again and read the ammeter. How does this reading compare with the first one? The second? What part of the current does the second cell furnish to the circuit? Now connect a voltmeter and measure the voltage. (If you care to do so, you may add additional bulbs, sockets, and dry cells in parallel.) What conclusion can you make about the current furnished to a circuit by each cell in parallel? About the voltage?

c. (See Fig. 49.) Connect two dry cells in series as you did in Part **a.** Then connect two more cells in series. Now connect the two sets of cells in parallel. To do this, fasten a wire from the unconnected center post of one set to the unconnected center post of the other set. Then fasten another wire between the unconnected outside posts of the two sets of cells. Now connect the positive terminal of the voltmeter to center post of one set that is connected to the center post of the other set. Connect the negative terminal of the meter to the outside post of one set that is connected to the outside post of the other set. Measure the voltage of the cells in series-parallel. (If you wish to do so, you can also make another series-parallel connection of cells. Connect two cells in parallel and then connect two more in parallel. Connect the two sets of cells in series. Measure the voltage as before. How does it compare with the other reading? How many more wires does it take to make this connection of cells?)

Experiment 21: **Internal Resistance, Voltage Drop, and Closed-Circuit Voltage of Cells**

THINGS NEEDED: Four No. 6 dry cells (all showing about the same current when tested with a pocket meter, preferably no more than 10 amperes). Ammeter reading to at least 5 amperes. Voltmeter reading to at least 6 volts. 10-ohm rheostat. Knife switch (single-pole, single-throw). No. 18 insulated copper wire.

WHAT TO DO: **a.** (See Fig. 51.) Connect the positive terminal of the ammeter to the center post of a dry cell. Then connect the negative terminal of the ammeter to one terminal of the rheostat. Attach a wire from the other terminal of the rheostat to one terminal of the knife switch. Open the switch. Connect the other terminal of the knife switch to the outside post of the cell. Now connect the voltmeter across the cell. Attach a wire from the positive terminal of the meter to the center post of the cell and another wire from the negative terminal to the outside post of the cell. What is the voltmeter reading? Set the rheostat so that all of its wire is included in the circuit. In other words, set it at its greatest resistance. Then close the knife switch, completing the circuit. Adjust the movable contact on the rheostat until the ammeter shows a current of 2 amperes flowing in the circuit. Quickly take the voltmeter reading and then open the switch. What is the voltmeter reading when the circuit is closed? What does this reading indicate? From the closed-circuit voltage shown by the voltmeter find the voltage drop through the cell. Then calculate the internal resistance of the cell. To do this, divide the voltage drop by the current in amperes.

b. Using the same circuit as in Part **a**, close the switch and adjust the rheostat until the ammeter shows 1 ampere of current flowing in the circuit. Again take the voltmeter reading. Then open the switch. Has the closed-circuit voltage increased or decreased? Why? Is the voltage drop more or less? Explain. What has happened to the internal resistance of the cell? Now add another cell in series with the first one. (See Fig. 46.) Disconnect the voltmeter wire from the center post of the cell and attach it to the center post of the added cell. What does the voltmeter reading indicate? Now close the switch and take the meter readings. Then open the switch. How much current flows through the circuit when the switch is closed? What is the closed-circuit voltage of the two cells in series? Does the voltage drop increase or decrease, compared with Part **a**? Why? Find the internal resistance of the two cells in series.

c. Using the same circuit as in Part **a**, close the switch and adjust the rheostat until the ammeter shows a current of 2 amperes flowing through the circuit. Notice the closed-circuit voltage and then open the switch. Now add a dry cell in parallel with the first one. (See Fig. 48.) What is the open-circuit voltage of the two cells in parallel? Close the switch and take the meter readings as before. Open the switch again. What is the voltage drop through the two cells in parallel? How much current flows in the circuit? Calculate the internal resistance of the battery of two cells in parallel. Is the internal resistance more or less than that of one cell? Why?

d. Using the same circuit as in Part **b**, close the knife switch and adjust the rheostat until the ammeter shows 2 amperes of current flowing through the circuit. Notice the closed-circuit voltage of the two cells in series. Then open the switch. Connect another set of cells in series and then connect this set in parallel with the first set. (See Fig. 49.) What is the open-circuit voltage of the battery of four cells in series-parallel? Close the knife switch and take the meter readings. Then open the switch. What is the closed-circuit voltage of the battery? What is the voltage drop through the battery? Does the current increase or decrease? Why? Calculate the internal resistance of the battery. How does it compare with the internal resistance of one cell?

e. (*Optional*) Repeat Part **b**, adding one or more cells in series. Then repeat Part **c**, adding one or more cells in parallel. Repeat Part **d**, connecting the cells first in parallel and then in series.

Experiment 22: **Making and Using a Storage Cell**

THINGS NEEDED: Glass tumbler or small jar. Concentrated sulphuric acid. Glass stirring rod. Hammer. Small nail. Two lead plates, 1 inch wide and 5 inches long. No. 18 insulated copper wire. Three No. 6 dry cells. Small bell (or buzzer). Ammeter reading to at least 5 amperes. Voltmeter reading to at least 3 volts.

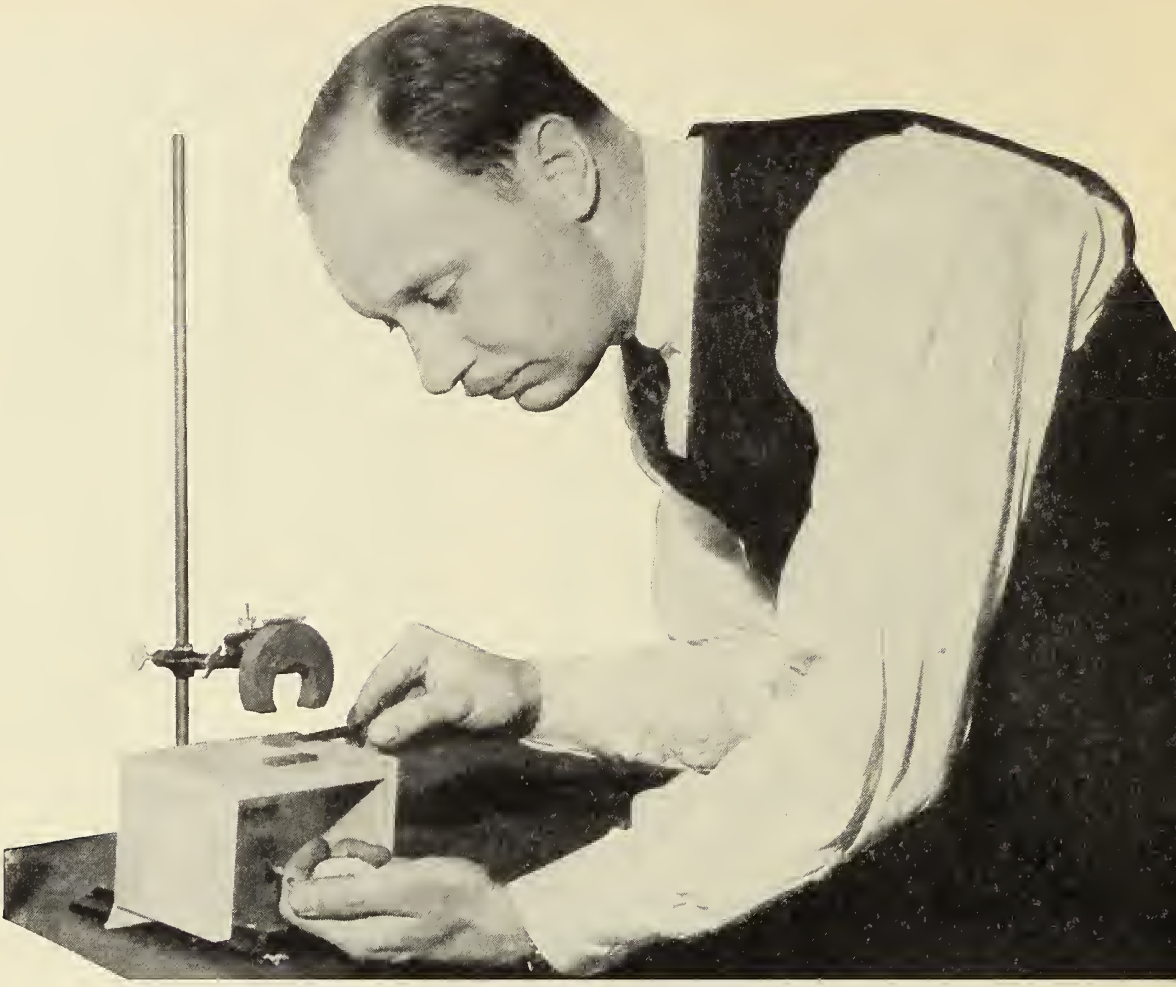
WHAT TO DO: **a.** (See Fig. 52.) Fill the glass tumbler or small jar about two-thirds full of dilute sulphuric acid. (To dilute the acid, pour 1 part of concentrated acid slowly into 3 parts of water, stirring with a glass rod as you do so. **Do not pour water into the acid.**) With a hammer and small nail punch holes near one end of each lead strip. Fasten the bare end of a piece of No. 18 insulated copper wire to each strip by putting the wire through the hole and then twisting the wire about itself. Bend the strips at the ends where the wires are attached. Now put the lead strips in the tumbler or jar containing the acid solution. Connect the wires to the terminals of a bell (or buzzer) or to an ammeter. (See Fig. 53.) Does the bell ring? (Or what does the ammeter show?)

b. Now connect three dry cells in series and then attach the wires from the lead strips to the terminals of the battery. Send the current of the battery through the lead strips and solution for several minutes. Watch carefully for any signs of chemical action. What do you notice? Lift the strips out and examine them. (**In lifting the strips, be careful not to spill acid on yourself or on the table.**)

c. Return the strips to the acid solution and connect the wires to the terminals of the bell. What happens now? Then connect the wires to an ammeter. How much current does it show? Connect the wires to a voltmeter and take the open-circuit voltage of the cell. How much is it?

d. Connect the wires to the bell again and let the bell ring until it stops. Disconnect the wires and attach them to the ammeter. What is the reading now? Then connect the wires to the voltmeter and take the reading. What is the open-circuit voltage? Lift the lead strips out of the solution and examine them. What do you notice?

e. Connect the lead strips to the battery of dry cells again. Be sure to connect the brownish strip to the positive terminal of the battery. Again send a current through the lead strips and solution. Notice what happens. After a few minutes lift out the strips and examine them. Then connect the wires to the terminals of the bell. What happens? Also take the ammeter and voltmeter readings as you did before. What do they show?



5. Magnetism

FINDING OUT WHAT YOU KNOW

1. Name three materials that are attracted by a magnet and three that are not. Are most materials attracted or not attracted?

2. How can you make a magnet? There are several different ways to do this.

3. Does a compass needle always point toward the north pole of the earth? Explain your answer.

4. Draw an outline of a magnet and then around it draw a map of its lines of force. What do we call the space filled by these lines?

5. Where on a magnet does its force appear to be concentrated? How many of these places are there on a magnet? What are they called?

6. If a magnet is broken in two, is each piece a complete magnet? Why?

7. Tell why steel is used to make permanent magnets, while iron is used to make temporary magnets.

8. What happens to a magnet if it is pounded or heated? Explain.

ALMOST EVERYONE is familiar with magnets. As a child, perhaps you had toy boats that would follow a magnet, or you might have used magnets to perform tricks. Certainly almost everyone is familiar with the magnetic compass.

In the preceding chapter Experiment 16 called for the construction of a galvanometer, and you observed the effect of an electric current on the needle of a magnetic compass. You know, then, that there must be some relation between electricity and magnetism.

Magnets and Magnetic Fields

Probably one of the first things you learned about magnets was that they would pick up or stick to some kinds of materials and not to others. You found that a magnet would pick up nails but not coins. It would pick up certain pins but not others. It would stick to iron or steel but not to wood, glass, or stone. You might have discovered that some of the nails you picked up with the magnet also became magnets, though they were not so strong as the one you had first used.

If a material is attracted by a magnet, or if a magnet can be made of it, we call it a **magnetic substance.** There are comparatively few such substances. Iron and steel are the commonest, though nickel and cobalt are also magnetic substances. Some alloys of iron and steel are exceptionally good magnetic substances. For example, one alloy called *alnico,* a mixture of aluminum, nickel, cobalt, carbon, manganese, silicon, and iron, makes an exceptionally strong

Magnetic substance: Any substance that can be magnetized or attracted by a magnet.
Non-magnetic substance: Any substance not ordinarily attracted by a magnet.

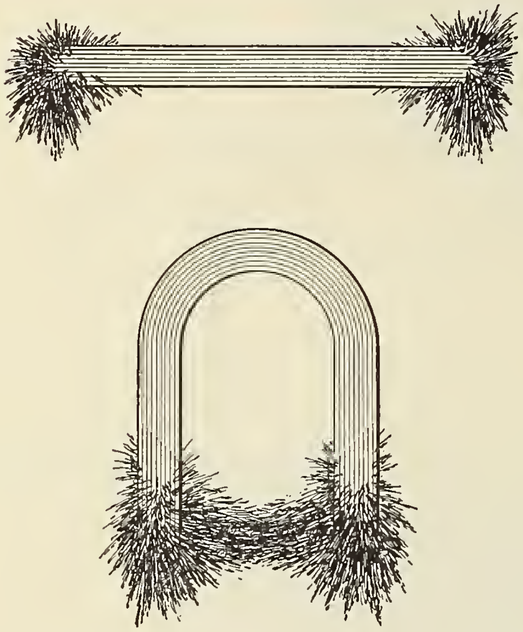


Figure 56 *shows what happens when two magnets of different shapes are placed on a pile of iron filings and then lifted. The straight magnet at the top is usually called a* bar magnet. *Notice the way in which the filings cling together at each end or pole of a bar magnet. The U-shaped magnet at the bottom is generally called a* U-magnet. *(When bent so that the two ends nearly touch, such a magnet is called a* horseshoe magnet.) *Notice that the filings not only cling in a mass to each end or pole of the U-magnet but actually bridge the gap between the two poles. With both magnets the filings cling most firmly at the poles and most weakly,* if at all, *near the center.*

magnet. A magnet of alnico will lift about 50 times its own weight.

Most materials belong in the group of **non-magnetic substances.** Some, such as brass, copper, zinc, glass, and wood are practically always non-magnetic. Other substances are so little magnetic that we class them with the non-magnetic substances.

It is perfectly obvious that a magnet exerts some kind of force. Perhaps the best way to find out something about the nature of this force is to perform a few simple experiments.

First do Experiment 23 (page 129). In doing the first part of this experiment, you placed a magnet in a pile of iron filings and then picked it up. You did not find the same amount of iron filings clinging to all parts of the magnet. You can show the same thing by scattering a box of tacks or small nails, placing the magnet on them and then lifting it as before. Apparently the magnetic force is stronger at the ends of the magnet, whether the magnet is straight (*bar magnet*) or U-shaped (*U-magnet* or *horseshoe magnet*). The places where the magnetic force seems to be concentrated are called **poles.** These poles are often labeled N and S, meaning north and south.

You can learn something more about this concentration of force if you do the second part of Experiment 23. Get a piece of thin cardboard or a glass plate and some fine iron filings. Place the cardboard or glass over a bar magnet. Sprinkle some iron filings on the cardboard or glass, gently tapping it as you do so. The filings will assume a regular arrangement or pattern. Take the cardboard or glass plate away, remove the filings, and try the experiment again. You will see that the filings again arrange themselves in the same pattern. If you want a permanent record of this arrangement of filings, spread a very thin coat of melted paraffin on the cardboard or glass plate. When the paraffin hardens, perform the experiment. Then, without shaking the cardboard or glass plate, heat it carefully until the paraffin melts. When the paraffin cools again, the iron filings will be firmly imbedded in the paraffin, but perfectly visible.

Poles: The places on a magnet (usually at the ends) where the magnetic force appears to be concentrated. An ordinary magnet has both a north (N) pole and a south (S) pole. The magnet is said to have **polarity,** or a difference in poles.

Lines of force: The lines that show the direction in which a magnetic force is exerted. They run between the north and south poles of a magnet and do not cross one another.

Magnetic field: The space in which the force of a magnet is exerted. Also called **field of force.**

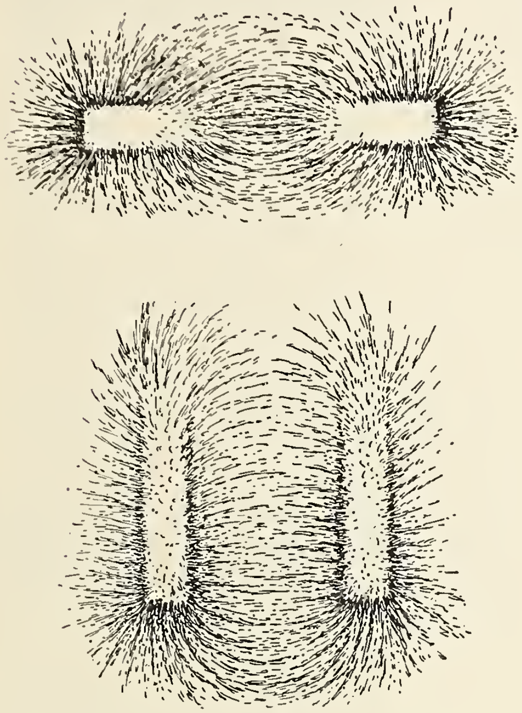


Figure 57 *shows the pattern made by iron filings sprinkled lightly on a piece of cardboard held over the two magnets shown in Figure 56. The filings arrange themselves in this way because they are affected by the magnetic force that appears to extend from one pole to the other in a series of lines called lines of force. The upper pattern is one caused by a bar magnet. Notice that the lines of force are concentrated at the poles and that they appear to exert a sideways pressure on one another. The lower pattern is one caused by a U-magnet. Because the ends are closer, many more lines of force appear to stretch between the poles of the U-magnet. The field of each magnet consists of lines of force extending in all directions around the magnet.*

The iron filings arrange themselves in a series of lines, which are called **lines of force** because the force of the magnet appears to be exerted along these lines. These lines of force extend in all directions around the magnet and form what is called its **magnetic field.** The field of a magnet is the space in which its force is exerted. For this reason the space is also called the **field of force.**

By looking at the pattern made by the iron filings in a magnetic field, you can see that the lines of force are closest together at the poles of the magnet, showing that the magnetic force is strongest at the poles. If a stronger magnet is used, the lines of force will be even closer together. There is not only a pull exerted along every line of force in a lengthwise direction, but careful experiments show that each line of force pushes sidewise against its neighbors. You can think of the lines of force as a stretched and tightly crowded bundle of rubber bands, always pulling on the things to which they are fastened. If they become shorter, the bundle thickens and bulges out in the middle.

If you do the second part of Experiment 23 again and change the position of the magnet so that the other side is uppermost, you will see that the lines of force are the same. Think of the lines of force as extending out around the entire magnet. If the lines of force were visible when you looked at a magnet, they would cover the whole magnet and hide it from view. They appear to flow out in all directions from the poles of the

Magnetic flux: All the lines of force appearing to flow out from the poles of a magnet.
Flux density: The strength of the magnetic flux in a magnetic field. It is determined by counting the number of lines of force in a square centimeter set across the field.

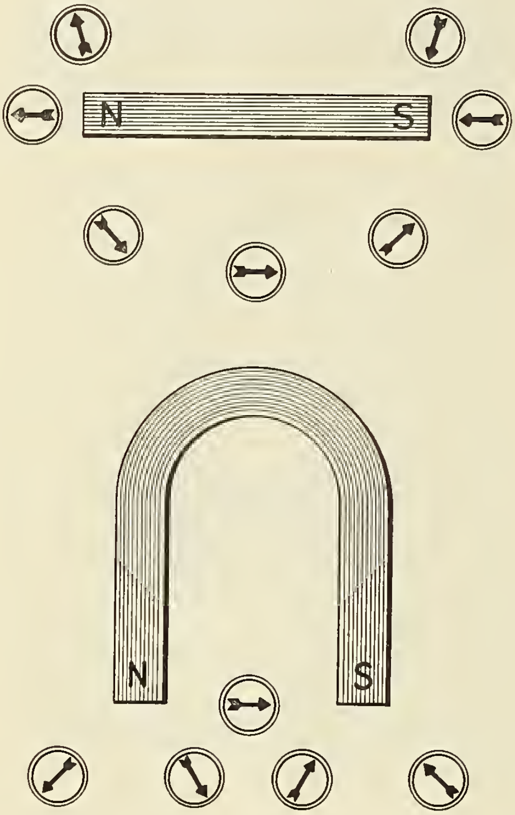


Figure 58 *shows that the magnetic force in the field of a magnet appears to flow in one direction from pole to pole. For example, the needle of the small testing compass placed in various positions around the bar magnet at the upper left indicates that the lines of force flow out at the N pole and in at the S pole of the magnet. The same thing is shown when the small testing compass is moved around the poles of the U-magnet at the lower left. In fact, by moving the compass around the magnet on all sides from one pole to the other, you can see the pattern formed by the lines of force leaving the N pole in all directions and entering the S pole from all directions. Inside the magnet the flow is considered to be from S to N, making a complete path. You will find it helpful to think of the lines of force in a magnetic field as closed loops so arranged that they do not cross one another.*

magnet and so are spoken of as **magnetic flux.** (*Flux* means flow.) The strength of this magnetic flux, or **flux density**, can be determined by counting the lines of force in a given area across the field.

There are two things to notice about the pattern of the lines of force. First, the lines of force run between the north and the south poles. If you do the third part of Experiment 23, you will see that this is true as you move a small compass along the lines of force between the north and south poles of a bar magnet. The compass needle is just a small bar magnet mounted on a pivot so that it can turn freely and point along the lines of force in a magnetic field. If you start at the north pole, you will see that the black end of the compass needle points away from the north pole of the magnet. As the compass is moved around the side of the magnet to the south pole, the compass needle will change direction. Thus a compass needle can be used to make a map of the magnetic field such as is also shown by the iron filings. If you use a U-magnet or horseshoe magnet, you will see that the lines of force also pass between the north and south poles, for a U-shaped magnet is just a bar magnet bent into a curved form. Occasionally it is necessary to make rules covering the action of magnetic lines of force, and it is also sometimes necessary to speak of the direction of the lines of force. For the sake of uniformity, scientists have agreed to consider the lines of force as leaving the north pole and entering the south pole. Outside the magnet, the direction of the lines of force is thus from north pole to south pole, and inside the magnet the direction is from

Magnetic induction and induced magnetism: A piece of iron or steel will become a magnet when it is brought into the field of a magnet or when it touches the magnet. The process is called **magnetic induction.** The result is called **induced magnetism.**
Temporary magnet: A magnet that loses its magnetism soon after it is removed from a magnetic field. Iron is ordinarily used in temporary magnets.

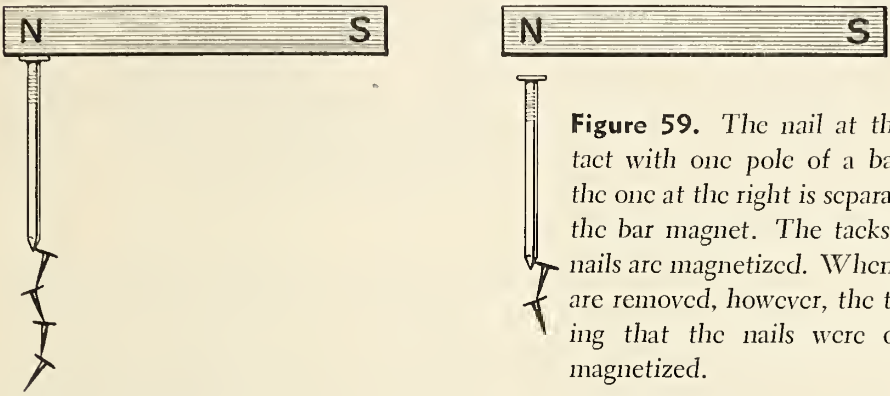


Figure 59. *The nail at the left is in contact with one pole of a bar magnet, while the one at the right is separated slightly from the bar magnet. The tacks show that both nails are magnetized. When the bar magnets are removed, however, the tacks drop, showing that the nails were only temporarily magnetized.*

south pole to north pole. The second thing to notice about lines of force is that they go around and through a magnet but do not cross one another.

Magnets may be either natural or man-made. A natural magnet is simply a piece of *magnetite,* a kind of iron ore. The ancients knew the properties of this ore and called it *lodestone,* which means "leading stone." The only use that was later found for it was in making magnetic compasses for telling direction. In modern times scientists have discovered more about magnets and the relation of magnetism to electricity. They have also found ways to make magnets artificially, or as we say, to *magnetize* certain materials.

Magnetic substances may be magnetized by using **magnetic induction.** You can do this in Experiment 24. Let one end of a bar magnet project over the edge of a table. Bring the head of an iron nail up under the magnet so that its head touches the magnet. The lower end will now hold up several tacks. The nail has been made into a magnet by touching the magnet. We say that the magnetism is *induced* in the nail. Now take away the magnet. The tacks soon fall off, showing that the nail has lost its induced magnetism and is no longer magnetized.

Curiously enough, the nail does not need to be in contact with the magnet in order for magnetism to be induced. If you will bring the nail directly under the magnet, but not touching it, the nail will still hold one or more tacks, showing that magnetism has been induced in it. Or you can put one or more pieces of paper or a sheet of glass between the magnet and the nail, and magnetism will still be induced. If, however, the magnet is removed, or if a sheet of iron or steel is put in the space between the magnet and the nail, the nail will lose its magnetism. Thus, the magnetism induced in an iron nail makes it only a **temporary magnet.** As soon as the magnet is removed, the nail loses its **induced magnetism.** The experiment shows that a piece of iron will become a magnet when it is brought into the field of a magnet or when it touches the magnet.

You can also make a magnet, this time a **permanent magnet,** not a temporary one, by doing the first part of Experiment 25. Stroke a piece of steel in one direction with one pole of a strong bar magnet. Or you can leave a piece of steel in contact with a permanent magnet for several days, and it will become a magnet although not a very strong one. You can also make a permanent mag-

Permanent magnet: A magnet that keeps its magnetism for a long time after it is removed from a magnetic field. Steel and certain special alloys are commonly used in permanent magnets.

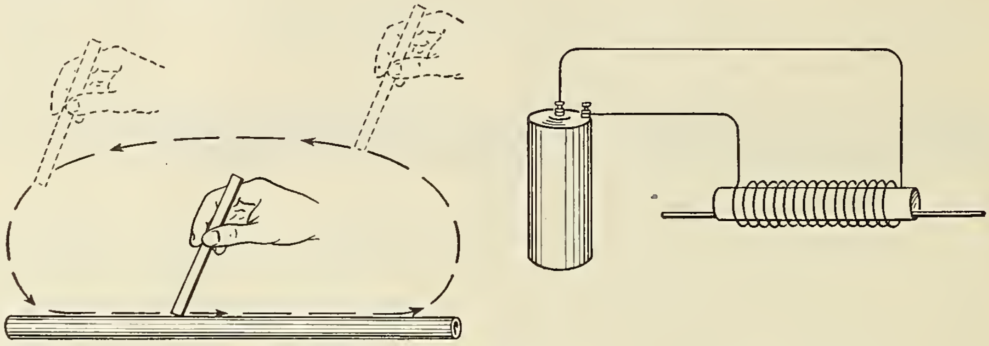


Figure 60 *shows two ways in which a piece of steel can be made into a permanent magnet. The diagram at the left shows how one pole of a strong bar magnet can be used to magnetize a piece of steel by stroking it in one direction. The drawing at the right shows how a coil of wire connected to a dry cell can be used to magnetize a steel rod or knitting needle. The end of the piece being magnetized should be struck several times with a hammer while current is flowing through the coil.*

net by holding a piece of steel in north-south direction and then hammering it vigorously.

Magnets of the kind you have been using in your experiments are not made in these ways, however. They are made commercially by an electrical method. You can see how this is done by doing the second part of Experiment 25. Wind about 200 turns of small, cotton-covered or enamel-coated copper wire (No. 26) around a cardboard tube about one-half inch in diameter. Test a thin piece of steel, such as a knitting needle or a long, thin nail, to make sure that it is not magnetized. Then place it inside the wire-wound tube. Connect the ends of the wire to a dry cell so that an electric current passes through the coil of wire around the piece of steel. Strike one end of the piece of steel several times with a hammer. Disconnect the wire from the dry cell and take the piece of steel out of the tube. When you test it, you will see that it has become magnetized.

The magnets you buy—the horseshoe kind and the bar kind—are made by using an electric coil, only a much stronger electric current is passed through the coil. Steel, not iron, is used for making these magnets because steel holds its magnetism for a much longer time. You can see that this is true by doing the third part of Experiment 25. If you put a piece of iron and a piece of steel in the wire coil and magnetize them, they will both pick up about the same number of tacks while the current is on. If there is any difference, probably the steel will pick up less. But when the current is turned off, and the pieces are taken out of the coil of wire, you will find that the piece of steel will be able to pick up more tacks than the piece of iron. In fact, the iron usually loses most of its magnetism as soon as the current stops flowing through the coil of wire.

Because steel and certain alloys hold magnetism for a long time, they are used to make perma-

Residual magnetism: The magnetic flux that exists in a material (such as iron or steel) after the magnetizing force has been removed.

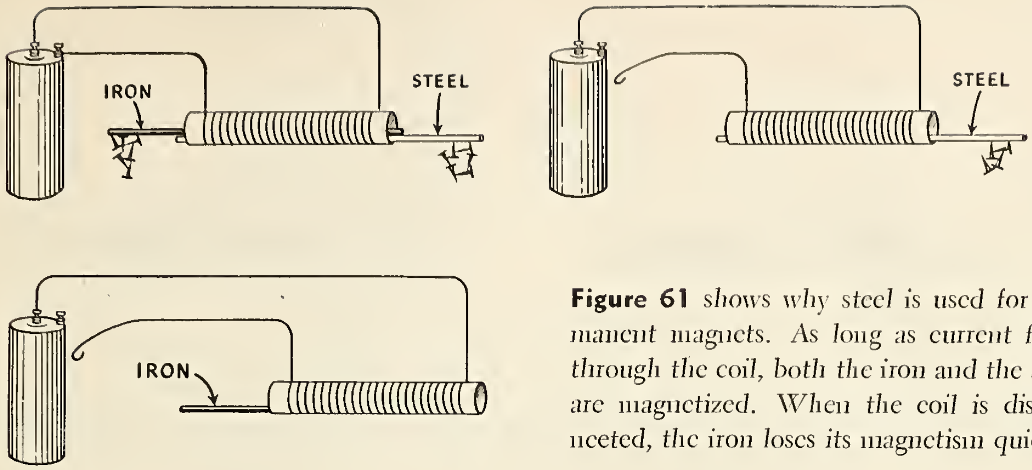


Figure 61 *shows why steel is used for permanent magnets. As long as current flows through the coil, both the iron and the steel are magnetized. When the coil is disconnected, the iron loses its magnetism quickly.*

nent magnets. Iron, on the other hand, is used to make temporary magnets. Remember this difference in the magnetic qualities of iron and steel, as you will need to use it later.

CHECKING WHAT YOU LEARNED

1. **a.** Is a magnetic substance the same as a magnet? Explain. **b.** What is a non-magnetic substance? Name several examples.
2. A magnet is said to have poles. What does this mean?
3. Is a magnetic field flat like a piece of cardboard or glass plate? Or do its lines of force go out in all directions from the poles? How do you know your answer is correct?
4. **a.** What do we call all the lines of force that appear to flow out from the poles of a magnet? **b.** How is the strength of this determined? What is its strength called?
5. State at least two important things that you should know about lines of force.
6. Explain what is meant by magnetic induction.
7. Give three different ways of making magnets.
8. **a.** What is the difference between a permanent magnet and a temporary magnet? **b.** What substance is usually used to make each kind?

USING WHAT YOU LEARNED

1. Explain why a magnet will pick up some kinds of pins but not others, even though the pins may all look alike.
2. A powerful magnet is sometimes used to remove bits of metal from a person's eyes. If the magnet fails to remove the metal, what is probably the reason?
3. Tin cans are attracted by magnets, but tin is a non-magnetic substance. Explain how it is possible for a magnet to attract the cans.
4. A piece of iron or steel attracts a magnet just as truly as the magnet attracts the iron or steel. Plan an experiment to prove that this is true.
5. **a.** Through what kinds of substances will the force of a magnet pass? **b.** Through what kinds of substances will the force of a magnet not pass? **c.** How could you use this information to keep magnetic force from reaching an object that might become magnetized or affected by a magnet?
6. Two bars of metal look exactly alike, but one is iron and the other is steel. How could you use magnetism to find out which is iron and which is steel?
7. After a time a permanent magnet becomes weaker. How can you make it strong again?

Polarity of Magnets

You have already noticed that one end of a bar magnet, or one pole of a U-shaped magnet is marked with the letter N. And you know that the needle of a *magnetic compass* swings until the black end of the needle comes to rest pointing

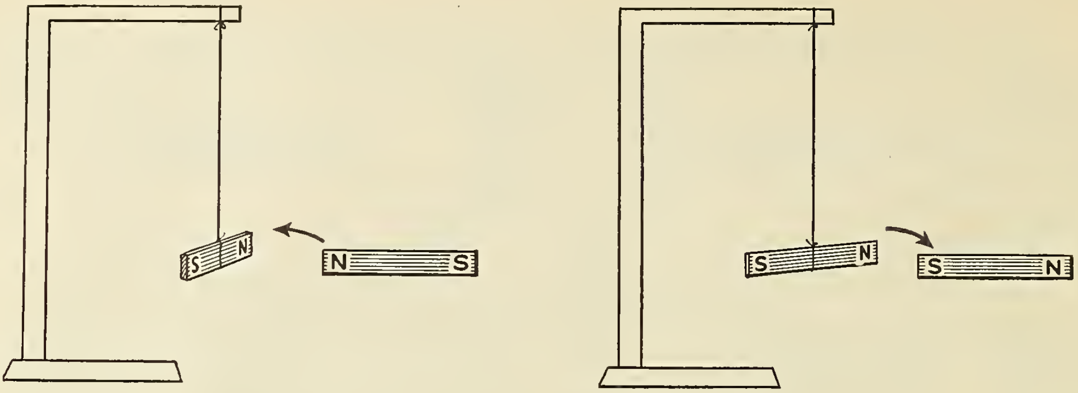
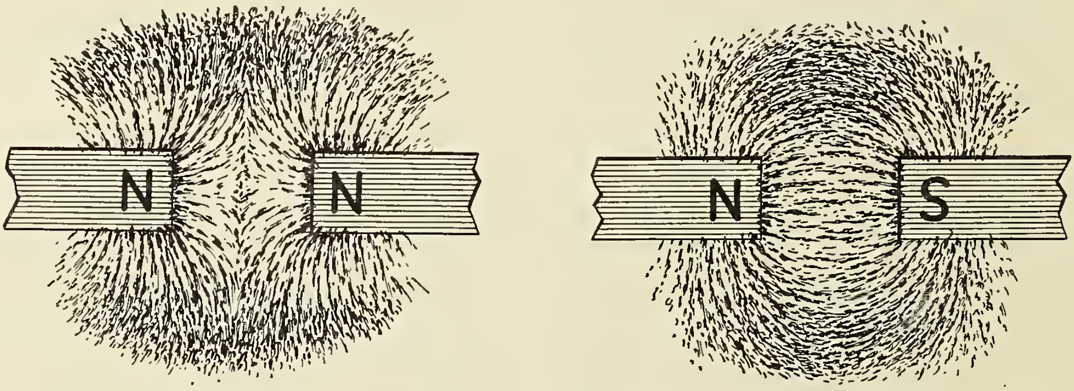


Figure 62. *The picture at the upper left shows that like poles repel each other. The N pole of the suspended magnet swings away from the N pole of the other magnet. The picture at the upper right shows that unlike poles attract each other. The N pole of the suspended magnet swings toward the S pole of the other magnet. The two diagrams below show how the lines of force from the two N poles push against each other, while the lines of force between the N and the S poles pull toward each other.*



approximately north. If you hang a bar magnet on a string so that it is free to turn, it will act in the same way as a compass needle. What makes a magnet point as it does?

You can learn the answer to this question by doing two experiments and drawing conclusions from what you observe. First of all, in doing Experiment 26, hang a bar magnet on a string and allow it to swing until it comes to rest. It will be pointing approximately north and south. With chalk, mark the north-pointing end N and the south-pointing end S. Repeat this with another bar magnet, marking the ends N and S as before.

Now you have two magnets, and on each is a pole marked N. This pole of a magnet is called the *north-seeking pole,* or the north pole, or the N pole, for short. The pole that points south is called the *south-seeking pole,* or the south pole, or the S pole.

If you hang up one of these magnets so that it can swing freely on a string, the magnet will, of course, swing until the north-seeking pole points approximately north. Then if you slowly bring the N pole of the other magnet near the N pole of the suspended magnet, the N pole of the suspended magnet will be repelled, that is, it will swing away from the N pole of the magnet you are holding. If you approach the south-seeking pole of the suspended magnet with the south-seeking pole of the other magnet, the S pole of the sus-

Figure 63 *shows how a magnetized needle suspended by a thread is affected by the lines of force surrounding a bar magnet. When held above the magnet and midway between the poles, the needle is horizontal, as shown in the left-hand picture. When held near one of the poles of the magnet, the needle dips downward, as shown in the right-hand picture.*

pended magnet will also be repelled by the S pole of the magnet you are holding.

However, if you bring the south-seeking pole of the second magnet near the north-seeking pole of the suspended magnet, the N pole of the suspended magnet will be attracted, that is, it will swing toward the S pole of the magnet you are holding. And in similar fashion you can show that the north-seeking pole of the magnet in your hand will attract the south-seeking pole of the suspended magnet. Now we can state two rules about the *polarity* of magnets:

1. Like magnetic poles always repel each other.
2. Unlike magnetic poles always attract each other.

Experiment 27 requires a bar magnet and a magnetized darning needle. You can magnetize the needle by stroking with the bar magnet or by means of an electric current in a coil of wire. Suspend the magnetized needle on a piece of thread so that it balances. Hold it so that it hangs about two inches above the center of the bar magnet. If you move the needle all around the magnet, you will find that it seems to follow the lines of force, which were indicated by the iron filings and the compass needle in Experiment 23.

The magnetized needle in this experiment will dip downward when it approaches the poles of the bar magnet. The south pole of the needle will dip downward toward the north pole of the magnet. And the north pole of the needle will dip downward as it approaches the south pole of the bar magnet. Between the two poles of the bar magnet the needle will point in the general direction of the magnet's north pole or south pole, whichever is nearer.

CHECKING WHAT YOU LEARNED

1. What part of a compass is a magnet? How do you know?
2. **a.** How many poles does a magnet have? In what parts of the magnet are they? **b.** Describe one way in which you can identify the poles of a magnet.

Polarity of magnets and electrical charges: There is a similarity between the polarity of magnets and electrical charges, for like electrical charges always repel each other and unlike electrical charges always attract each other. However, there are striking differences. A charged object usually has the same kind of charge throughout, that is, the object is either all negatively charged or all positively charged. But a magnetized object usually has two poles where the magnetic force appears to be concentrated, and these two poles are always unlike. An apparent exception is a ring of magnetic substance, which can be magnetized and yet not have north and south poles. However, if the ring is broken, the ends of each piece will be unlike poles of a magnet.

3. State the two rules that describe the behavior of magnetic poles toward one another.
4. Tell how a magnetized needle behaves when it is moved about a magnet.

USING WHAT YOU LEARNED

1. Why can a compass be used to test substances for magnetism?
2. If no compass, magnet, or magnetic substance is available, how can you find out if a steel rod is magnetized? Explain why this will work.
3. Repulsion is a surer test for magnetism than attraction. Tell why this is true.
4. An unmagnetized bar of steel is supported in a horizontal position by a string tied about its middle. The bar is then magnetized. **a.** In what general direction will it point? **b.** Will it still be horizontal? **c.** Explain your answers.

The Earth As a Magnet

Scientists have constructed a special kind of compass called a *dipping needle,* which is made so that the needle can point up or down at any angle or stand horizontally. When dipping needles are carried about in different parts of the world, they act in much the same way the needle acted in the last experiment as it was moved about the bar magnet. Explorers found a spot in the far north where the N pole of the dipping needle pointed straight down. And in the far south a place was found where the S pole of a dipping needle pointed straight down. In between these places the needle dips downward at different angles, except near the equator, where the needle stands horizontal to the earth's surface.

There seems to be only one good explanation for the way compass needles and dipping needles act. All the experiments that have been tried seem to show that the earth itself is a huge magnet. Its *magnetic poles* are in the far north and the far south. The earth's magnetic pole in the far north attracts the north-seeking pole of a compass or dipping needle. The earth's magnetic pole in the far south attracts the south-seeking pole of a compass or dipping needle. The needle of a compass points to the magnetic poles of the earth because the earth itself is a magnet. Curiously enough, the earth's north magnetic pole is a S pole, while its south magnetic pole is a N pole. Compass needles and dipping needles show the direction of the lines of force in the magnetic field of the earth. The horizontal lines along which a compass needle points are usually called the *magnetic meridians.*

The magnetic poles of the earth are not at the spots we call the *geographic poles.* The north magnetic pole is located near Hudson Bay nearly 1300 miles from the north geographic pole. The south magnetic pole is located in Antarctica about 1300 miles from the south geographic pole. If you locate these magnetic poles on a globe, you will see that there must be many places where the compass needle does not point to the true north.

Figure 64 shows that a line can be drawn on the map along which the compass needle will always point due north. The line is called the *zero-degree line* or the *agonic line.* East of this line the compass needle will point west of true north. And west of this line the needle will point east of true north. The number of degrees which the north-seeking pole of a compass needle points away from true north is called *declination.* In New York, for example, the declination is about 11 degrees West, or as usually written, 11°W. To find true north, the compass is turned so that the needle points 11° west of the N on the compass card. The N then points to true north.

Inclination: The dip of the free magnetic needle. Navigators express it as the angle formed by the dipping needle and the horizon. At the magnetic equator (halfway between the magnetic poles), the angle is 0°; at the magnetic poles, it is 90°. Also called **dip.**

Declination: The angle the compass needle forms with the geographic meridian. Declination is described as either east or west, depending on which side of the geographic meridian the north-seeking pole of the needle points. Declination is stated in the number of degrees by which the compass needle points away from the geographic north. Also called **variation.**

Deviation: The angle the compass needle forms with the magnetic meridian. It is caused by masses of iron or steel in a ship, airplane, etc.

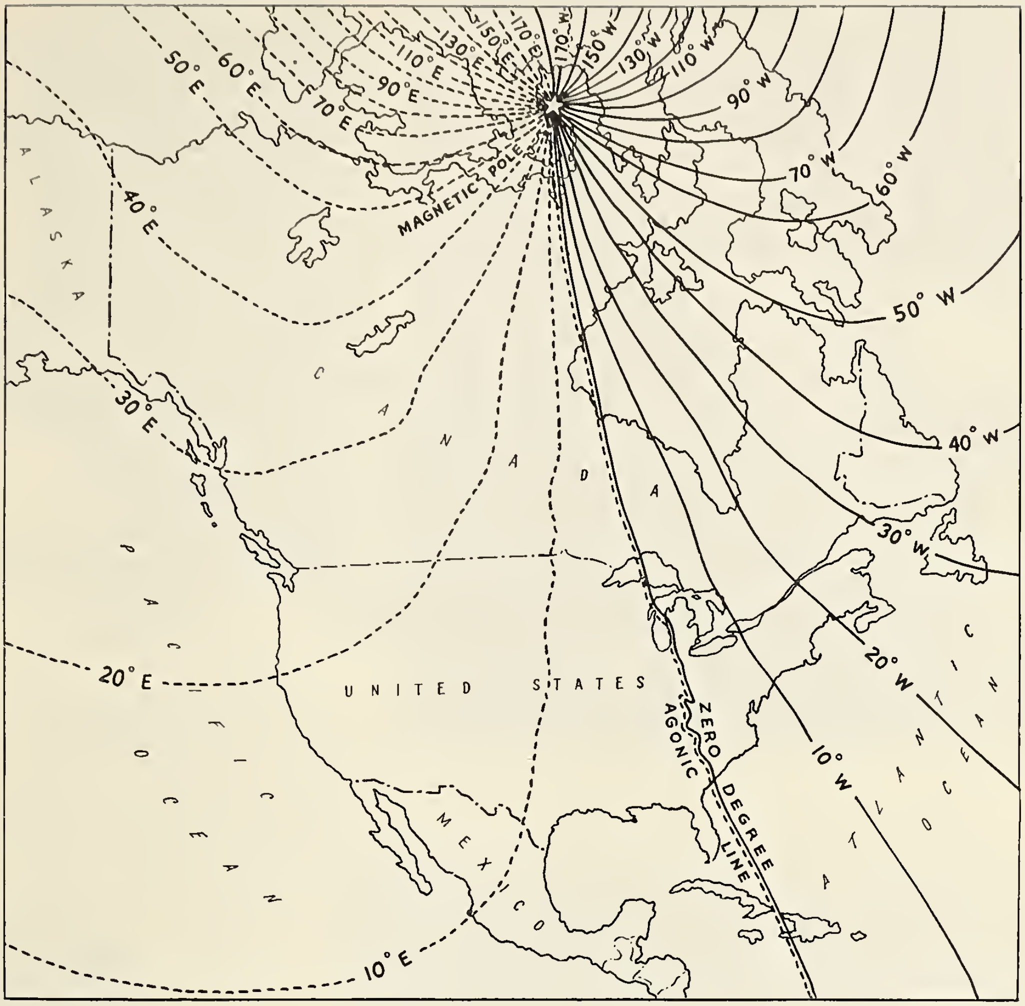
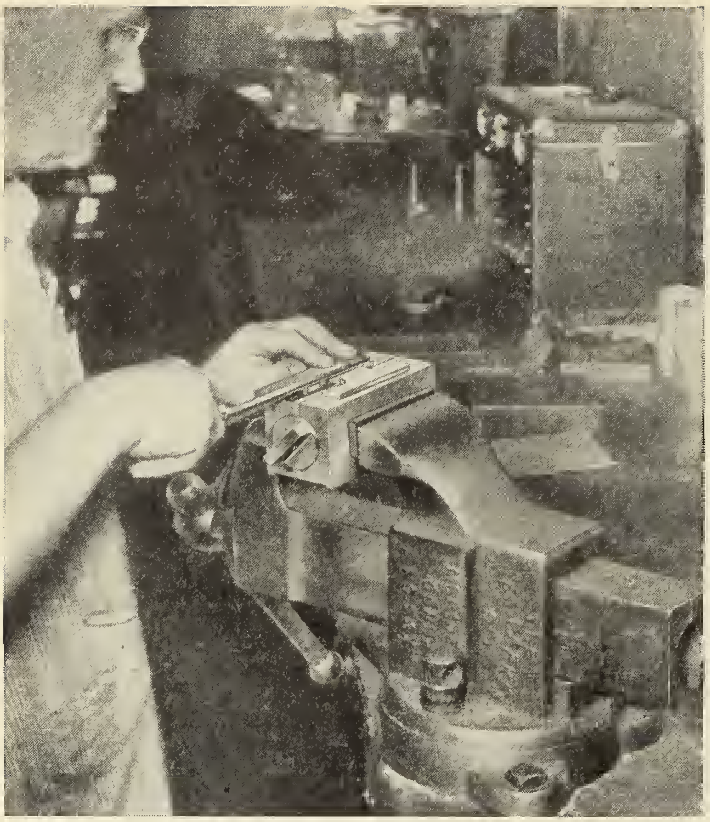


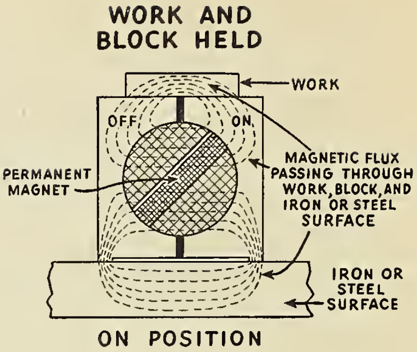
Figure 64. *Maps like this are used to correct the readings of magnetic compasses. Along the zero-degree, or agonic line, the compass needle points true north. The dotted lines show where the needle points too far east. The solid lines show where the needle points too far west. The numbers show how much correction is needed.*

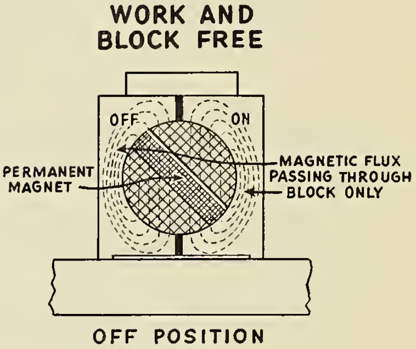
To use a compass accurately, as navigators and surveyors must do, tables and maps are required that show how much to change the reading of the compass for the place where the compass is to be used. In maps such as the one shown in Figure 64 the lines east and west of the zero-degree or agonic line show exactly how much correction must be made to the compass reading. These tables or maps have to be remade from time to time, as the magnetic poles of the earth are slowly changing their positions.

CHECKING WHAT YOU LEARNED

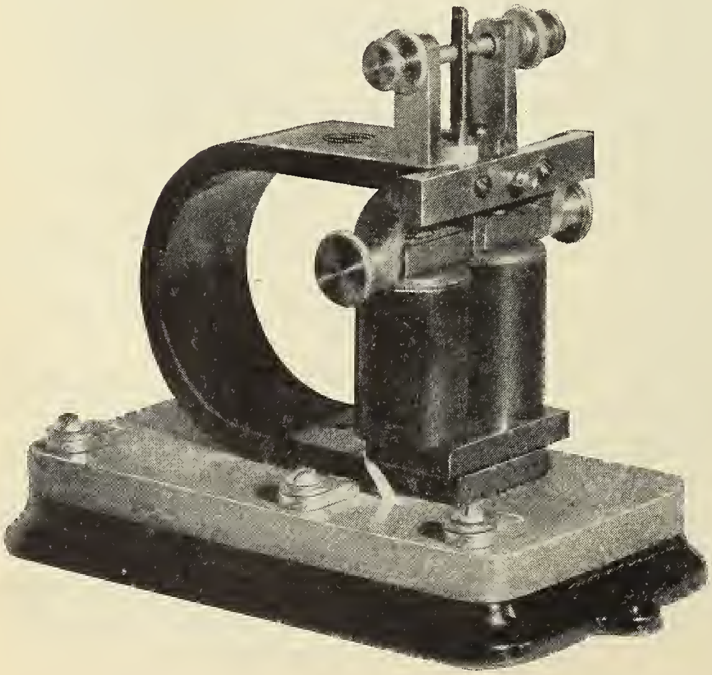
1. What kind of pole is the earth's north magnetic pole? Its south magnetic pole?
2. How is a dipping needle used to locate the earth's magnetic poles?
3. Why do magnetic compasses seldom point to the true north?
4. **a.** What is meant by declination? **b.** Why must declination be considered in using a compass to show direction?







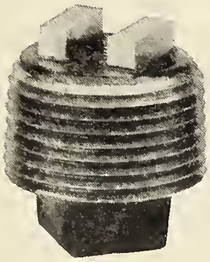
If you have the idea that magnets are interesting toys but not particularly useful, you will be surprised to learn that there are many practical uses for permanent magnets. For instance, the machinist above is using a toolmaker's magnetic block to hold firmly the small piece of steel that he is filing. No clamps are needed, and turning the control knob to OFF *releases the piece immediately. The diagrams at the right show how turning the magnet regulates the holding power of this interesting device.*

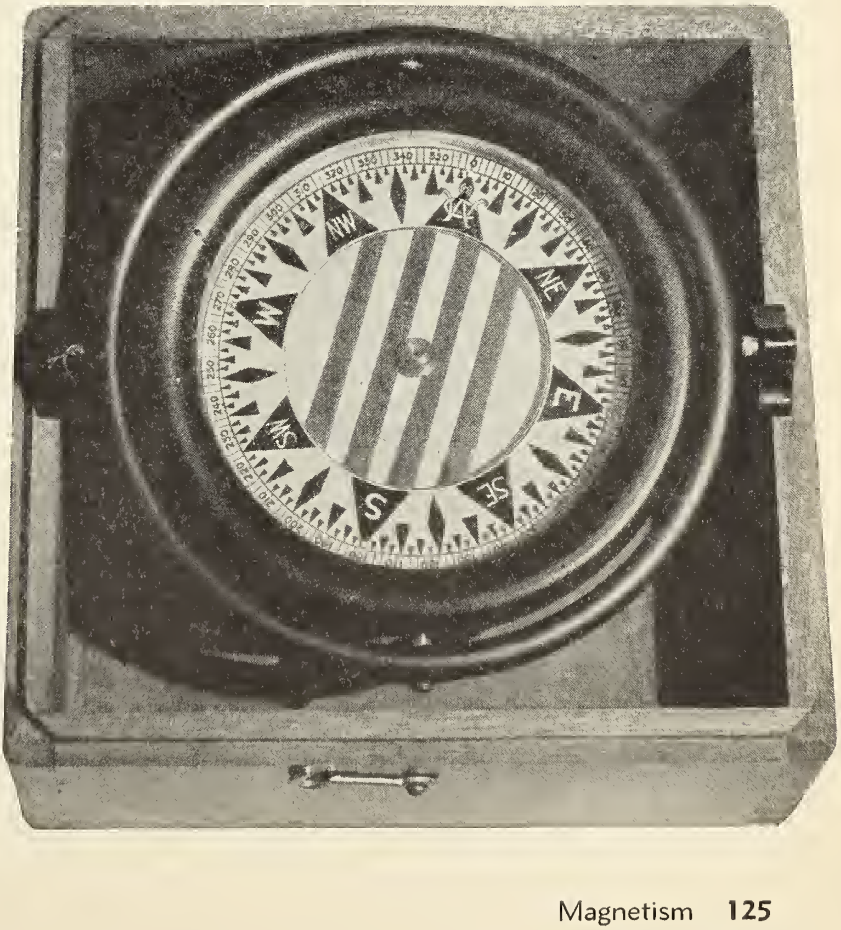


By means of the instrument at the left, weak signals from long-distance telegraph lines are transferred to a circuit containing a telegraph sounder or some other device for reproducing dots and dashes. The large U-magnet provides a strong magnetic field so that the contact lever will move when very weak currents flow through the two coils between the poles of the magnet.

Turning the crank of the magneto shown at the left produces enough current to light the small bulb. Notice the four large U-magnets. More compact forms of this device are used in the portable telephone sets of the Signal Corps to ring other stations. Still other kinds are used to ignite the explosive mixture in the cylinders of gasoline engines.

The mariner's compass at the lower right represents one of the oldest practical uses of magnets —to show direction. The magnetic drain plug at the left represents a new use for magnets— to protect machine bearings by removing small particles of iron and steel from the oil in crankcases and gear boxes. The lower picture shows what the magnet collects in use.





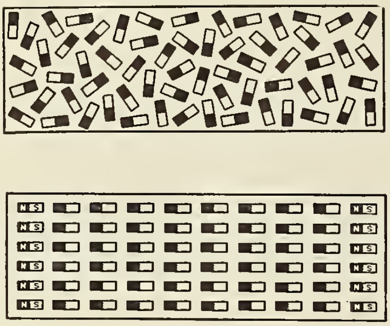


Figure 65 *illustrates the theory of magnetism. Each of the small rectangles represents one molecule with N and S magnetic poles. The upper diagram shows the irregular arrangement of these molecules in an unmagnetized object. The lower diagram shows how the molecules arrange themselves when the object is magnetized. Notice that all the N poles of the molecules now point in one direction, and all the S poles point in the other direction.*

USING WHAT YOU LEARNED

1. If a compass always pointed to the true north, no matter where it was located, what would this tell you about the position of the north magnetic pole and the north geographic pole?
2. At a place in the northern hemisphere a compass needle points 20° west of true north. **a.** On which side of the agonic line or zero-degree line is the place located? **b.** How far and in what direction must the compass needle be turned to make it point to the true north in this place?
3. In what general direction will the black end of a compass needle point at the north geographic pole? Why?
4. If you examine tables or maps showing magnetic declination that were published in different years, you may find that they show different declinations for the same place on the earth's surface. Does this mean that the tables are wrong? Explain.
5. A soldier is using a compass to guide him. **a.** How might his rifle interfere with the proper use of his compass? **b.** What should he do with his rifle while he is reading the compass? **c.** How can he make sure that the rifle is not affecting the compass?

The Theory of Magnetism

An ordinary piece of steel, such as you used in Experiment 25, is not a magnet, yet you found that it could be magnetized. It becomes a magnet when stroked with another magnet, when pounded in a certain way, or when an electric current is sent through a wire wound around it. Some change must take place in the piece of steel when it becomes magnetized. No one knows exactly what happens, but scientists have a theory that fits everything we can observe about magnets and magnetism.

The basic idea of the theory of magnetism is that every molecule of a magnetic substance is a tiny magnet. Since each molecule is a magnet, each one has a north and a south pole. Now it would seem that if a piece of iron, for example, was made of molecules that were magnets, the iron would always be magnetized; but we know that this is not the case. Ordinarily the iron is not magnetized. The reason for this can be explained by the arrangement of the molecules themselves. When the iron was made, the molecules arranged themselves in an irregular fashion. As each molecule is a little magnet, the north poles faced south poles because these poles attract one another. The upper diagram in Figure 65 shows how the north and south poles of the molecules neutralized one another. The poles of the tiny magnets just balance or neutralize one another, and the bar is not magnetized.

When the bar is magnetized, the molecules are moved into a new arrangement. The lines of force that pass through the iron bar, either from a strong magnet or from an electric current in a coil of wire, cause the molecules to swing so that their poles are pointing in the same direction. If you look at the lower diagram in Figure 65, you can see that the poles no longer neutralize one another. At the ends, for example, you can see why the piece of iron has a north and a south pole. The iron

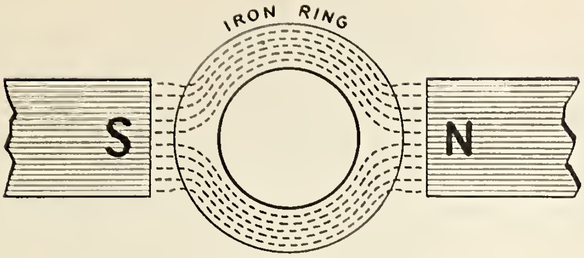


Figure 66 *shows what is meant by permeability. When an iron ring is placed between unlike magnetic poles, the lines of force travel through the longer iron path rather than through the shorter air path. This indicates that the iron has greater permeability than air.*

bar has become a magnet. If you do the first part of Experiment 28, you will get a good idea of what happens. Of course the iron filings used in the experiment are much larger than molecules, but they show what scientists believe must happen when a material is magnetized or demagnetized.

If this theory is a good one, it should explain other facts about magnetism. If you do the second part of Experiment 28, you will find that a magnet loses some of its magnetism when it is pounded. How does the theory explain this? When a magnet is pounded, the molecules are shaken up. They are jarred out of their position in line. Then some of the poles neutralize one another, and the magnet becomes weaker. This also explains why the piece of steel in the coil of wire was struck with a hammer while it was being magnetized. The blows helped to shake up the molecules so that they could be influenced to a greater degree by the electric current in the coil. Now you can see why magnets should be handled with care.

Scientists explain that when a material is heated, the molecules move faster. In fact, heat is the energy of molecular movement. As the material is heated, it expands. This permits the molecules to move about more easily and change their position. If that is the case, then heating a magnet should produce some effect on it. If you wish to try it, you can do the third part of Experiment 28. It will show you that heating helps to destroy magnetism. Letting a magnet stand in the sun will also weaken its magnetism, because the magnet is heated by the sun's rays.

This theory of magnetism also explains something that puzzled observers for a long time. When a magnet is broken in two pieces, each piece becomes a magnet. The fourth part of Experiment 28 shows that this is true. The north pole of the magnet remains a north pole, but the broken end of that piece becomes a south pole. The south pole of the original magnet remains a south pole, but the broken end of that piece becomes a north pole. In other words, opposite poles are found on each side of the break. If you look again at the lower part of Figure 65, showing the arrangement of molecules in a magnet, and draw an imaginary line through it at any point between molecules, you will see how the theory explains this fact.

Another fact about magnets is explained by this theory of magnetism. There is a limit to the amount of magnetism that a piece of steel or any magnetic substance can have. When that limit is reached, the substance becomes *saturated,* or as we say, the *magnetic saturation point* has been reached. No matter what is done, the substance will not become more strongly magnetized. If you refer again to Figure 65, you will see that when all the molecules are aligned, as they would be when the saturation point is reached, there is nothing more to be done.

This magnetic saturation point varies for different materials. You demonstrated that fact in Experiment 25, in which you made a steel magnet and an iron magnet electrically. Some materials are capable of being more strongly magnetized than others. The terms used to describe these qualities of a material are *permeability* and *reluctance.* Permeability is the ease with which lines of force may be established in a substance. For example, ordinary iron has great permeability. It is very easy to establish magnetic lines of force in iron. For this reason, iron is frequently used as a kind of magnetic screen to protect things from the effects of magnetic lines of force. The lines of force pass through the iron around the object and thus do not cut through the object itself. But there is no material that insulates magnetism. Magnetism can be diverted, but it cannot be cut off.

Reluctance is the opposite of permeability. It is the opposition that a substance offers to magnetic lines of force. A magnetic material with low reluctance offers an easy path for the lines of force. Wrought iron has a low reluctance, but permalloy, an alloy consisting of about 78 per cent nickel and 22 per cent iron, has an even lower reluctance, and is a better conductor of the lines of force. Steel, on the other hand, has a higher reluctance than iron; and air has a much higher reluctance than steel. In fact, air is such a poor conductor of magnetic lines of force that they pass through it with difficulty.

Experiment 25, in which iron and steel magnets were made electrically, also demonstrated another quality of magnetic substances, called *retentivity*. The steel retained most of its magnetism, while the iron quickly lost almost all of its magnetism as soon as the electric current was shut off. Magnetic substances vary a great deal in their retentivity. In general, substances that have low reluctance also have low retentivity. Substances with low retentivity, such as iron, are used for making temporary magnets. Steel, on the other hand, is commonly used for making permanent magnets, because it has high retentivity.

CHECKING WHAT YOU LEARNED

1. **a.** How do scientists explain magnetism and the behavior of magnets? **b.** Is their explanation a good one? Why?
2. Not all magnetic substances are magnets. Explain why this is so.
3. The theory of magnetism explains at least five different facts about magnets. **a.** What are they? **b.** How does the theory of magnetism explain each fact you give?
4. **a.** What is meant by permeability? Reluctance? Retentivity? **b.** Using these terms, tell why steel is used to make permanent magnets, while iron is used to make temporary magnets.

USING WHAT YOU LEARNED

1. Can you make a magnet with one pole? Three poles? Explain your answers.
2. When permanent magnets are stored, a "keeper" (bar of iron or steel) is put between the poles of each magnet or the magnets are piled up with unlike poles in contact with one another. Explain why these things are done.
3. You can make a magnet by pounding a steel rod, but pounding a magnetized rod will weaken or destroy its magnetism. How can both of these things be true?
4. **a.** Magnetism, such as that of the earth, cannot be turned off. Explain how iron can be used as a sort of magnetic screen. **b.** Why is an iron screen not placed around a compass to shield it from magnets or magnetic substances that will affect its reading?
5. A magnetized steel ring has no poles, yet it is a magnet. **a.** How is this possible? **b.** If the ring is broken in two, will the pieces have poles? Why?
6. Two bar magnets are placed together in order to get a stronger magnetic field than that of one. **a.** Should like or unlike poles be placed together? Why? **b.** What will happen if the other arrangement is used?

THINKING OVER WHAT YOU LEARNED

1. After the four topics of this chapter write down in complete sentences the big ideas or principles you have learned about magnetism from your study of each topic.
2. Show by using definitions or sentences that you understand the meaning of each of the following: **a.** pole of a magnet, **b.** lines of force, **c.** temporary magnet, **d.** magnetic induction, **e.** compass, **f.** magnetic flux, **g.** non-magnetic substance, **h.** dipping needle, **i.** declination, **j.** magnetic field, **k.** flux density, **l.** permanent magnet, **m.** magnetic substance, **n.** retentivity, **o.** magnetic saturation, **p.** reluctance, **q.** permeability, **r.** induced magnetism, **s.** polarity.

Experiment 23: **Poles, Field, and Lines of Force of a Magnet**

THINGS NEEDED: Bar magnet. U-magnet or horseshoe magnet. Iron filings. Box of iron tacks or small nails. Piece of thin cardboard or glass plate. Paraffin. Cup. Source of heat. Small magnetic compass. (See Figs. 56, 57, and 58.)

WHAT TO DO: **a.** Place a bar magnet in a pile of iron filings. Lift the magnet and notice what happens. Do the same amounts of filings cling to all parts of the magnet? If not, where are the greatest amounts? Remove the filings from the magnet. Scatter a box of iron tacks or small nails over a small surface. Put the bar magnet on the tacks or nails and then lift the magnet. What happens? How does this compare with what happened when iron filings were used? Repeat this part of the experiment, using a U-magnet or horseshoe magnet instead of a bar magnet.

b. Put a piece of thin cardboard or a glass plate over a bar magnet lying flat on your desk. Sprinkle some iron filings on the cardboard or glass, gently tapping it with your finger as you do so. Do the filings form a regular pattern about the magnet? Remove the cardboard or glass and brush off the filings. Then turn the bar magnet over. Replace the cardboard or glass. Sprinkle filings on as before and notice what happens. To make a permanent record of the magnetic field and its lines of force, melt some paraffin in a cup and spread a very thin coat over the cardboard or glass. Let the paraffin harden. Then set the cardboard or glass over the bar magnet and sprinkle on the iron filings as before. Remove the cardboard or glass without disturbing the pattern of filings. Heat the paraffin coating carefully until it melts and softens. Then let the paraffin cool again with the filings firmly imbedded in it. (If you care to do so, you may repeat Part **b**, using the U-magnet or the horseshoe magnet instead of the bar magnet.) Examine the pattern of filings, representing the lines of force in the magnetic field. Notice that they extend from one pole of the magnet to the other. Also notice that they do not cross one another.

c. Lay a bar magnet on your desk. Move a small compass along the lines of force from the N pole to the S pole. Starting from the N pole, move the compass around the side of the magnet to the S pole. Which way does the black end of the needle point at the N pole? At the S pole? What happens to the needle as it moves from the N pole to the S pole? Repeat Part **c**, using a U-magnet or a horseshoe magnet.

Experiment 24: **Making Temporary Magnets**

THINGS NEEDED: Bar magnet. Large iron nail. Box of iron tacks or small nails. Pieces of paper or glass plate. Sheet of iron or steel. (See Fig. 59.)

WHAT TO DO: Let one end of the bar magnet project over the edge of a table. Bring the head of a large iron nail up under the magnet so that its head touches the magnet. Now see how many iron tacks or small nails the large nail will hold up. Remove the magnet from the end of the large nail. What happens? Explain. Now bring the nail up under the magnet so that it is close to but not touching the magnet. See how many tacks the nail will support. Remove the magnet and notice what happens. Try this again but put one or more pieces of paper or a glass plate between the nail head and the bar magnet. To cause magnetism in the nail, must the nail and magnet be in contact? Now put a sheet of iron or steel in the space between the magnet and the nail (but not touching the nail). What happens now?

Experiment 25: **Making Permanent Magnets**

THINGS NEEDED: Thin pieces of steel and iron (knitting needles, thin nails, etc.). Magnetic compass. Bar magnet. String. Hammer. Spool of No. 26 cotton-covered or enamel-coated copper wire. Cardboard tube, ½ inch in diameter and about 6 inches long. Dry cell. Box of iron tacks or small nails. (See Figs. 60 and 61.)

WHAT TO DO: **a.** Test a thin piece of steel with a compass to make sure that it is not magnetized. Then stroke the steel in one direction with one end of a bar magnet. Lift the magnet at the end of each stroke and hold it away from the steel as you return it to the other end of the piece of steel to begin a new stroke. After several strokes test the steel for magnetism. What do you find? Take another piece of steel and test it to see that it is not magnetized. Lay it along one side of the bar magnet and fasten it firmly in place with string. After several days test it with the compass. Has the steel become magnetized? Test another piece of steel to make sure that it is not magnetized. Hold it in a north-south direction with the north end pointing down. Hammer on the other end. When the steel stops vibrating, test it for magnetism. What do you find?

b. Wind a coil of 200 turns of No. 26 wire around the cardboard tube. Test a thin piece of steel to make sure that it is not magnetized. Then put the steel inside the tube around which the wire is wound. Connect the ends of the wire to a dry cell so that a current flows through the coil. Hit the piece of steel several blows with a hammer. Disconnect the wire from the dry cell and take the steel out of the tube. Test it for magnetism. What has happened to the steel?

c. Put a piece of iron and a piece of steel (both unmagnetized) into the coil you made in Part **b.** Magnetize the iron and steel by connecting the coil to the dry cell as before. While each is still in the coil, test the two pieces of metal by dipping each into a box of iron tacks. Which picks up more tacks, the iron or the steel? Now disconnect the dry cell. Again try to pick up tacks with each of the two pieces of metal. Which piece picks up more tacks now? Which piece has lost most of its magnetism?

Experiment 26: **Attraction and Repulsion of Magnetic Poles**

THINGS NEEDED: Two bar magnets. String. Support. Chalk. (See Fig. 62.)

WHAT TO DO: **a.** Tie a string around the middle of one bar magnet and attach the string to a support so that the magnet can swing freely from side to side. Let it swing until it stops. (Be sure there are no magnets or magnetic substances near the suspended magnet.) In what direction are the ends pointing? If the ends are not properly marked, label the end that points north N (north-seeking) and the end that points south S (south-seeking). Repeat this with the other bar magnet.

b. Hang up one of the bar magnets as in Part **a.** When it comes to rest, bring the N pole of the other bar magnet near the N pole of the suspended magnet. What happens? Now bring the S pole of the other magnet near the S pole of the suspended magnet. What happens this time? Now approach the N pole of the suspended magnet with the S pole of the other magnet. Also try bringing the N pole of the other magnet close to the S pole of the suspended magnet. Notice what happens. What have you learned about attraction and repulsion of magnetic poles?

Experiment 27: **Dipping Needle**

THINGS NEEDED: Steel darning needle. Thread. Bar magnet. Coil and dry cell used in Experiment 25. Steel knitting needle. Cork. Two glass tumblers. (See Figs. 63 and 67.)

WHAT TO DO: **a.** Magnetize the darning needle by stroking it with the bar magnet or putting it in the coil connected to a dry cell as you did in Experiment 25. Tie a piece of thread around the middle of the needle. Suspend the needle from the thread and adjust its position until it balances. Lay the bar magnet on your desk. Hold the magnetized needle about 2 inches above the center of the magnet. Notice what happens. Move the needle toward one pole of the magnet and then the other. What happens? Move the needle all around the magnet and notice the position of the needle as you move it from side to side and in a circle around the magnet.

b. Make a dipping needle as follows: Use a steel knitting needle for the dipping needle and a darning needle for a pivot. Demagnetize both needles by heating them red-hot. Push them through a cork at right angles to each other. Lay the darning needle on the rims of two glass tumblers so that the cork and knitting needle are supported between the tumblers and can turn freely. Adjust the knitting needle in the cork until the needle is horizontal. Point the knitting needle in

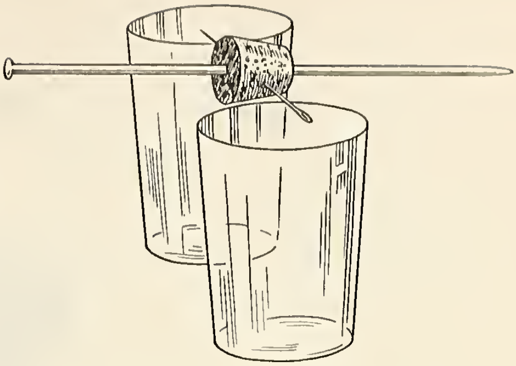


Figure 67 *illustrates the dipping needle in part* **b** *of Experiment 27.*

a north-south direction. Now stroke the knitting needle from north to south with the N pole of a bar magnet. After several strokes notice what happens when you release the knitting needle. Explain why this happens. Then tell why the knitting needle must be demagnetized before it is balanced in a horizontal position in a north-south direction.

Experiment 28: **Theory of Magnetism**

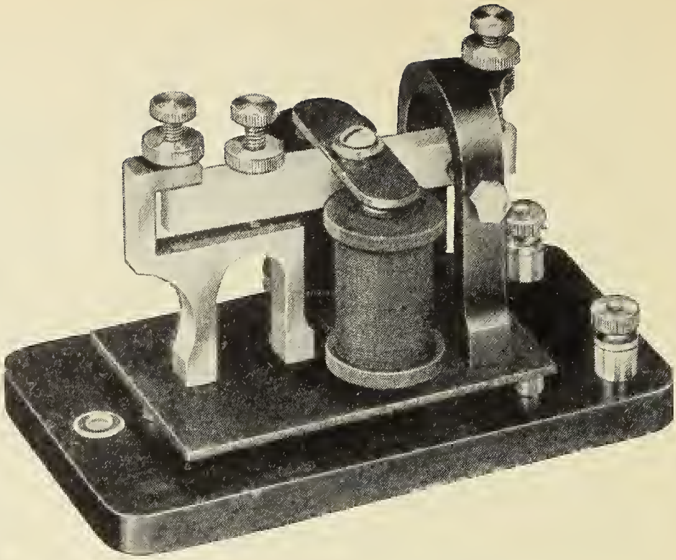
THINGS NEEDED: Medicine bottle and cork. Iron filings. Bar magnet. Steel knitting needle. Coil and dry cell used in Experiment 25. Magnetic compass. Hammer. Tongs or forceps. Source of heat. Old hacksaw blade or piece of clock spring. Two pairs of pliers. Chalk.

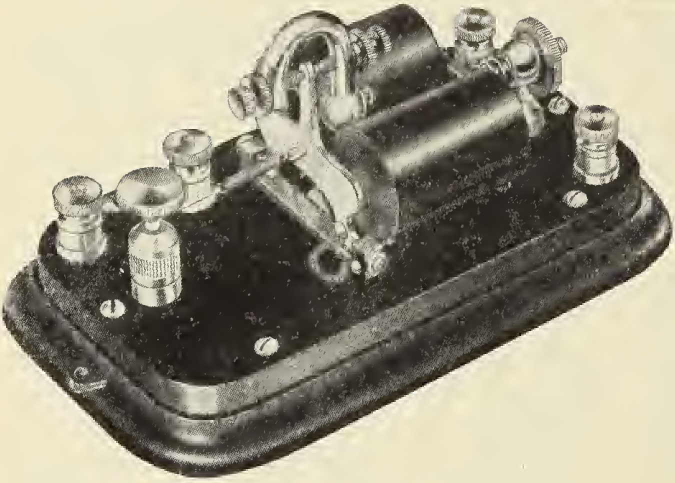
WHAT TO DO: **a.** Fill the medicine bottle about half full of iron filings and put the cork in the bottle. Lay the bottle on its side and shake it back and forth gently until the filings are evenly distributed from one end to the other. Now stroke the bottle with one end of a bar magnet, in the way shown in Fig. 60. What happens to the iron filings? Tap the filings or shake them up and then repeat the stroking but use the other end of the bar magnet. Notice what happens to the filings. Now stroke the bottle in the same direction but use the other end of the bar magnet (the end you used first). What happens now?

b. Using a bar magnet or the coil and cell, magnetize a steel knitting needle. Test it for magnetism with the compass. Place the needle in an east-west direction and hit it with several sharp blows of a hammer. Now test it for magnetism. What happens? (If it is still magnetized, hammer it again.)

c. Magnetize the knitting needle as before. Test it for magnetism. Grasp the needle with tongs or forceps and hold it over a source of heat until it becomes red-hot. Let it cool in an east-west direction and then test it for magnetism once more. What happens?

d. Magnetize an old hacksaw blade or a piece of clock spring, using a bar magnet or the coil and cell. Test the blade or spring for magnetism. Mark the north pole with an N and the south pole with an S. With the pliers break off a piece of the blade or spring. Test both pieces for magnetism. What do you find? Mark the poles as before. If you wish, you may break off another piece and repeat the test for magnetism. What poles do you find at the broken ends?





6. Electromagnetism

FINDING OUT WHAT YOU KNOW

1. How can you use electric current to make a temporary magnet?
2. What is an electromagnet?
   State two reasons for using an electromagnet instead of a permanent magnet.
3. Give some important uses of electromagnets.
4. Why do electromagnets usually have cores of iron rather than of steel or some other metal?
5. Tell how an electromagnet can be made stronger.
6. How does an electric bell or buzzer work?

IN THE LAST CHAPTER you saw that there is a relation between electric current and magnetism. In Experiment 25 a piece of steel was magnetized by sending an electric current through a coil of wire around the steel. Obviously the current caused some change in the steel that resulted in making the steel a magnet. This is the third effect of the electric current you have observed. The other two were the heating effect, which you studied in the chapter on resistance, and the electrochemical effect, which you studied in the chapter on cells. This third one is called the *electromagnetic effect.*

The relation between magnetic force and the electric current is an extremely important one. Until scientists began to understand it, little progress was made in either using or producing electrical energy. We might say that today almost our entire electrical industry is based on practical applications of what has been discovered about electromagnetism. The generators that make the huge quantities of current required in modern life use the principles of electromagnetism. Motors, radios, telephones, and hundreds of appliances are based on the same principles. To understand how these appliances work and why they act as they do, you must know something of this relation between electric current and magnetism.

Magnetic Field around a Conductor

If we start with the coil of wire used in Experiment 25, we can soon show that there is a mag-

Electromagnet: A temporary magnet made by sending an electric current through a coil of wire usually wound around an iron core. When the current stops, the electromagnet loses all or nearly all of its magnetism.

Solenoid: A temporary magnet made by sending an electric current through a tube-shaped coil of wire. A solenoid has an air core or sometimes a movable iron core called a plunger.

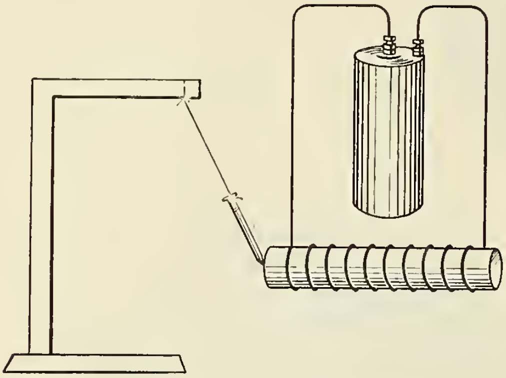


Figure 68 *shows that a coil of wire connected to a dry cell attracts an iron nail in the same way that a magnet does. When disconnected from the dry cell, the coil of copper wire has no effect on the iron nail. The coil has been simplified in this drawing and in those that follow. Instead of 10 turns, the coil actually has about 200 turns of No. 26 cotton-covered copper wire.*

netic field around the coil when a current supplied by a dry cell is sent through the wire of the coil. The first part of Experiment 29 (page 148) shows that this is true. Fasten a string to an iron nail and then hang the nail so that it is free to swing, as shown in Figure 68. Before connecting the coil to the dry cell, bring each end close to the nail. With no current flowing through it, the coil does not attract the iron nail; it is obviously not a magnet. Now connect the coil, or **solenoid** as it is sometimes called, to a dry cell. Bring one end of the coil near the suspended nail. You will see that the nail is attracted. If you turn the coil end for end, the nail will be attracted to the other end of the coil. Now disconnect one wire from the dry cell and again bring the coil near the nail. Neither end of the coil will attract the nail. You see that the coil acts like a magnet only so long as a current flows through the wire. When the flow of current stops, the coil loses its magnetism. The coil thus forms a kind of temporary magnet, called an **electromagnet**, whose magnetism can be turned off or on by opening or closing a circuit. Usually an electromagnet has an iron *core,* for a reason you will learn later in this chapter.

If this coil has a magnetic field around it when current is passing through the wire, it should have poles like a magnet. This is easy to prove by doing the second part of Experiment 29. If you suspend a bar magnet so that it is free to turn horizontally, you can test the coil with it. You know that another magnet would have certain very definite effects on the suspended magnet. The north poles of the two magnets would repel each other. So would the south poles. And the north pole of one magnet would attract the south pole of the other. You will find that the coil, when the current is flowing through it, acts precisely as another magnet would act. One end of the coil is like the north pole of a magnet; the other is like the south pole. In other words, we say that the coil has polarity. (See Fig. 69.)

Now reverse the direction of the current from the dry cell. Just switch the wires that are attached to the posts of the cell. Put the wire that was on the outside post on the center post, and then fasten the other wire to the outside post. Now the current will flow through the circuit (and through the coil which is a part of the circuit) in the opposite direction.

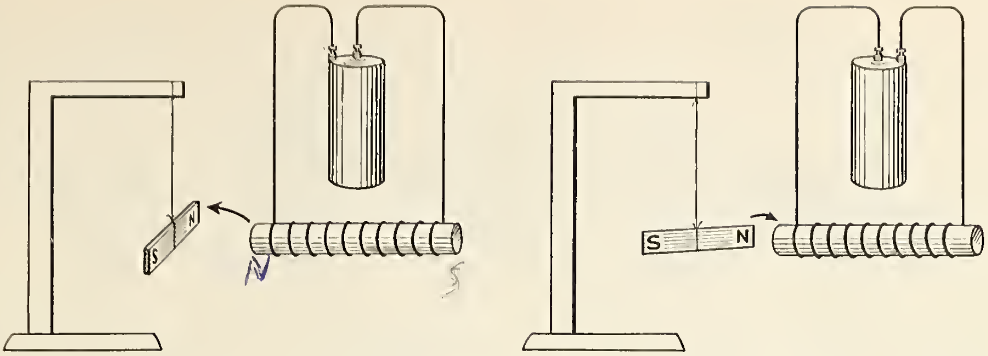


Figure 69 *shows that the polarity of a solenoid depends on which way the current flows through the winding. For example, the N pole of the suspended bar magnet shown at the left is repelled by the solenoid, thus indicating that this end of the coil is a N pole also. When the connections to the dry cell are reversed, the N pole of the bar magnet is attracted, thus indicating that the same end of the solenoid is now a S pole.*

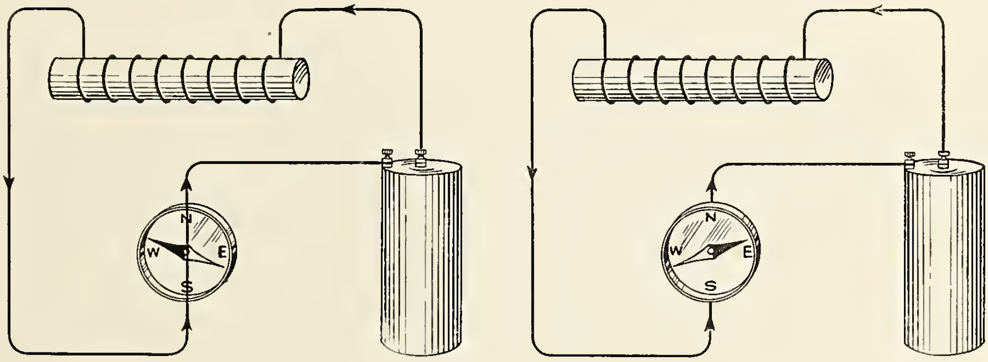


Figure 70 *shows why a solenoid becomes a magnet when a current is sent through the wire. As long as the current flows from south to north, the N pole of the needle of a compass swings toward the west when the wire is held over the compass, as shown at the left, and toward the east when the wire is held under the compass, as shown at the right. This indicates that magnetic lines of force surround a wire carrying an electric current.*

When you test the coil with a suspended magnet as before, you discover that the poles of the coil have changed, too. What was the north pole is now the south, and the south pole has become the north. You can therefore conclude that an electric current sets up a magnetic field around a coil, and that the polarity of the coil is determined by the direction of the current.

A natural question to ask is whether these results are obtained because the wire is coiled or for some other reason. You can answer that easily enough by unwinding a few turns of the coil and trying a similar experiment with a single wire. The first part of Experiment 30 is called Oersted's Experiment, after Hans Christian Oersted, a Danish scientist who confirmed by this experiment

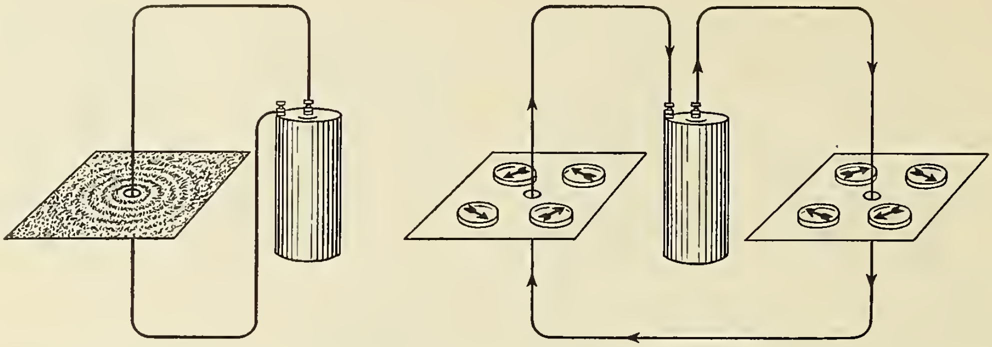


Figure 71. *When iron filings are sprinkled on a piece of cardboard surrounding a wire carrying an electric current, the lines of force cause the filings to arrange themselves in a pattern like that shown at the left. The direction of the magnetic flux can be shown with one or more small testing compasses, as at the right. Notice that the direction of the flux depends upon which way the current flows.*

and others the relation between magnetism and electricity that scientists had long suspected.

Oersted discovered that when a wire was held *over* a compass needle so that wire and needle were parallel, and a current was sent through the wire, the needle swung toward the west when the direction of the current (flowing from positive to negative) was from south to north. Oersted further found that when the wire was placed *under* the compass, the needle swung in the opposite direction, that is, toward the east when the current flowed from south to north. When he sent a current through the wire from north to south, the compass needle swung to the east if the wire was held *over* the compass needle and to the west if the wire was held *under* the needle. Obviously, a wire carrying a current is surrounded by a magnetic field, and the direction of its lines of force is determined by the direction of the current. And these things are true whether the wire is straight or wound into a coil.

Another way to show this is by doing the second part of Experiment 30. Make a hole in a piece of cardboard and put a wire through it so that the wire is at right angles to the surface of the cardboard. Sprinkle iron filings on the cardboard and connect the ends of the wire to a dry cell. Tap the cardboard gently when the current is on, and the filings will arrange themselves in rings about the wire. (See Fig. 71.)

If you place a small compass at various points on the cardboard, you will see that the needle swings in the direction of the lines of force as shown by the iron filings. As a matter of fact, what you have done is to make, in the pattern of the filings, a cross section of a magnetic field. It is much the same as the field of force that exists around a bar magnet. If you reverse the direction of the current as before, you will see that the compass needle swings in the opposite direction.

What the flow of current has done is to set up a magnetic field around the conducting wire. This field is at right angles to the conductor. And the lines of force are arranged *around* the wire. The direction of this flux is determined by the direction of the current flowing through the conductor.

There is a rule, called the **right-hand rule**, that makes it easy to remember the direction of the flux around a straight wire carrying a current. Grasp the wire with the right hand so that the thumb points in the direction of the current. (The thumb will be pointing along the wire leading to the negative terminal of the source.) The fingers of the hand will curl around the wire in the direction of the magnetic flux. (See Fig. 72.)

Right-hand rule for wire: When a wire is grasped with the right hand so that the thumb points in the direction of the current (that is, toward the negative terminal), the fingers point in the direction of the magnetic flux.

Right-hand rule for coil or electromagnet: When a coil is grasped so that the fingers curl in the direction of the current, the thumb will point to the north pole of the coil.

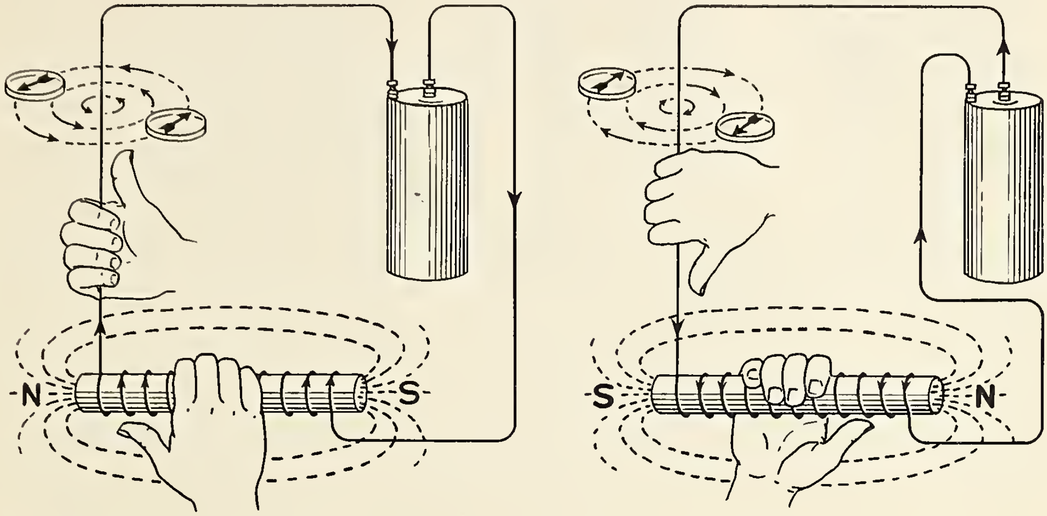


Figure 72. *These two diagrams will help you remember the right-hand rules for wires and coils. The upper hand in each drawing shows that the fingers indicate the direction of the magnetic flux when the wire is grasped so that the thumb points in the direction of the current. The lower hand in each drawing shows that the thumb points in the direction of the north pole of the coil when the fingers curl around the coil in the direction of the current. The rules work both ways. When the fingers point in the direction of the flux, the thumb indicates the direction of the current in a wire. When the thumb points to the north pole of a coil, the fingers indicate the direction of the current.*

This right-hand rule is also useful in determining the polarity of a coil when a current is passing through it. If the fingers curl around the coil in the direction of the current (from positive to negative), the thumb will point to the north pole of the coil. This rule is useful in determining the poles of electromagnets.

CHECKING WHAT YOU LEARNED

1. Is an electromagnet a permanent or temporary magnet? Explain.
2. State two facts about the electromagnetic effect of a current in a wire.
3. **a.** What is the right-hand rule for a wire carrying a current? **b.** For a coil? **c.** In using either of these rules, what must you remember about the current?
4. Name the three effects of an electric current that you have studied in this book and give an example of each effect.

USING WHAT YOU LEARNED

1. Tell how you could use a second coil and dry cell instead of a bar magnet to show that a coil carrying a current has poles.
2. How could you use a compass to test the polarity of a coil through which a current flows?
3. **a.** Explain why a coil carrying a current can

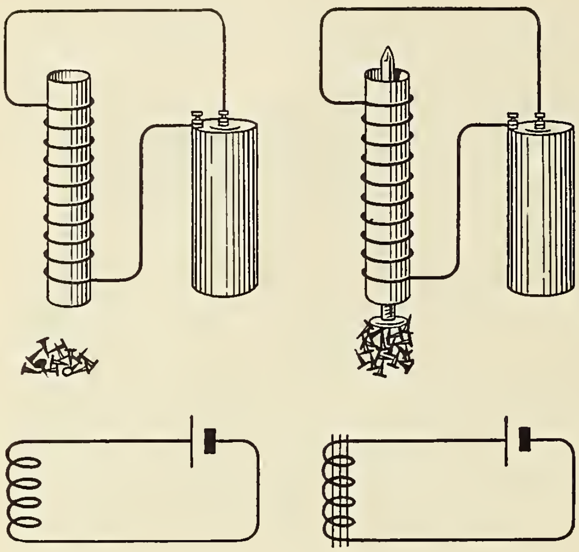


Figure 73. *The upper pictures show how the strength of an electromagnet is increased when an iron core is used. At the left is shown the coil with an air core. Although able to exert considerable magnetic force, such a coil will probably lift few if any of the tacks. At the right is shown what happens when an iron core is provided for the magnetic flux. With one cell and the same coil, all the tacks can now be lifted. The lower diagrams show the symbol for a coil in electrical circuits. Notice how the iron core is indicated in the diagram at the right.*

be used in making permanent magnets. **b.** Tell how you could determine the poles of a permanent magnet made in this way, using the right-hand rule.

4. How can a compass be used to find the direction of a current in a wire?
5. A coil carrying a current has poles, while a straight wire does not. Explain.

Strength of Electromagnets

Unlike the magnetism of a permanent magnet, electromagnetism may be easily controlled by turning the current on or off or by varying the current. For when the current stops flowing or decreases, the magnetic field around a coil disappears or becomes weaker. Later in this chapter and in other chapters of this book you will see that electromagnets are used in devices where the magnetism must be controlled. Electromagnets may also be made much stronger than permanent magnets. There are thus two good reasons for using electromagnets instead of permanent magnets: (1) control of magnetism and (2) greater strength.

In Experiment 25 an electromagnet was made when an electric current was sent through a coil containing pieces of iron and steel. The iron was a magnet only so long as the current flowed through the coil; it lost most of its magnetism soon after the current stopped flowing. However, the piece of steel kept most of its magnetism after the current was turned off. This ability of steel to keep its magnetism makes it very suitable for permanent magnets but very unsuitable for temporary magnets, such as electromagnets. Iron, on the other hand, is more easily magnetized than steel; since it loses its magnetism very easily, it is particularly suitable for temporary magnets of all kinds. The magnetism of an iron core in an electromagnet may be controlled by turning the current through the coil on or off. For all practical purposes, the iron core of an electromagnet is a magnet only while a current is flowing through the coil around the iron.

An iron core within the coil of an electromagnet greatly strengthens its magnetism, as you can see by doing Experiment 31. First use a coil without an iron core; in other words, use an air core. Notice how many tacks are picked up when a current is sent through it. Then put an iron core in the coil. When a current is sent through the coil this time, many more tacks can be picked up. An electromagnet with an iron core has far more strength than that of a coil alone. (See Fig. 73.)

Magnetizing force: The force needed to produce magnetic flux around a conductor carrying a current or to magnetize a magnetic substance. Also called **magnetomotive force**, or **M.M.F.**

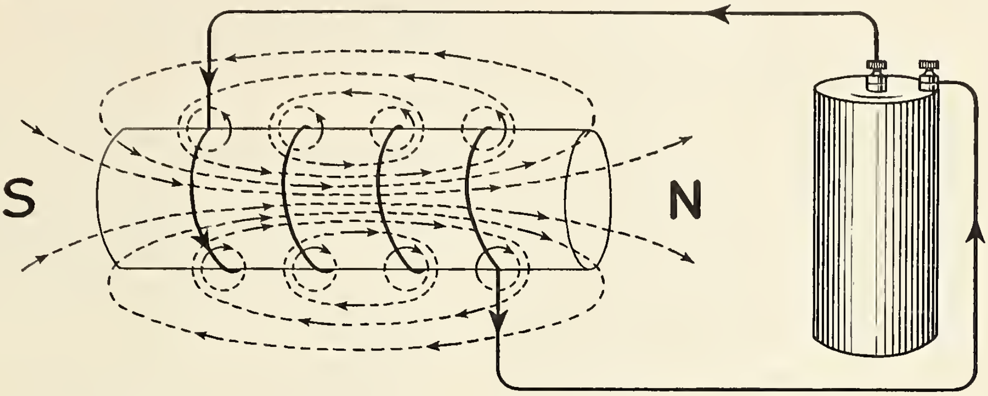


Figure 74. *This diagram shows how the lines of force which surround a wire carrying a current combine in a coil to form a much more concentrated magnetic field. Since each turn added to the coil strengthens the magnetic field, the magnetizing force of such a coil is measured in ampere-turns. A coil of 10 turns of wire carrying 1 ampere has 10 ampere-turns; so has a coil of 2 turns of wire carrying 5 amperes.*

good [illegible] 10 ampere-turns.

You have already seen that a coil has a more concentrated magnetic field than that of a wire. The lines of force not only run around each turn of the coil, but they reinforce one another and spread. However, they must pass through air, which has a low permeability, as you remember from Chapter 5. Therefore, the air (particularly that inside the coil) offers a great deal of opposition to these lines of force. But if an iron core instead of an air core is used inside the coil, the lines of force are carried more easily, because iron has a high permeability. The lines of force meet with far less opposition in passing through an iron core than they do in traveling through an air core. Moreover, iron has a low reluctance and a low retentivity; it is easily magnetized and loses its magnetism almost as easily. Thus an iron core not only strengthens an electromagnet, but it is also very satisfactory from the standpoint of control of magnetism.

The cores of electromagnets are made in various shapes. If only one pole is used, the shape may resemble that of a bar magnet. However, if a more concentrated field is desired, the poles of the electromagnet may be placed close together like those of a U-magnet or a horseshoe magnet. The shape of an electromagnet and its core depends on the use for which the electromagnet is intended. In any case, an electromagnet has a coil surrounding a core, which is usually made of iron.

Besides the use of an iron core, there are other ways to strengthen an electromagnet. If you do Experiment 32, you will see that this is true. The **magnetizing force**, or **magnetomotive force** as it is also called, of a coil is increased by increasing the current through the coil or by increasing the number of turns in the coil. Very strong electromagnets are made by doing both of these things. A straight wire, of course, has no turns and no core; its magnetizing force depends solely on the current in amperes flowing through it. In a coil, however, the magnetic flux around each turn of wire reinforces that around the turns next to it.

The number of turns in a coil affects its magnetizing force in much the same way as putting permanent magnets together with like poles touch-

Ampere-turn: A unit for measuring the magnetizing force of a coil through which a current flows. A current of one ampere in a coil of one turn produces a magnetizing force of one ampere-turn.

ing increases the strength of the magnetic field around them. Two bar magnets or horseshoe magnets put together in this way have a stronger field than that of one. If another magnet is added in the same way, the strength of the field is further increased. Or you may think of the field around a coil carrying a current as made up of all the lines of force (magnetic flux) around many feet of wire concentrated in a small space. The lines of force seem to join and form one large magnetic field with poles at each end of the coil.

Because the magnetizing force of a coil depends on the current and the number of turns in the coil, it is often measured in a unit called the **ampere-turn**. A current of one ampere in a coil of one turn produces a magnetizing force of one ampere-turn. To find the magnetizing force of any coil in ampere-turns, multiply the amperes of current flowing through the coil by the number of turns in the coil. For example, if a current of 2 amperes flows through a coil of 50 turns, the magnetizing force of the coil is 2 amperes times 50 turns, or 100 ampere-turns. A coil of 25 turns carrying a current of 2 amperes has a magnetizing force of only 50 ampere-turns—half as much; so has a coil of 50 turns through which a current of 1 ampere flows.

Strong electromagnets have coils of many turns around their iron cores, and many amperes of current are sent through the coils. Yet it is a curious fact that the magnetizing force of a coil does not depend on the resistance of the coil or the voltage of the circuit except insofar as the voltage and resistance affect the current in accordance with Ohm's Law. For example, suppose that a 50-turn coil has a 10-ohm resistance. In order to make a current of 2 amperes flow through the coil and thus produce a magnetizing force of 100 ampere-turns, a pressure of 20 volts must be supplied. If the resistance of the coil is doubled, the voltage must be doubled to drive 2 amperes of current through the coil and produce the same magnetizing force (100 ampere-turns). Any combination of voltage and resistance that will cause a current of 2 amperes to flow through a 50-turn coil will produce a magnetizing force of 100 ampere-turns.

Thus the strength of an electromagnet (and of its field) depends on three things:

1. The material of the core (its permeability).
2. The current flowing through the coil.
3. The number of turns in the coil.

CHECKING WHAT YOU LEARNED

1. What three things determine the strength of an electromagnet?
2. **a.** How is the magnetizing force of an electromagnet measured? **b.** Give an example to show that you understand what this means.
3. Why is iron instead of steel used for the cores of most electromagnets?
4. State the two main reasons for using electromagnets instead of permanent magnets in electrical devices. Explain your answer.

USING WHAT YOU LEARNED

1. What advantages does an electromagnet have compared with a permanent magnet? What disadvantages?
2. Tell what would happen if you made an electromagnet and used a steel core.
3. One electromagnet has a coil of 35 turns through which a current of 3 amperes flows, while another magnet has a coil of 25 turns carrying a current of 4 amperes. Which one is stronger? Give your reasons.
4. Each of two electromagnets with identical iron cores has a coil of 300 turns; but one has a resistance of 12 ohms, while the other has a resistance of 24 ohms. **a.** If current at a pressure of 6 volts is supplied to each electromagnet, which one will be stronger? How do

Armature: The part of an electrical device acted on by a magnetic field.

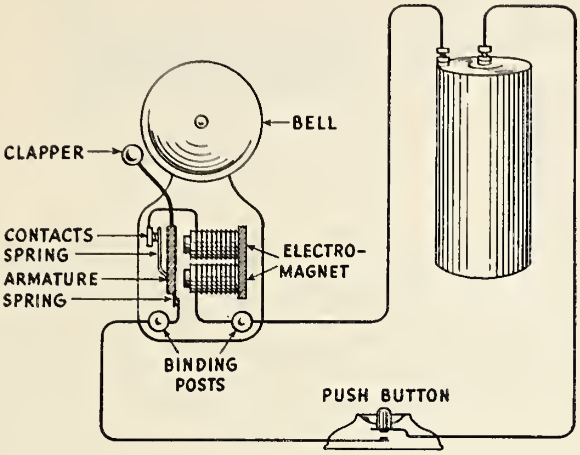


Figure 75 *shows the parts of an electric bell. When the circuit is closed by pressing the push button, the electromagnet attracts the iron armature, which moves toward the electromagnet until the clapper strikes the bell and the contacts separate. When current stops flowing through the coils, a spring causes the armature to swing back until the contacts close the circuit and current once more flows through the electromagnet.*

you know? **b.** What must be done to make the strength of the other magnet as great? Tell why this will work.

Some Uses of Electromagnets

Electromagnets are extremely important parts of many electrical devices. A spectacular use is the huge electromagnetic hoist used in foundries and steel mills for lifting heavy loads of steel and iron. But we must not overlook the smaller electromagnets used in bells, buzzers, telephone receivers, and telegraph sounders, or the large ones used in generators and motors.

Electric bell or buzzer. The electric bell or buzzer is a simple application of the electromagnet. The common type usually has two coils on a U-shaped iron core. The coils of wire are wound in opposite directions, as you can see by referring to Figure 75. If you apply the right-hand rule, you will see that this method of winding gives a north pole and south pole close together. A short distance away from the core, but within its range when it becomes magnetized, is a flat piece of iron called an **armature.** The armature is mounted on a spring that forces it away from the poles of the electromagnet. Another small, flat spring is attached to the armature and forms a part of the electric circuit, as you can see by referring to the diagram.

When the circuit is closed by pressing the push button, current flows through the circuit and the coils of the electromagnet are energized. The iron core almost instantly becomes a magnet and attracts the armature. But when the armature moves toward the core, the circuit is broken, as you can see by looking at the diagram. When this happens, the coils and thus the core immediately lose their magnetism. The spring pushes the armature away from the core and back to the position where the circuit is closed again. With the circuit closed once more, the electromagnet is again energized, the armature is again attracted, and the whole process goes on, over and over—as long as the push button is held down. In a bell, a clapper is attached to the armature; as the armature vibrates back and forth, the clapper strikes against the bell. In a buzzer, the vibration of the armature makes a buzzing sound. If you do the first part of Experiment 33, you can examine and connect a bell or buzzer.

Telephone receiver. Another very common application of the electromagnet is found in the receiver of a telephone. The receiver consists of a plastic or hard-rubber case containing a disk of metal, called a diaphragm, that can vibrate, and

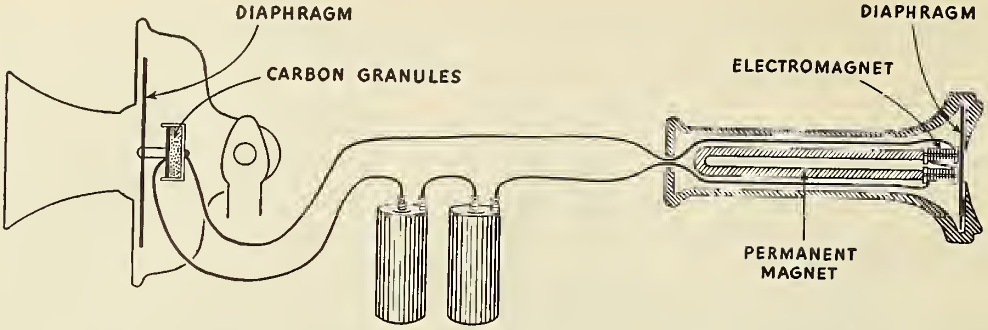


Figure 76 *shows a simple one-way telephone circuit. Sound waves striking the diaphragm of the transmitter cause the resistance of the carbon granules to vary. This results in a pulsating or fluctuating current which vibrates the diaphragm of the receiver, causing sound waves very much like those which struck the diaphragm of the transmitter. The permanent magnet in the receiver keeps the diaphragm in place and strengthens the action of the small electromagnet.*

an electromagnet, as shown in Figure 76. The core of this electromagnet is a permanent magnet, which holds the diaphragm in place and keeps it from rattling. The coils around the core are supplied with a current whose strength varies because of the varying resistance of the transmitter.

As explained in Chapter 3, a telephone transmitter is a kind of variable resistance operated by sound waves. When a sound wave reaches the diaphragm of the transmitter, it makes the diaphragm vibrate. When the diaphragm moves in, the carbon granules in the transmitter are crowded closer together, and their resistance decreases. For an instant more current flows through the circuit. When the diaphragm moves out, the carbon granules move slightly apart, and their resistance increases. For an instant less current flows in the circuit. The result is a *pulsating* or *fluctuating current.* In the receiver this pulsating current energizes the coils around the permanent magnet, strengthening or weakening its pull against the diaphragm. As a result, the receiver diaphragm moves back and forth, setting in motion sound waves like the original sound waves that struck the diaphragm of the transmitter. If you do the second part of Experiment 33, you can examine and connect a telephone receiver to see how it operates.

Telegraph sounder. One of the first practical applications of the electromagnet was in a telegraph sounder. The sounder, as used today, is an electromagnet with an iron armature fastened to a metal bar. (See Fig. 77.) The bar is pivoted so that the armature can move it down when the armature is attracted by the electromagnet. A spring pulls the bar back again. Above and on the bar are set screws that can be adjusted so that the bar clicks against them as it moves up and down.

The *telegraph key* is simply a form of switch, constructed so that it can be operated rapidly. When the key is pressed, the circuit is closed and the electromagnet of the sounder is energized. The armature is attracted, and the bar clicks against the lower set screw. When the key is released, the circuit is broken, and the electromagnet of the sounder loses its magnetism, the armature is pulled up, and the bar clicks against the upper set screw. The click made by the rising bar has a different sound from the click of the descending bar. A telegraph operator listens to these clicks and distinguishes the short and long intervals between them. A short interval is a dot, a long one is a dash. You can examine and connect a telegraph sounder if you do the third part of Experiment 33.

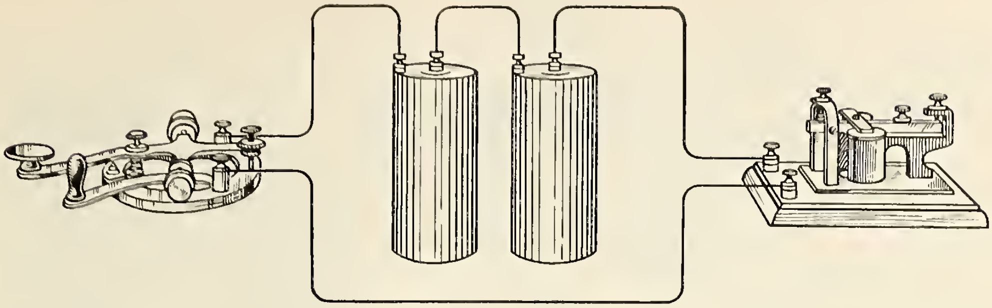


Figure 77 *shows a simple one-way telegraph circuit. Pressing down on the key closes the circuit and causes the electromagnet in the sounder to pull down a metal bar with a loud click. Releasing the key opens the circuit, and a spring raises the bar with a slightly different click. Short and long intervals between the two clicks are called dots and dashes.*

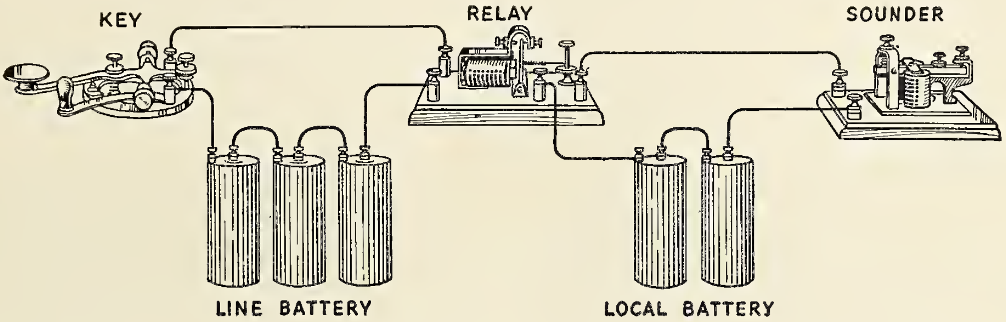
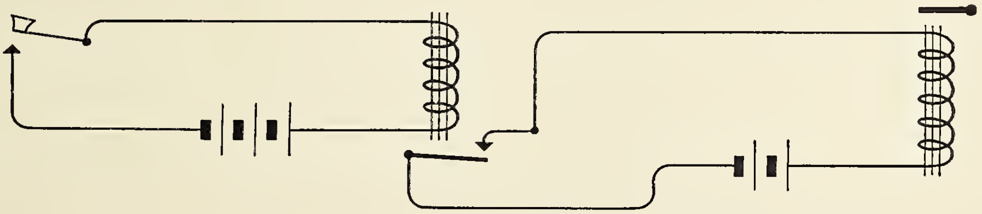


Figure 78 *shows a simple one-way telegraph circuit with a relay. Pressing down on the key closes the line-battery circuit and causes the relay armature to move until the contacts close the local-battery circuit, which operates the sounder. Releasing the key opens the line circuit, and the relay armature moves back, opening the local circuit. A diagram of this circuit is shown below. Notice the symbols for the key, relay, and sounder.*



Relays. When a long distance separates the key from the sounder, the resistance of the circuit is often so high that the sounder will not operate. Even when many cells are connected in series, the current is too weak to energize the electromagnet and pull the bar hard enough to make a click the operator can hear. This problem has been solved by the use of a *relay*. The type of relay used for telegraph work is simply a very sensitive electromagnet, as shown in Figure 78.

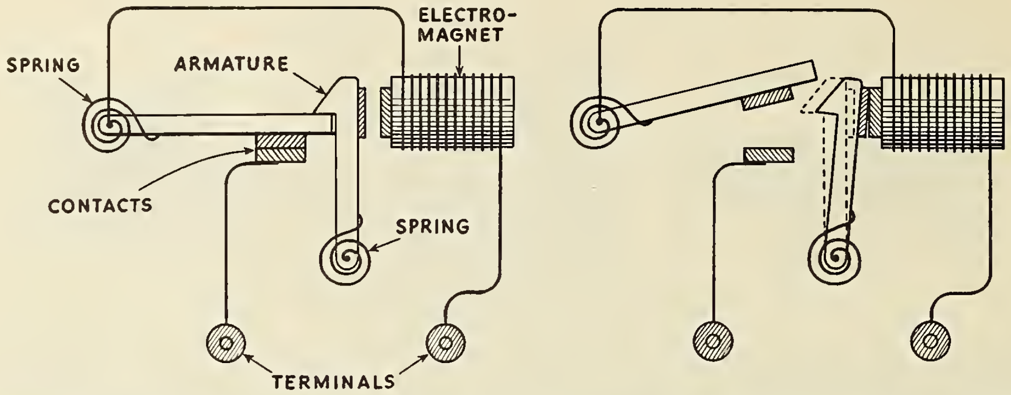


Figure 79 *shows how a magnetic circuit breaker operates. At the left the circuit breaker is shown in the closed position. Notice the path of the current through the electromagnet, the contact arm, and the contacts. An overload pulls the armature back, releasing the contact arm, and opening the circuit, as at the right. When the circuit breaker is reset by pushing the contact arm down, current will flow in the circuit again.*

Instead of several hundred turns of rather large wire in the coil, the relay coil has several thousand turns of smaller wire. Although the current is weak, the ampere-turns of the coil are fairly high because of the many turns of wire. Close to the electromagnet of the relay is a light armature, held away by a small spring. On this armature is a contact point that will close another circuit, which has its own source of electrical energy (usually a battery). This armature operates in much the same way as the armature of an electric bell or buzzer, except that the contact point on the relay armature is not a part of the electric circuit that operates the relay.

A relay like the one described is quite sensitive, and even a weak current will cause it to attract the armature when the telegraph key at the other end of the circuit is pressed. In other words, the armature of the relay will follow the movements of the key that may be miles away. The relay, then, acts as a switch, opening and closing another circuit that has a separate source of electrical energy and its own sounder. Figure 78 shows how the relay operates the sounder.

There are many kinds of relays, but all are alike in that a variation in the current flowing through an electromagnet opens or closes contact points that are parts of an electric circuit. Thus every relay is really an electrically operated switch. Where a motor or other electrical device using a large current must be controlled from a distance, a relay is ordinarily used. Because the circuit containing the relay needs to carry only enough current to open or close the contact points, the wires can be much smaller than those in the main circuit. In addition to the saving in copper wire, such an arrangement is safer, more efficient, and considerably more convenient than the usual circuit would be. Other kinds of relays are automatic in action, so that the contacts open or close when the current increases above or decreases below a certain amount. Relays of this type are used in automobiles to control the amount of generator current needed to charge the storage battery, in burglar- and fire-alarm circuits, and in railroad signal circuits.

Circuit breakers. Another use of the electromagnet that is fairly common is in the magnetic circuit breaker. In Chapter 3 you learned about the thermostatic (or heat-operated) circuit breaker that is a device for safeguarding the circuit. The magnetic circuit breaker, shown in Figure 79, also safeguards the circuit but in a different way. It is sometimes used on washing machines and other

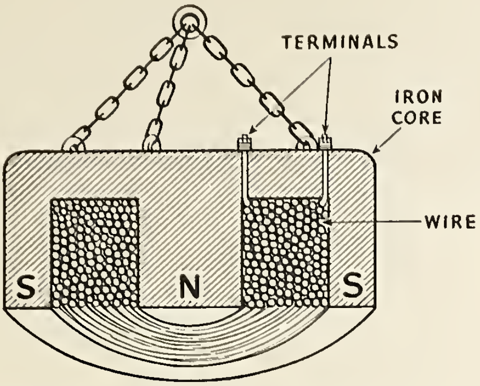
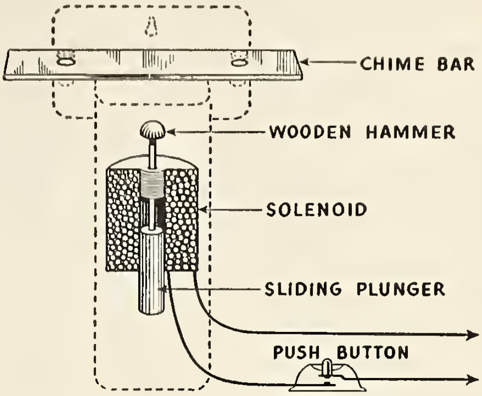


Figure 80. *The picture above shows a cross section of a lifting magnet, which is interesting because the winding is inside the "core." As long as current flows in the winding, iron and steel cling to the lower surface, because one pole of the electromagnet is in the center and the other pole is at the outer edge of this surface.*



The picture above shows a solenoid-plunger type of electromagnet used to operate an electric door chime. When the circuit is closed, current flowing through the coil causes the iron plunger to move upward and force the wooden hammer against the chime bar. When the circuit is opened, the sliding plunger drops back.

devices run by electric motors that must start with a heavy load. When the ON button is pressed, a switch is closed and current flows through the circuit. In part of the circuit there is an electromagnet placed so that it will open the switch when the electromagnet is sufficiently energized. Under ordinary conditions the amount of current flowing through the circuit will not energize the electromagnet enough to open the switch. But when the motor becomes overloaded, as it may if the washing machine becomes clogged so that its parts cannot move, there is a large increase in the current flowing through the circuit. This larger current strengthens the field of the electromagnet, which is then strong enough to open the switch and turn off the motor.

Lifting magnets. Another kind of electromagnet is the lifting magnet, shown in Figure 80. When current flows through the winding of a lifting magnet, the iron case becomes strongly magnetized. Since one pole of the electromagnet is at the center of the bottom surface and the other pole is around the edge, magnetic substances will cling to the bottom surface of a lifting magnet as long as current flows through the winding. When the current is shut off, the iron case quickly loses its magnetism, and the magnetic substances drop from the bottom surface. Huge derricks and hoists use large electromagnets of this kind to lift and move heavy loads of bridge girders, railroad rails, boiler plates, water pipes, and other objects made of iron and steel.

Solenoid-plunger magnets. Also shown in Figure 80 is an electric door chime, operated by a solenoid-plunger magnet. Pressure on the push button causes an electric current to flow through the winding of the solenoid, strongly magnetizing the iron plunger and causing it to be drawn upward into the hollow core of the solenoid. The movement of the sliding plunger forces the wooden hammer against the chime bar, and the sound is produced. When the push button is released, the plunger drops back. Electromagnets of the solenoid-plunger type are also used for throwing switches, opening valves, and releasing the latch on locked doors.

The uses of electromagnets we have discussed in this chapter all involve changing electrical energy into mechanical energy. In other words, the electromagnetic effect of an electric current is used to produce some kind of motion. In some of these devices the motion is used to produce sound waves, as in the electric bell, buzzer, telephone receiver, and telegraph sounder. In others, the motion is used to open or close a switch, as in a relay or circuit breaker. Of course in electric bells and buzzers the electromagnetic effect of the current is used to do both. Their armatures have contact points that open the circuit when attracted by the electromagnets. In Chapters 10 and 11 you will study motors and meters, which also change electrical energy into mechanical energy. To do this, all motors and most meters make use of the electromagnetic effect of an electric current.

CHECKING WHAT YOU LEARNED

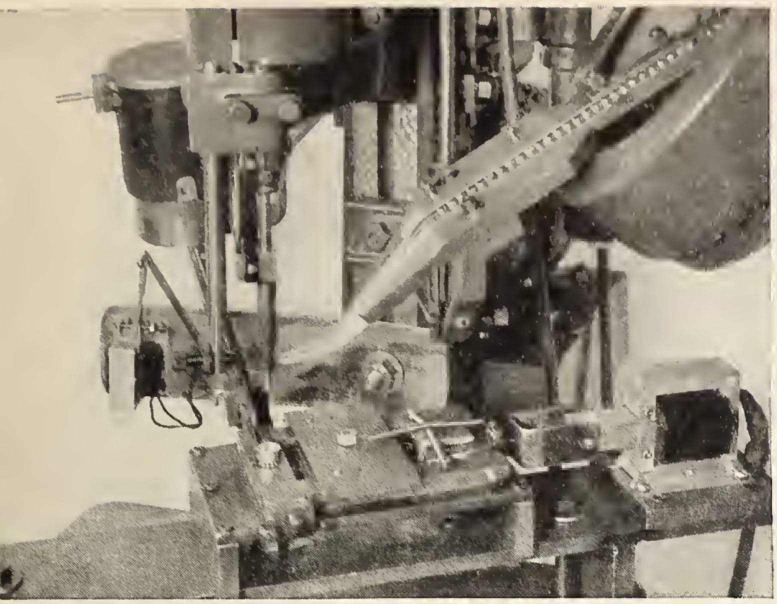
1. Tell what happens in an electric bell or buzzer when the circuit is closed by pressing the push button.
2. Are sound waves carried along the wires from a telephone transmitter to the receiver? Explain your answer.
3. What happens in a telegraph sounder when the telegraph key is pressed down and then released?
4. **a.** State the purpose of a telegraph relay. **b.** Why are separate sources of electrical energy used in the relay circuit and in the sounder circuit?
5. **a.** In what way are all relays alike? **b.** Give some uses of relays.
6. Tell how a magnetic circuit breaker is like a thermostatic circuit breaker and also how it is different.
7. **a.** How does a lifting magnet work? **b.** What makes the plunger of a solenoid move?

USING WHAT YOU LEARNED

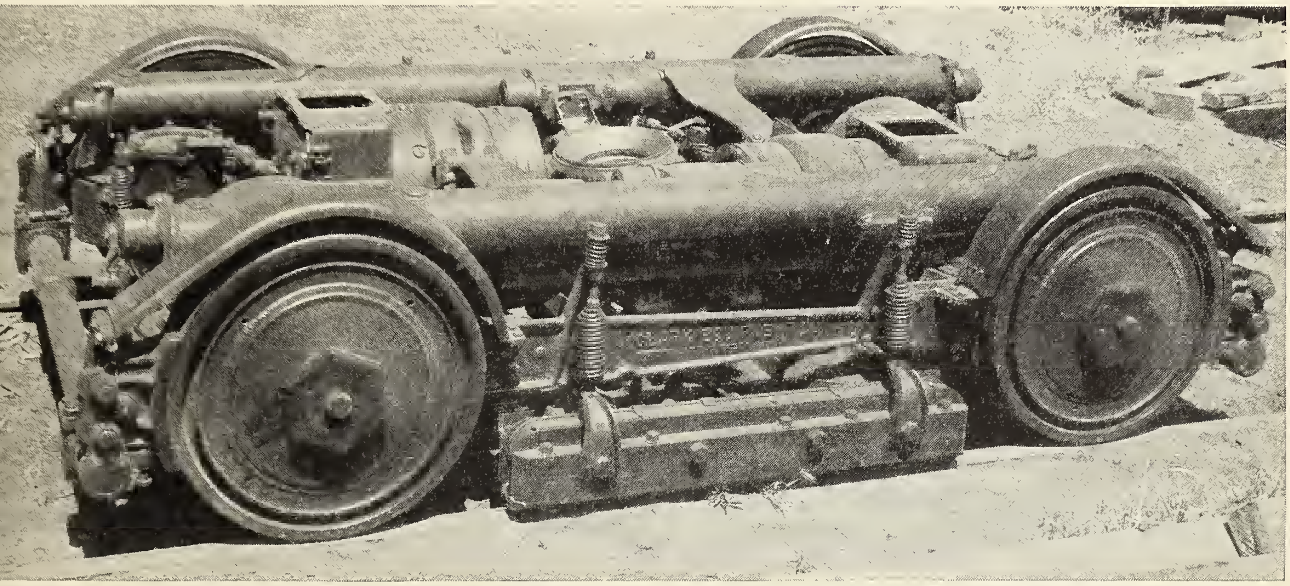
1. When a telegraph key is pressed down like the push button in a bell or buzzer circuit, the armature of the sounder does not vibrate like that of a bell or buzzer. Explain why this is so.
2. Why do you think the coils in the electromagnet of a telephone receiver contain many turns of fine wire?
3. A magnetic circuit breaker usually has a fairly small number of turns of rather large wire in its electromagnet. Why is it made in this way?
4. A common use of relays is in circuits that must be closed all or nearly all the time. What is one advantage of using relays in circuits of this kind?

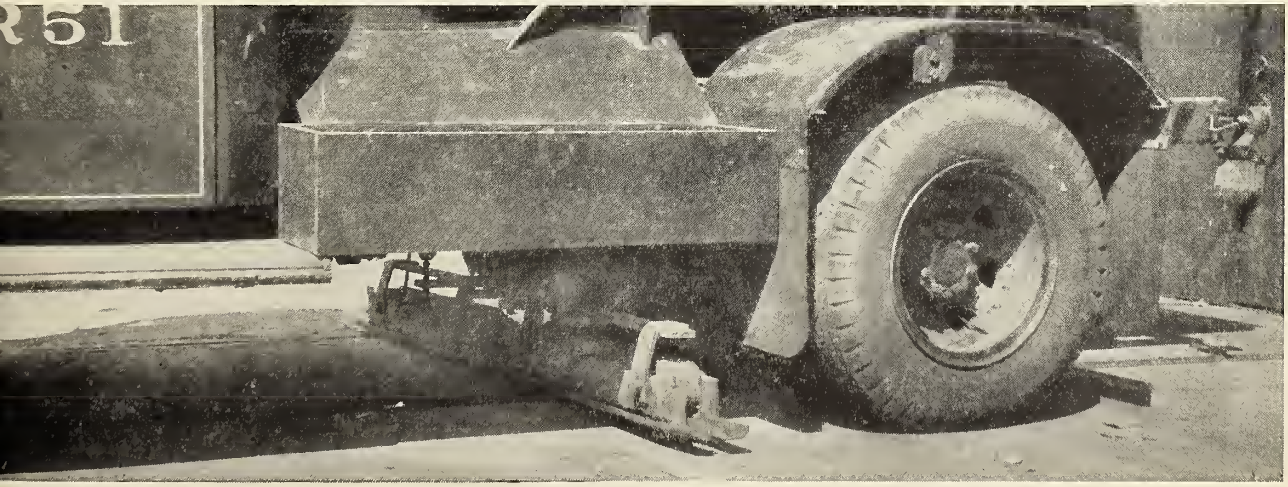
THINKING OVER WHAT YOU LEARNED

1. For each topic in this chapter state in complete sentences the important ideas you learned.
2. By using sentences or definitions show that you understand the following: **a.** relay, **b.** pulsating current, **c.** core, **d.** solenoid, **e.** armature, **f.** ampere-turn, **g.** magnetic circuit breaker, **h.** electromagnet, **i.** telegraph sounder, **j.** telephone receiver, **k.** magnetizing force, **l.** right-hand rule for a wire, **m.** lifting magnet.



Electromagnets find many uses in modern machinery like the power screwdriver at the left, which uses two solenoid-plunger electromagnets. In the middle picture is shown one of the trucks of a modern street car. Between the wheels is the magnetic brake used for stopping the car. When current is sent through the coil, the big electromagnet is attracted to the steel rail and drags on the track. At the bottom is a magnetic street sweeper, used to keep bus routes free of nails and tacks that might damage tires. Made from two magnetic street-car brakes, the electromagnet picks up about 7½ pounds of scrap metal per mile.





Experiment 29: **Magnetic Field and Polarity of a Coil**

THINGS NEEDED: Coil and dry cell from Experiment 25. Iron nail. String. Support. Bar magnet.

WHAT TO DO: **a.** (See Fig. 68.) Tie a string just under the head of an iron nail and fasten the string to a support so that the nail can swing freely. Before connecting the coil to the dry cell, bring each end close to the nail and notice what happens. Now connect the coil to the dry cell and bring one end near the nail. What happens this time? Try the other end of the coil and observe what happens. Now disconnect the coil from the cell and then bring it near the nail. What conclusion can you make about a coil carrying a current?

b. (See Fig. 69.) Tie a string around the middle of a bar magnet and fasten the string to a support so that the bar magnet can swing freely. When the magnet comes to rest, bring one end of the coil connected to the dry cell near the N pole of the magnet. What happens? Approach the S pole of the magnet with the same end of the coil and observe what happens. Repeat, using the other end of the coil. From what you have observed mark the N pole of the coil by tying a piece of string at that end. Now switch the connections on the dry cell and then repeat this part of the experiment. What effect on the polarity of the coil does reversing the current have?

Experiment 30: **Magnetic Field around a Wire**

THINGS NEEDED: Coil and dry cell from Experiment 25. Magnetic compass. Iron filings. Cardboard. Support for cardboard.

WHAT TO DO: **a.** (See Fig. 70.) Unwind a few turns from the coil. Place the magnetic compass on your desk or table and let the needle come to rest. Place a straight section of the wire over the compass needle and parallel with it. Now connect the ends of the wire to the dry cell and notice what happens. Disconnect one end of the wire from the cell and place the straight section of wire under the compass needle and parallel with it. Again connect the wire to the cell. What happens this time? Repeat this part of the experiment but reverse the connections so that the current goes through the wire in the opposite direction. What happens to the compass needle when the wire is placed over it? Under it? What conclusions can you make about a wire carrying a current?

b. (See Fig. 71.) Make a hole in a piece of cardboard and put a straight section of wire through the hole so that it is at right angles to the cardboard. Set the cardboard on a support so that its surface is horizontal. Sprinkle iron filings on the cardboard around the wire. What happens? Now connect the ends of the wire to the dry cell and gently tap the cardboard. What do you notice? Disconnect one wire from the cell and remove the filings from the cardboard. Set a small compass on the cardboard and connect the wire again. Notice what happens. Move the compass around the wire and observe the position of the needle. Now change the connections on the dry cell so that the current flows in the opposite direction. Notice the direction of the compass needle and move the compass around the wire as before. What effect does reversing the current have on the direction of the magnetic flux around a wire?

Experiment 31: **Air and Iron Cores in Electromagnets**

THINGS NEEDED: Coil and dry cell from Experiment 25. Large iron nail (or bolt). Box of iron tacks or small nails.

WHAT TO DO: (See Fig. 73.) Connect the wires from the coil to the dry cell. Lower the end of the coil onto a pile of iron tacks or small nails. How many tacks or nails does the coil pick up with only air for a core? To what part of the coil do the tacks or nails cling most firmly? Disconnect one wire from the dry cell and remove any tacks or nails from the coil. Now insert the large iron nail so that it becomes a core for the coil and connect the wire to the dry cell again. Lower the end of the coil onto the pile of tacks or small nails. How many tacks or nails does the electromagnet pick up? Where do they cling most firmly?

Experiment 32: **Strengthening an Electromagnet**

THINGS NEEDED: Large iron nail or bolt. No. 26 cotton-covered or enamel-coated copper wire. Box of iron tacks or small nails. Two dry cells.

WHAT TO DO: Dip the large iron nail into the box of tacks. Does it act like a magnet? Now wind about 50 turns of cotton-covered or enamel-coated wire around the nail and connect the ends of the wire to a dry cell. Dip the nail in the box of tacks and notice how many tacks are picked up. Disconnect one end of the wire from the dry cell and add another cell in series with the first. Now connect the wire again and notice how many tacks are picked up. Disconnect the ends of the wires and wind about 50 more turns of wire around the nail. Connect the ends to one dry cell as before. Notice how many tacks the electromagnet will now pick up. Try the electromagnet, using two cells in series as before. What conclusions can you make about the strength of an electromagnet?

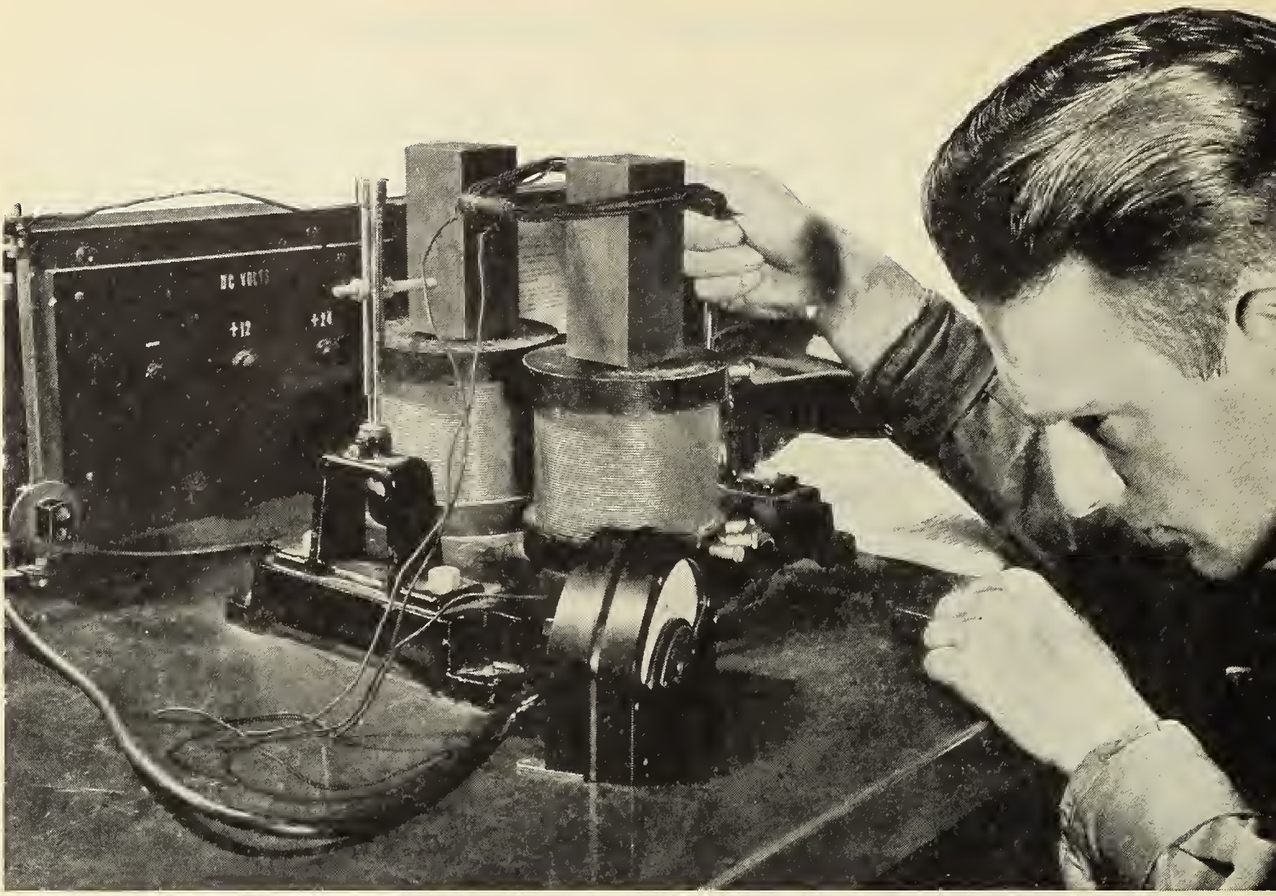
Experiment 33: **Electromagnets in Use**

THINGS NEEDED: Two dry cells. No. 18 insulated copper wire. Electric bell or buzzer. Push button. Telephone receiver and transmitter. Telegraph sounder and key.

WHAT TO DO: **a.** (See Fig. 75.) Remove the cover from an electric bell or buzzer and locate its parts. Move the armature back and forth with your finger and observe what happens to the contact spring. Now connect the bell or buzzer in series with one or two dry cells and a push button. Press the button and observe what happens.

b. (See Fig. 76.) Unscrew the cap from a telephone receiver and carefully remove the diaphragm. Notice how it is attracted by the permanent magnet. Locate the permanent magnet used as a core and also the coils of the electromagnet. Replace the diaphragm and screw cap. Attach two wires to the receiver and fasten one of them to a dry cell. Touch the other wire to the other terminal of the dry cell. What happens? If a transmitter is available, connect the receiver, transmitter, and two dry cells in series. Talk into the transmitter and have someone listen at the receiver.

c. (See Fig. 77.) Examine a telegraph sounder and locate its parts. Press the armature down and notice what happens. Now connect the sounder in series with a telegraph key and two dry cells. (Open the switch on the key before connecting it to the cell and sounder.) Now press the key down. What happens to the armature of the sounder? To the bar? Release the key and observe what happens. (If necessary, adjust the set screws.)



7. E.M.F. by Induction

FINDING OUT WHAT YOU KNOW

1. How can magnetism be used to produce electric current?

2. What is an induction coil?
   How does it work?
   Why is it used with a gasoline engine?

3. State three ways in which a small induced E.M.F. may be increased.

4. Explain why a coil resists any starting, stopping, or other change of the current flowing through it.

5. What is a transformer?
   How does it work?
   For what purposes are transformers used?

6. How does alternating current differ from direct current?

IN THE LAST CHAPTER you learned that there is a relation between electrical energy and the energy we call magnetism, for an electric current produces a magnetic field around a conductor. In this chapter you will learn how magnetism can be used to produce an E.M.F. and thus a current in a conductor. All generators and transformers operate on the principles that will be explained.

You know that an electric current induces magnetism in pieces of iron and steel, and you learned that when a current flows through a conductor, it produces a magnetic field around the conductor. Experiment 30 showed that the direction of the lines of force in the magnetic field around a wire depends on the direction of the current flowing through the wire. Now suppose we go a few steps further into this relation between electric current and magnetism, and see what happens when a conductor is moved through the lines of force in a magnetic field.

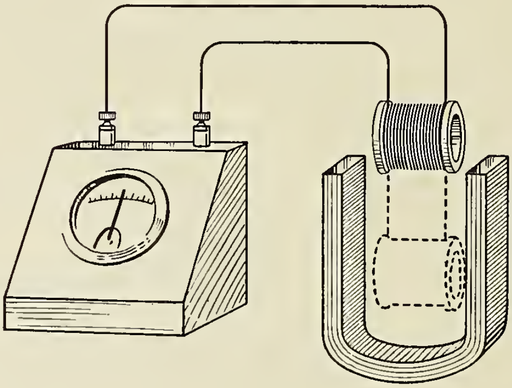
Inducing Current in a Conductor

As you know, you can make a magnet by sending a current through a coil around a piece of iron or steel. In other words, you can induce magnetism in the metal by placing it in the magnetic field around a coil of wire through which a current flows. Now suppose that we try moving a coil of wire through the lines of force in a magnetic field and see what happens. Experiment 34 (page 177) tells you how to do this. A coil of many turns of wire is connected to a galvanometer in a continuous path of wire through the coil,

Induced E.M.F.: An E.M.F. is produced in a conductor whenever there is a change in the magnetic field around the conductor. The strength of the E.M.F. depends on the number of lines of force cut in a certain time.

Induced current: An induced current flows through a conductor in a closed circuit whenever there is a change in the magnetic field around the conductor. The direction of the current depends on the direction in which the lines of force are cut. The size of the current depends on the strength of the induced E.M.F.

Figure 81 *shows how an E.M.F. can be induced in a coil of wire. Moving the coil, which consists of 300 to 400 turns of fine copper wire, to the position shown by the dotted line causes the needle of the galvanometer to swing to one side of the center zero mark. Moving the coil back causes the needle to swing to the other side of the zero mark. When coil and magnet are stationary, no lines of force are cut, and the needle of the meter remains at zero.*



connecting wires, and the galvanometer. However, no current flows in this path because there is no source of E.M.F. A permanent magnet (U-shaped) is set so that its poles point upward, as shown in Figure 81. If you move the coil edgewise down between the poles of the magnet, the galvanometer needle will swing to one side, indicating that a current is flowing. If the coil is moved up between the poles of the magnet, the needle will swing in the opposite direction, indicating that a current is now flowing in the opposite direction. When the coil is moved down or up and then stopped, the needle swings back to the zero position. No matter where the coil is stopped, the needle returns to zero, showing that no current is flowing.

When a coil is moved through a magnetic field, the wires in the coil cut the lines of force and an **induced current** flows in the coil. When the coil is moved back, the lines of force are cut in the opposite direction, and an induced current flows in the opposite direction. However, the galvanometer needle stands at zero while the coil is stationary because no current flows unless the coil is actually cutting lines of force in a magnetic field.

If you try the experiment again but this time move the coil more slowly, the galvanometer needle will not swing so far, indicating that there is less E.M.F. in the circuit. Moving the coil faster will make the needle swing farther, indicating that there is E.M.F. in the circuit. Thus the speed with which the lines of force are cut affects the pressure, that is, the **induced E.M.F.** causing the current, and thus changes the amount of current flowing; the greater the speed, the more lines of force that are cut in a certain time, and the larger the current.

Now if you repeat the experiment, using a coil of more turns or fewer turns, you will see that more turns increase the current while fewer turns decrease it. Moving these coils faster or slower produces the same results as before; the faster the motion, the greater is the current. Cutting more lines of force by using more turns or more speed increases the induced E.M.F., and thus a larger current flows in the coil.

Perhaps you are wondering what will happen if you move the magnet but keep the coil stationary or if you use a bar magnet instead of a U-shaped magnet. If you do all of Experiment 34,

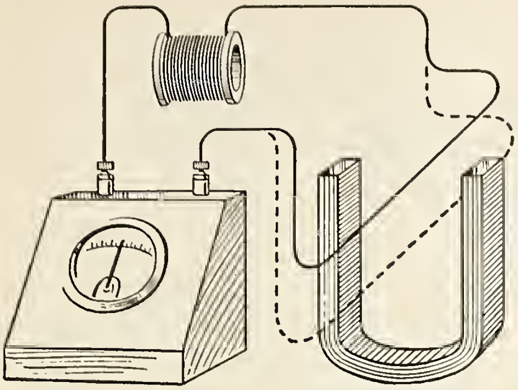


Figure 82. *If several turns are removed from the coil shown in Figure 81, the wire can be moved back and forth through the field of the magnet, cutting lines of force and causing the needle of the galvanometer to swing slightly from side to side of the center zero mark. This indicates that an E.M.F. is induced in the wire itself. The coil makes it possible for the same wire to cut many lines of force each time the coil or the magnetic field moves.*

you will see that the results are the same as before. As long as lines of force are cut by the coil, a current will flow in the coil. If you use stronger or weaker magnets, the results will be what you might expect. The stronger the magnet, the stronger is its magnetic field. In other words, a stronger magnet has a greater magnetic flux because it contains more lines of force. When a coil cuts the lines of force in a stronger magnetic field, more lines are cut in a certain time. As a result, a greater E.M.F. is induced in the coil and a larger current flows. An E.M.F. of 1 volt is induced in a conductor that cuts lines of force at the rate of 100,000,000 per second.

Now let us summarize what you have learned so far in this chapter.

1. An E.M.F. is induced in a coil when the coil cuts lines of force in a magnetic field. This causes a current in a closed circuit.
2. The direction of the induced current depends on the direction in which the lines of force are cut. If the direction of cutting is reversed, the direction of the current is also reversed.
3. The size of the induced current depends on the strength of the induced E.M.F. The greater the E.M.F., the larger is the current.
4. The strength of the induced E.M.F. depends on the number of lines of force cut in a certain time. The more lines of force cut, the greater is the E.M.F.
5. The number of lines of force cut in a certain time depends on the speed of cutting the lines, the number of turns in the coil, and the density of the magnetic flux. That is, more lines of force are cut in a certain time, **a** when the coil or magnetic field is moved faster, **b** when more turns of wire are used in the coil, or **c** when a stronger magnetic field with a greater magnetic flux (more lines of force) is used.

You remember that experiments in electromagnetism were performed first with a coil and then with a wire. The results were the same except that the magnetic field produced by the current in the wire was much weaker than that produced in the coil. The coil thus proved to be an effective way of concentrating the magnetic field made by a current flowing through a long wire. In the same way, the coil used in Experiment 34 may be partly unwound and the experiment repeated with a single wire as shown in Figure 82. If you have a galvanometer sensitive enough to indicate very weak currents, you will get the same results as you did with the coil. Again you will see that winding a wire into a coil is simply a convenient way to concentrate the effect that a single wire will produce.

Although you may not be able to do all parts of Experiment 34, you should study carefully Figure 83, on the next page. It makes clear an important point—the direction of the induced current in the wire. The picture shows the exact relation between the direction of magnetic flux, the direction of movement of the wire, and the direction of the induced current. The induced E.M.F. will of course act in the same direction as that in which the induced current flows; otherwise the

Right-hand rule for induced current: Extend the thumb, forefinger, and middle finger of the right hand so that they are at right angles to one another, as shown in Figure 83. Point the thumb in the direction in which the wire moves and the forefinger in the direction of the magnetic flux. The middle finger will then point in the direction in which the induced current flows, that is, toward the negative end of the wire. Also called **Fleming's rule** or **right-hand rule for generator.**

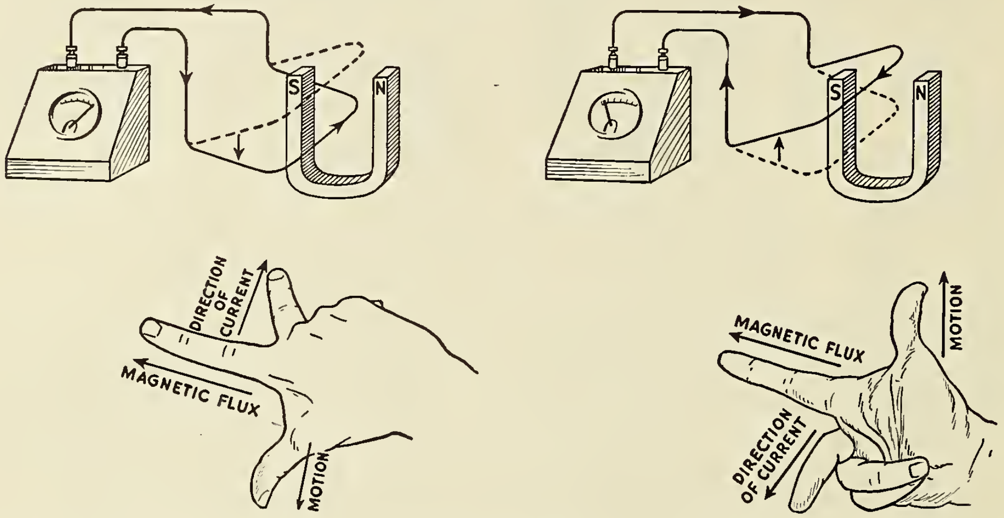


Figure 83 *is intended to help you remember the right-hand rule for induced current. In both drawings the forefinger points in the direction of the magnetic flux, from N to S. At the left the wire has moved downward; and when the hand is turned so that the thumb points downward, the middle finger points in the direction of the induced current, as shown by the arrows. At the right the wire has moved upward; when the thumb points upward, the middle finger shows that the induced current is reversed.*

current would not flow in that direction. By using the **right-hand rule for induced current,** you can determine the direction of an induced current. (The rule assumes that current flows from positive to negative. Actually, the electrons move in the opposite direction.)

In applying the right-hand rule for induced current, you will meet with situations in which the magnetic field moves instead of the wire. Then you must consider the relative motion of the wire. If the magnetic field moves in one direction across the wire, the induced current will flow in the same direction as when the wire moves across the magnetic field in the opposite direction. In Experiment 34 this fact was demonstrated by moving first the magnet and then the coil or wire.

Perhaps you are wondering what will happen if an electromagnet instead of a permanent magnet is used to induce an E.M.F. and thus a current in a conductor. You know that electromagnets can be made much stronger than permanent magnets and also that their magnetism can be easily controlled. Increasing the magnetic flux by adding more turns to the coil, by sending more current through each turn, or by rapidly turning the current on and off should increase the number of lines of force cut in a certain time. As a result, the induced E.M.F. and thus the current should be greater. Experiment 35 shows that this is true.

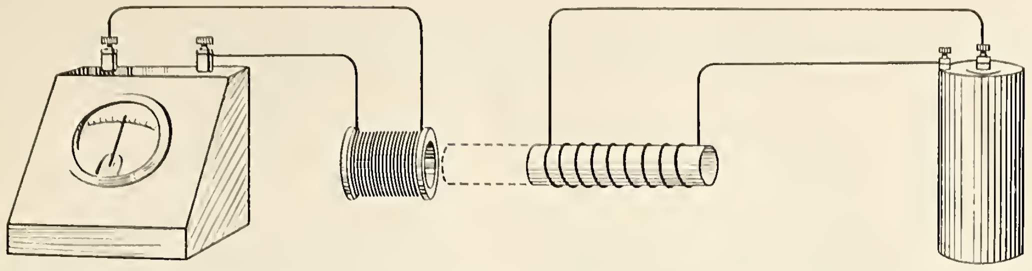


Figure 84. *In the upper picture, E.M.F. is induced in the large coil when the electromagnet is moved to the position indicated by the dotted line. In the lower picture the coils remain stationary while the magnetic field is moved. Pressing the push button causes lines of force to spring out from the electromagnet and induce E.M.F. in the large coil. When the button is released, the magnetic field collapses, and the lines of force are again cut by the large coil, but in the opposite direction.*

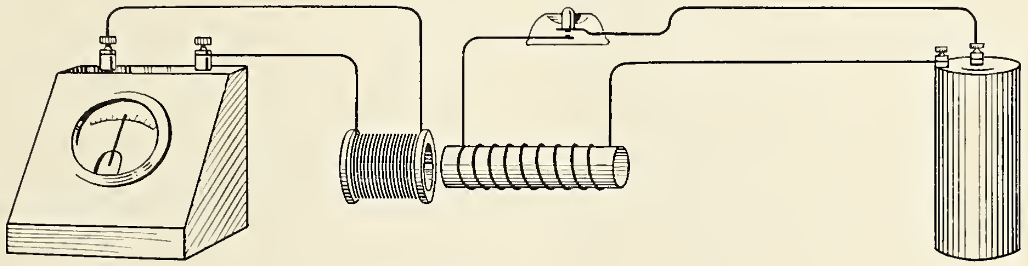


Figure 84 shows two coils placed end to end. One coil is connected to a galvanometer as in Experiment 34. The other coil is connected to a dry cell as in Experiment 25. This coil is thus a solenoid, or an electromagnet with an air core. The circuit through the solenoid is closed, and the coil is energized. If you move either coil toward the other, the galvanometer needle will swing to one side, indicating that a current has been induced. When the coil is moved back, the needle swings to the other side, indicating that the induced current flows in the opposite direction. Just as in the preceding experiment, no current flows through the coil connected to the galvanometer when both coils are stationary, because no lines of force are cut.

Moving either coil faster or slower will cause an increase or decrease in the current induced. Using more or fewer turns on the coil connected to the galvanometer will have the same effects. If you strengthen the electromagnet by using an iron core, by increasing the current through it, or by adding more turns, the induced E.M.F. and thus the current will be increased. In every way, the results are the same as those with a permanent magnet—except that they are much greater.

Mutual induction. Now using the push button (or knife switch) connected in series with the electromagnet and the dry cell, you can see what happens when the current is turned on and off without moving either coil. When the circuit through the electromagnet coil is closed, the electromagnet is energized. The galvanometer needle swings to one side, indicating that an E.M.F. has been induced in the coil connected to it. The current flowing through the coil of the electromagnet built up a magnetic field. Scientists visualize the lines of force of this field as springing outward from the coil of the electromagnet. As they spring outward to form the magnetic field,

Mutual induction: The production of an induced E.M.F. and thus a current in one circuit as a result of changes in the magnetic field of another circuit.

they are cut by the coil connected to the galvanometer. Thus a current is induced in that coil.

If the circuit through the electromagnet coil is left closed, the induced current in the other coil flows for only an instant. The needle swings to one side and then back to zero. Although the electromagnet is still energized, no more current is induced in the coil. Once the magnetic field is built up, no more lines of force are cut by the coil. Since neither coil is moved, the induced current stops flowing. But if the circuit through the electromagnet coil is opened, the galvanometer needle moves again. It will swing in the opposite direction for an instant and then back to zero.

What has happened? Opening the circuit in which the coil of the electromagnet is connected stopped the flow of current through the coil. The magnetic field around the electromagnet faded away, or *collapsed*, as scientists say. As its lines of force fell back into the electromagnet coil, they were cut by the coil connected to the galvanometer. A current was thus induced in the coil, and it flowed in the opposite direction from that of the current first induced. When the magnetic field is built up, a current flows in one direction as lines of force are cut by the coil. When the magnetic field collapses, lines of force are cut in the opposite direction by the coil and the induced current flows in the opposite direction.

As before, the induced E.M.F. and thus the current can be increased by cutting more lines of force in a certain time. Using a larger coil connected to the galvanometer is one way to get a larger induced E.M.F. Another way is to strengthen the electromagnet by using an iron core, by adding more turns, or by increasing the current through the coil. A third way to increase the induced E.M.F. and current is to close and open the electromagnet circuit more rapidly, thus cutting lines of force faster. All of these ways are used, as you will see later on in this chapter and in other chapters of this book.

When changes in the magnetic field of one circuit induce an E.M.F. and thus a current in another circuit, the induced E.M.F. and current are said to be caused by **mutual induction.** In Experiment 35 the current induced in the coil connected to the galvanometer was a result of mutual induction with the coil of the electromagnet. Mutual induction also occurs in the induction coil and transformer, which you will study later in this chapter. However, the results of mutual induction may be troublesome as well as useful. Have you ever heard "cross talk" (another conversation) or noises when you used a telephone? Both are results of mutual induction. Cross talk is caused by induction between telephone circuits, while the noises may be produced by currents in electric-wiring circuits, power lines, and trolley wires near the telephone wires.

Here is a good place to get firmly in your mind a very important fact: There is an E.M.F. in an open circuit; but no current flows until the circuit is closed, that is, until there is a complete path from the source of E.M.F. and back again. An E.M.F. is induced in any wire that cuts magnetic lines of force. One end of the wire is negative and the other is positive. However, no induced current flows through the wire until its ends are connected to form a closed circuit. This situation is similar to the water pipes in your home. Even when the faucets are closed and no water flows, there is pressure in the pipes. This pressure makes a flow of water available as soon as you turn on a faucet and make a path. In much the same way, an induced E.M.F. is present whenever lines of force are cut even though the circuit is open and no current can flow. This E.M.F. will make a current available as soon as the circuit is closed.

Faraday's discovery. The British scientist, Michael Faraday, was the first to discover that an E.M.F. is induced in a wire when it cuts lines of force in a magnetic field. His experiments led to the discovery of many important facts about the re-

Faraday's discovery: Whenever a conductor cuts across magnetic lines of force, an electromotive force is induced in the conductor. If the conductor is part of a closed circuit, the electromotive force will cause a current to flow.

lation between magnetism and electric current. One fact can be stated as follows: *Whenever a conductor cuts across magnetic lines of force, an E.M.F. is induced in the conductor. If the conductor is part of a closed circuit, the E.M.F. will cause a current to flow.* These statements tell what happened in Experiments 34 and 35. When a coil is placed in a magnetic field and neither of them moves, or the strength of the field is not changed, no E.M.F. and thus no current are induced because no lines of force are cut. However, if either the coil or magnetic field is moved, lines of force are cut. As a result, an E.M.F. is induced and a current flows. Making (or closing) the circuit of an electromagnet builds up a magnetic field, which then collapses when you break (or open) the circuit. The coil cuts lines of force which move in one direction while the magnetic field is being built up and in the opposite direction when the magnetic field collapses. Later in this chapter you will learn how a varying current in an electromagnet also produces a magnetic field that gets stronger and weaker so that its changing lines of force may be cut by a coil.

CHECKING WHAT YOU LEARNED

1. Tell how a permanent magnet can be used to produce a current in a coil.
2. **a.** What is meant by an induced current? An induced E.M.F.? **b.** On what does each depend?
3. **a.** How is the right-hand rule used to find the direction of an induced current? **b.** In using the rule, what must you remember about the current?
4. Is it possible to induce a current without inducing an E.M.F.? To induce an E.M.F. without inducing a current? Explain your answers.
5. How can a current be induced in a coil by using an electromagnet? Give at least two different ways.
6. Give three ways of increasing the induced E.M.F. and current in a conductor and tell how each one causes an increase.

USING WHAT YOU LEARNED

1. Can a wire be moved through a magnetic field in such a way that no E.M.F. will be induced in it? Give reasons for your answer.
2. How can you use the right-hand rule for induced current to find the direction of an induced E.M.F.?
3. What advantages are there in using an electromagnet instead of a permanent magnet to induce a current? What disadvantages?
4. Is an induced current produced by moving an electromagnet a result of mutual induction? Give your reasons.
5. **a.** What energy change takes place when a permanent magnet is used to induce an E.M.F. in a conductor? **b.** Name the energy changes that take place when a stationary electromagnet connected to a dry cell is used instead of a permanent magnet.
6. If an induced current flows through a wire or coil, does the current set up a magnetic field around the wire or coil? How do you know?

Lenz's Law

From your study of electromagnetism in the last chapter you know that a magnetic field is set up around a conductor carrying a current. A conductor carrying an induced current is no exception. Whenever a current has been induced in a conductor by cutting lines of force in a magnetic field, the induced current sets up its own magnetic field around the conductor. The magnetic field set up by the induced current might do either of two things: (1) reinforce and strengthen the field that induced the current or (2) oppose and weaken the field that induced the current. Care-

Lenz's Law: An induced current sets up around a conductor a magnetic field that opposes the magnetic field which induced the current. **Or:** An induced current has such a direction that its magnetic field opposes the motion or change which induced the current.

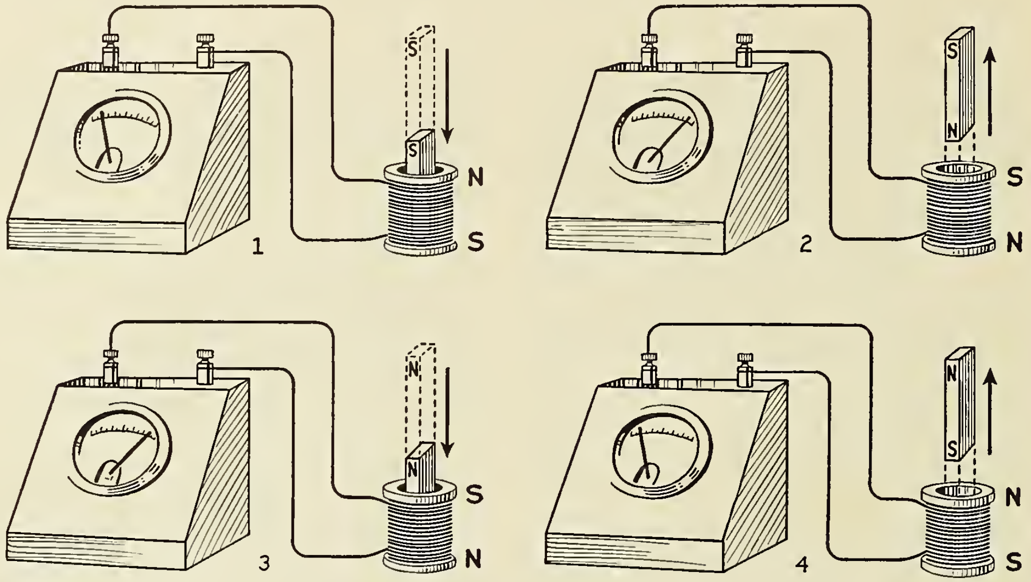


Figure 85. *Picture 1 shows what happens when the N pole of a bar magnet is pushed into the center of the coil. The direction of the induced current is such as to set up a magnetic field opposing the motion of the bar magnet. Picture 2 shows that, when the magnet is withdrawn, the direction of the induced current changes so that the magnetic field of the coil again opposes the motion of the magnet. Pictures 3 and 4 show a similar reversal of induced current when the S pole of the magnet is used.*

ful experiments by a Russian scientist named Lenz showed that the second thing happens: *The magnetic field set up around a conductor by an induced current opposes the magnetic field that induced the current.* This fact is stated as **Lenz's Law**, which expresses one of the most important principles in the study of electricity. Lenz's Law explains certain facts about every electrical device whose operation depends on induced currents. In this chapter you will study two of these devices, the induction coil and the transformer. In other chapters you will meet with several more, such as the generator, motor, and choke coil.

Do not be surprised when you see Lenz's Law stated in different ways. The way in which the law is stated depends on what we want to know in a particular situation. A statement of the law may emphasize the direction of the magnetic flux, the direction of the induced current (or E.M.F.), or the direction of movement of the conductor. Usually two of these ideas are combined into one statement. In any case, the basic idea of Lenz's Law remains the same. The right-hand rule for induced current, which you have already learned, and a similar left-hand rule for motors, which you will learn in Chapter 10, are merely practical applications of Lenz's Law.

If you do Experiment 36, you will understand Lenz's Law more clearly. Figure 85 shows a coil connected to a galvanometer. Unless lines of force

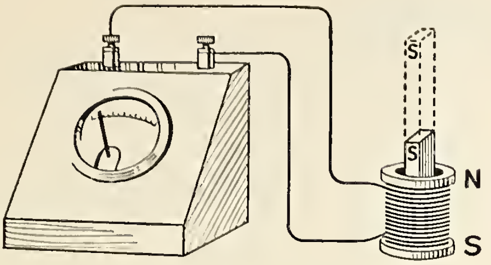
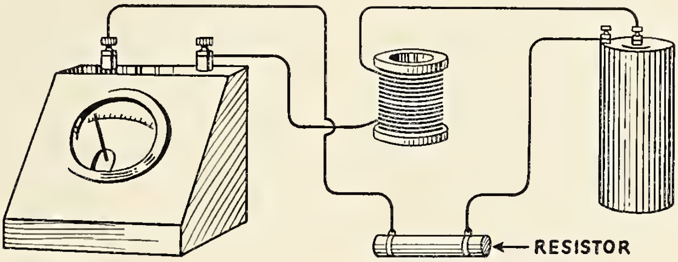
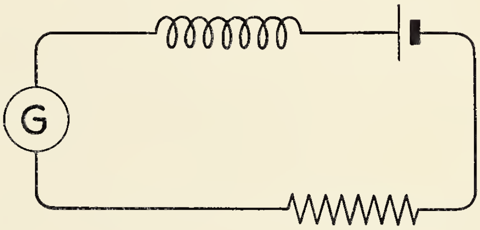


Figure 86 *shows one way of testing the polarity of the magnetic field set up by an induced current. Notice which way the needle of the galvanometer moves when the N pole of the bar magnet is pushed into the coil. Then connect a dry cell to the coil so that the needle moves in the same direction.*



The picture above shows how to connect the cell to the coil. The resistor limits the current flowing through the coil and protects the meter. Change wires at the posts of the cell if the needle moves the wrong way. The diagram of this circuit shows that the cell is in series with the coil and meter.



are cut, the coil has neither N pole nor S pole, because no current flows through it; therefore, there is no magnetic field around the coil. The first picture shows what happens when the N pole of a bar magnet is pushed into the center of the coil. A current is induced in the coil and the galvanometer needle swings to one side. Some force is needed to push the bar magnet inside the coil. Evidently, the N pole of the bar magnet is opposed by the upper end of the coil; the upper end of the coil must therefore be a N pole, since like poles repel each other. The second picture shows what happens when the N pole of the bar magnet is withdrawn from the coil. The galvanometer needle swings in the opposite direction, indicating that the induced current now flows in the opposite direction. Some force is needed to pull the bar magnet out of the coil. Evidently, the N pole of the bar magnet is now attracted by the upper end of the coil; since unlike poles attract each other, the upper end of the coil must be a S pole. The third picture shows what happens when the S pole of the bar magnet is pushed into the coil. The upper end of the coil becomes a S pole, and some force is required to push the magnet into the coil. The fourth picture shows that when the magnet is withdrawn, the upper end of the coil becomes a N pole. Thus a current is induced in the coil whenever lines of force are cut. The induced current has such a direction that the magnetic field around the coil opposes the motion which induced the current.

If you do all of Experiment 36, you can prove that the magnetic field set up by the induced current opposes the magnetic field that induced the current. The first picture of Figure 86 shows a

Self-induction: The production of an induced E.M.F. and sometimes a current in a circuit as a result of changes in the magnetic field of the same circuit.
Inductance: The ability of a circuit or conductor to induce an E.M.F. when the current in the circuit changes.

coil connected to a galvanometer. The needle swings to one side as the N pole of a bar magnet is brought near one end of the coil. The second picture shows a dry cell connected in series with the coil and galvanometer so that the current makes the needle swing to the same side. Applying the right-hand rule for a coil or using a magnetic compass, you can prove that the end of the coil near the N pole of the approaching magnet must have been a N pole, too. If you carry the experiment further, you can prove that the end of the coil near the N pole of the bar magnet becomes a S pole when the bar magnet is withdrawn from the coil. Thus an induced current always sets up a magnetic field that opposes the magnetic field which induced the current.

Self-induction. Lenz's Law explains the direction of an induced current resulting from mutual induction between two circuits; it also explains a curious form of induction that takes place in a single circuit. When changes in the magnetic field of a circuit induce an E.M.F. and sometimes a current in the same circuit, the induced E.M.F. or current is said to be caused by **self-induction.** Any change in the current flowing through the circuit is opposed by self-induction. It opposes starting or stopping a current in a circuit and also opposes any change in the amount of current.

As you might expect, self-induction is more noticeable in a coil than in a wire. An experiment performed by scientists clearly demonstrates this fact. A huge loop was made of 500 feet of No. 18 copper wire, whose resistance was about 3 ohms. The loop was connected to a 110-volt source of direct current. A current began to flow through the loop at once. In .01 second the current reached its full amount of 36.7 amperes (according to Ohm's Law, $I = \frac{E}{R} = \frac{110}{3}$). From then on a steady current of this amount continued to flow through the circuit. The same 500 feet of wire were then wound into a coil and connected to the same source of electrical energy. At the end of .01 second only 18 amperes of current flowed through the circuit. In .02 second the current increased to 28 amperes, and in .03 second it became 35 amperes. The full amount of 36.7 amperes, as determined by Ohm's Law, was not reached until .07 second had passed. Thus it took *seven* times as long for the current to reach its full amount when the wire was wound into a coil as it did when the single loop was used. The delay was caused by greater self-induction of the coil. Thus we say that the coil has a greater **inductance** than the same length of wire not wound in a coil. By inductance is meant the ability of a circuit or conductor to induce an E.M.F. when the current in the circuit changes.

If you do Experiment 37, you can observe the effects of self-induction in a circuit. Figure 87 shows a coil with an iron core connected in series with three dry cells and a push button (or knife switch). Across the coil a 6-volt bulb and its socket are connected. When the circuit is closed,

Inductance of a coil, wire, or circuit is measured in a unit called the **henry.** Since this is a rather large unit, the **millihenry** (1/1000 of a henry) is more commonly used. Inductance will be discussed again in Chapters 11 and 12.
Self-induced E.M.F.: The E.M.F. resulting from self-induction is also called **back E.M.F.** or **counter E.M.F.** when it opposes the E.M.F. of the circuit. Back E.M.F. or counter E.M.F. will be discussed again in connection with motors in Chapter 10.

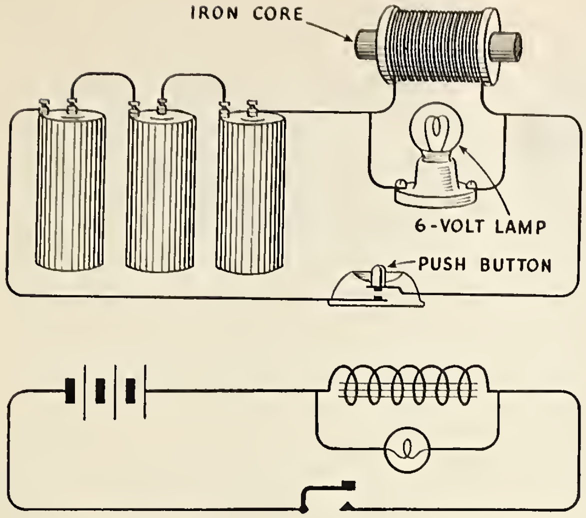


Figure 87 *illustrates a circuit for showing the effects of self-induction. The 6-volt lamp is connected in parallel with a coil having many turns of wire and an iron core. When the circuit is closed, current flows through the coil and the bulb, which lights up brightly and then becomes dim. When the circuit is opened, the bulb lights up brightly for a brief instant. This indicates that the E.M.F. induced in the coil by the sudden collapse of its own magnetic field causes a current to flow through the bulb for an instant after the circuit is opened.*

the bulb lights up brightly at first and then quickly becomes dim. When the circuit is opened, the battery of cells no longer furnishes current to the circuit. However, the bulb lights up for an instant after the circuit is opened. A current induced in the coil flows through the bulb.

By using Lenz's Law, we can explain what happens in the experiment. When the circuit is closed, a current flows through the circuit including the coil and the bulb. Since the coil and bulb are connected in parallel, part of the current flows through each of them. The part flowing through the coil builds up a magnetic field. As the field is built up, the turns of the coil cut the lines of force. Cutting lines of force induces an E.M.F. in the coil. Since the coil is part of a closed circuit, this E.M.F. tries to make a current flow in the circuit. From Lenz's Law, we know that the direction of the induced current would be opposite to that of the current supplied by the battery. Thus the induced E.M.F. must oppose the E.M.F. of the battery. This *self-induced E.M.F.*, as it is called, acts against the E.M.F. of the battery as the magnetic field is built up and thus reduces the current flowing through the coil. For this reason, it is also called *back E.M.F.* or *counter E.M.F.* when it opposes the E.M.F. of the circuit. Because the back E.M.F. at first prevents much current from flowing through the coil, more of the current is sent through the bulb, and it lights up brightly.

When the magnetic field has been slowly built up to its full strength, no more lines of force are cut by the coil and no more back E.M.F. is induced. The current supplied to the coil by the battery then reaches its greatest amount, as determined by Ohm's Law. The E.M.F. of the battery is no longer opposed by the self-induced E.M.F. As the part of the current that flows through the coil increases, the part flowing through the bulb decreases. The bulb then becomes dim. Now if the circuit is opened, the current in the battery circuit stops flowing. As a result, the magnetic field of the coil collapses. As the turns of the coil cut the lines of force of the collapsing field, an E.M.F. is again induced in the coil. This time, however, it acts in the opposite direction because the lines of force are cut in the opposite direction. The induced E.M.F. now acts in the same direction as the E.M.F. of the battery does. For a brief instant the self-induced E.M.F. is equal to or more than the E.M.F. of the battery. Since the bulb and coil form a closed path, the self-induced E.M.F. forces a current through the bulb. As a result, the bulb lights up once more. The self-induced E.M.F. thus opposes stopping as well as starting the current.

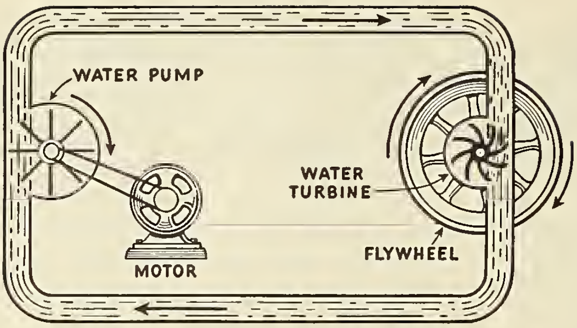


Figure 88. *When the pump begins to turn, the inertia of the heavy flywheel causes the turbine blades to resist the flow of water. However, once the flywheel is turning, its inertia causes the turbine blades to keep moving after the pump stops. This tendency of the flywheel to resist change is like self-induction in a coil of wire.*

You can understand self-induction better if you examine Figure 88. The picture shows a pump (operated by an electric motor) connected by a circuit of piping to a water turbine that has a flywheel. When the pump is started, water is sent through the piping, and the turbine begins to revolve. Before the water can reach the greatest speed that the pump can produce, it must first overcome the *inertia* of the flywheel on the turbine. Inertia, as you probably know, is the tendency of matter to resist change. When the inertia of the flywheel has been overcome, the water reaches the greatest speed that the pump will produce, and a steady flow of water through the piping is maintained. Now if the pump is turned off, the inertia of the flywheel keeps the turbine revolving for some time. The turbine acts as a pump and keeps the water moving until friction finally stops it. Self-induction in a circuit acts much like the inertia of the flywheel. It resists any attempt to start, stop, or change the current in a circuit. For this reason, self-induction is sometimes called *electromagnetic inertia.*

CHECKING WHAT YOU LEARNED

1. Is the magnetic field set up around a conductor carrying an induced current the same as the field that induced the current? Explain.
2. What is meant by self-induction? Inductance?
3. **a.** State Lenz's Law in two ways. **b.** Tell why Lenz's Law is stated in different ways.
4. **a.** What is the polarity of a coil when the N pole of a bar magnet is inserted in the upper end? When this pole is withdrawn? **b.** What is its polarity when the S pole is inserted at the same end? When this pole is withdrawn? **c.** Explain your answers, using Lenz's Law.
5. Why is self-induction sometimes called electromagnetic inertia?
6. Is a self-induced E.M.F. always the same as a back E.M.F.? Explain.

USING WHAT YOU LEARNED

1. Does an induced E.M.F. set up a magnetic field? Give reasons for your answer.
2. What kind of pole is one end of a coil when an S pole is brought near the other end? When the S pole is withdrawn? Explain.
3. How are self-induction and mutual induction alike? How are they different?
4. Explain why there is more self-induction when a coiled wire is connected in a circuit than when the same length of uncoiled wire is used.
5. Using Lenz's Law, tell why closing and opening the electromagnet circuit causes a reversal of current resulting from mutual induction.
6. Refer to Figure 87. **a.** When the circuit is closed, why does the back E.M.F. reduce the current through the coil but increase the current through the bulb? **b.** When the circuit is then opened, current continues to flow in the same direction through the coil but in the opposite direction through the bulb. Explain.

The Induction Coil

You know that an E.M.F. is induced in a coil whenever the turns cut lines of force in a magnetic

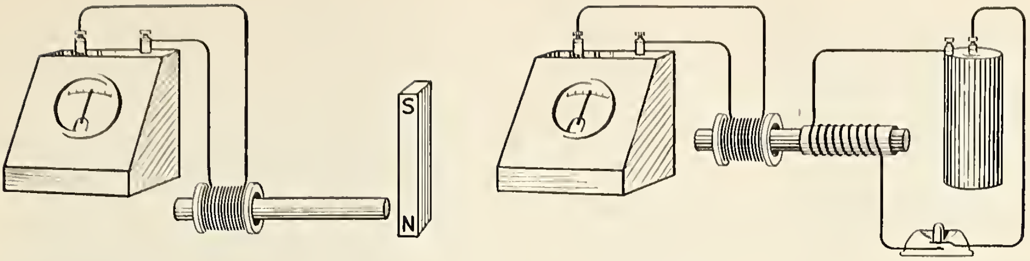


Figure 89 *shows two ways in which E.M.F. can be induced in a coil having an iron core. At the left a bar magnet is used to induce magnetism in the iron core. At the right an electromagnet is used to magnetize the core. Pressing and releasing the push button have about the same effect on the galvanometer needle as moving the magnet toward and away from the iron core. Each change in the magnetic field induces E.M.F. in the coil.*

field. If the coil is part of a closed circuit, an induced current will flow. Lines of force may be cut by moving the magnetic field, by moving the coil, or, in the case of an electromagnet, by closing and opening the circuit through its coil. Another way to cut lines of force with a coil is to vary the magnetic flux of the core in a coil. Experiment 38 shows how this may be done.

The picture at the left in Figure 89 shows a coil connected to a galvanometer, as in other experiments of this chapter. However, the coil has an iron rod for a core, and the ends of the rod project beyond the turns of the coil. If the N pole of a bar magnet is brought near or against one end of the rod, the galvanometer needle will indicate that a current is flowing through the coil. If the pole of the magnet is held steady, the needle will swing back to zero. However, when the bar magnet is removed, the needle will swing to the other side, indicating that a current now flows through the coil in the opposite direction. After an instant the needle swings back to zero, as before. If this part of the experiment is repeated with the S pole of the bar magnet or with the other end of the rod, you will find that a current is induced when the magnet is brought near or against the rod and again when it is removed.

From the chapter on magnetism you recall that a magnet can be used to magnetize a magnetic substance. If the substance has a low reluctance and a low retentivity, such as iron has, it is easily magnetized but loses its magnetism soon after the magnet is removed. In other words, the magnetic substance forms only a temporary magnet. Bringing the bar magnet near the iron rod magnetized the rod. The magnetic flux of the magnetized rod was cut by the turns of the coil. Thus an E.M.F. and current were induced in the coil connected to the galvanometer. When the bar magnet was removed, the iron rod lost its magnetism almost at once. Its magnetic flux disappeared, and the turns of the coil cut lines of force in the opposite direction. As a result, a current then flowed in the opposite direction through the coil. All this, of course, took place in accordance with Lenz's Law. When the rod was magnetized, the induced current had such a direction that its magnetic field opposed the magnetic field of the rod. As the rod lost its magnetism, the induced current had such a direction that its magnetic field opposed the loss of magnetism.

Now let us see what happens when an electromagnet is used in place of the bar magnet. The picture at the right in Figure 89 shows the coil of an electromagnet around the same iron rod used as a core for the coil connected to the galvanometer. Just as in the second part of Experiment 35, the electromagnet coil is in series with a push button. When the push button is pressed, the circuit through the electromagnet coil is closed. The electromagnet is energized, and the iron rod is magnetized. As before, the galvanometer needle

Induction coil: A device used to produce a high voltage by mutual induction. It consists of two coils wound around a core, usually of iron wires. One coil (the primary) has relatively few turns, while the other (the secondary) has many more turns. A pulsating direct current of low voltage in the primary produces a magnetic field whose lines of force are cut by the secondary, thus inducing a current of high voltage in the secondary.

Primary: The coil of an induction coil or transformer through which flows the current producing the variable magnetic field.

Secondary: The coil of an induction coil or transformer in which the E.M.F. and current are induced by cutting lines of force in the magnetic field set up by the current in the primary.

swings to one side, indicating that a current has been induced in the coil connected to it. The needle swings much farther than it did when a bar magnet was used, showing that a greater E.M.F. has been induced. After an instant the needle swings back to zero. If the push button is released, the circuit through the electromagnet is opened, and the iron rod quickly loses its magnetism. A current in the opposite direction is induced in the coil connected to the galvanometer. The needle will swing much farther than it did when the electromagnet circuit was closed, because the magnetic field around the iron collapses more rapidly than it was built up. More lines of force are thus cut in a certain time, and a greater E.M.F. results.

The two coils around the iron core, as shown in the picture at the right in Figure 89, really form a simple **induction coil.** The coil connected in series with the dry cell and push button is called the **primary,** while the coil connected to the galvanometer is called the **secondary.** A current in the primary produces a magnetic field whose lines of force are cut by the turns of the secondary, thus inducing an E.M.F. in the secondary. As a result of mutual induction, changes in the magnetic field of the primary circuit induce an E.M.F. in the secondary circuit. The changes in the magnetic field may be produced by closing (making) or opening (breaking) the primary circuit, or by varying the current through the primary.

Of course commercial induction coils are not so crude as the one made in Experiment 38. One type of induction coil is shown in Figure 90. It has a core made of a bundle of iron wires. The core is covered with a layer of insulation. Over this are wound several hundred turns of heavy wire for the primary. Over the primary coil there is another layer of insulation. Then the secondary consisting of several thousand turns of fine wire is wound over this. Winding the secondary over the primary and core in this way greatly increases the induced E.M.F., because practically every line of force in the magnetic field produced by the current in the primary is cut by the turns of the secondary.

The primary of an induction coil is connected to a source of direct current, such as a cell, battery, or direct-current generator. Connected in series with the primary and its source of electrical energy is a magnetic circuit breaker, called an *interrupter,* or *vibrator,* which takes the place of the push button used in Experiment 38. The interrupter works in the same way as the circuit breaker of an electric bell or buzzer. The iron core and primary coil of the induction coil form an electromagnet that attracts the iron armature of the interrupter. The condenser connected across the contacts of the interrupter is not essential; but it improves the operation of the induction coil, as you will see.

When the switch in the primary circuit is closed, current flows through the primary coil. The iron core and the coil form an electromagnet whose magnetic field is cut by the turns of the secondary coil. As a result, an E.M.F. is induced in the secondary; but no induced current flows because the secondary does not form a complete circuit. At the same time the electromagnet at-

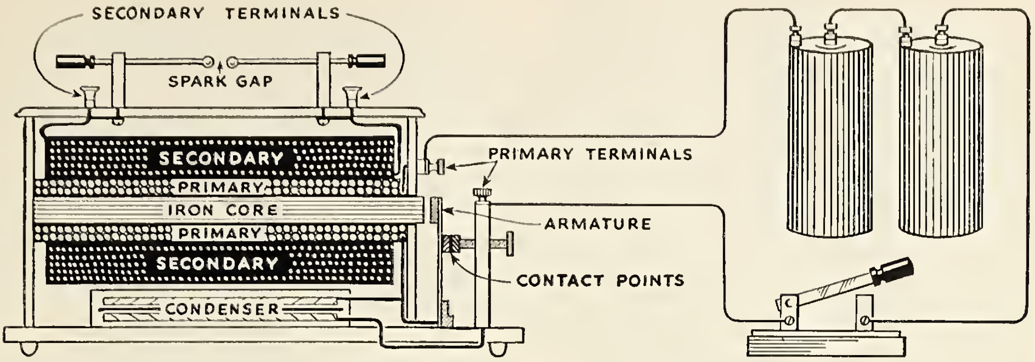
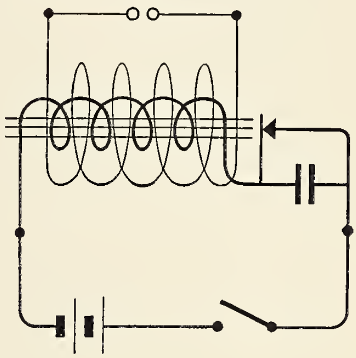


Figure 90. *This type of induction coil has the secondary wound over the primary. The armature vibrates like an electric buzzer, causing the contact points to open and close the primary circuit rapidly, and the condenser intensifies the resulting changes in the magnetic field. Current flows in the secondary when the fast-moving lines of force induce enough E.M.F. to force a spark across the gap. In the diagram at the right the heavy loops indicate the primary and the thinner ones, the secondary. Note the symbols used for the interrupter, condenser, and gap.*



tracts the interrupter, whose motion breaks the primary circuit. The magnetic field of the electromagnet collapses; its lines of force are cut in the opposite direction, thus inducing an E.M.F. in the opposite direction in the secondary. Also, the armature of the interrupter is no longer attracted by the electromagnet; the spring pulls the interrupter back. This closes the primary circuit once more. Again a magnetic field is built up, inducing an E.M.F. in the secondary. The field again collapses, and the induced E.M.F. acts in the opposite direction. This goes on as long as the switch is closed, just as an electric bell rings as long as the push button is pressed.

You know that the E.M.F. induced in the secondary depends on three things that affect the number of lines of force cut in a certain time: the speed of cutting lines of force, the number of turns, and the magnetic flux. The secondary has a large number of turns, and the magnetic flux of the primary and core is large. Moreover, the speed of cutting lines of force is great, because of the rapid building up and collapse of the magnetic field. The collapse of the field is more rapid than the building up, as shown in Experiment 38. As a result of the very rapid collapse of the field, such a great E.M.F. is induced that a spark jumps across the gap between the terminals of the secondary each time the primary circuit is broken. You may have been wondering about the gap in the secondary, because it is obvious from Figure 90 the secondary does not have a complete path. There is a small space, called the *spark gap,* which makes the path incomplete.

You know that an E.M.F. is induced whenever a conductor cuts lines of force but that an induced current will not flow unless there is a closed circuit. Like the water pressure always ready to furnish water when you turn on a faucet, the E.M.F. is always ready to furnish current when a closed circuit is provided. When the interrupter breaks the primary circuit, such a great E.M.F. is induced in the secondary that it drives a current across the gap, using air for a conductor.

Ordinarily, we think of air as a non-conductor or insulator; but if the voltage is high enough, a current can be sent through air. This happens whenever there is a flash of lightning or any other spark resulting from electrical action. The voltage, not the current, determines whether a substance is a conductor. When we say that metals are usually good conductors of a current, we really mean that they offer comparatively low resistance to the flow of current even at low voltages. Every non-conductor and insulator will conduct a current if the voltage is high enough. When this happens to an insulator, we say that it "breaks down." An E.M.F. of several thousand volts is induced in the secondary when the primary circuit is opened. As a result, the air in the gap breaks down; a spark jumps across the gap, completing the secondary circuit. An E.M.F. of about 20,000 volts is needed to force a spark across a one-inch gap in air between points.

The condenser connected across the contacts of the interrupter is not absolutely essential, but it greatly increases the E.M.F. induced in the secondary. It is a fixed condenser usually made of two long strips of tin foil separated by a strip of varnished paper. The strips are rolled or folded to make the condenser compact. If you look at Figure 17 (page 27), you can see how this is done. The insulator (paper) prevents a current from flowing between the two conductors (tin foil); but a current will flow in and out of the condenser as it is charged and discharged. When the contacts of the interrupter are touching, the condenser is discharged because there is a complete path between the two sheets of tin foil.

When the armature of the interrupter is attracted by the magnetized iron core, the contacts separate, and the primary circuit is broken. The self-induction of the primary tends to keep the current flowing. The self-induced E.M.F. in the primary will send a spark across the gap between the contacts. When this happens, a current continues to flow in the primary and slows down the collapse of the magnetic field. As a result, the turns of the secondary cut lines of force more slowly, and a lower E.M.F. is induced in it. The lower E.M.F. may not be sufficient to drive a spark across the gap in the secondary circuit. The condenser provides a place for the self-induced current in the primary circuit to be stored as a charge when the circuit is broken. By storing this charge the condenser greatly reduces the sparking at the interrupter contacts and thus increases the induced E.M.F. in the secondary. It is estimated that using a condenser across the contact points increases the E.M.F. induced in the secondary to about 25 times what the induced E.M.F. would be without a condenser. The increased E.M.F. will send a spark across a wider gap in the secondary circuit. Some sparking does occur between the contacts of the interrupter even when a condenser is connected across them. For this reason, the contact points are made of a metal, such as silver, platinum, or tungsten, that is not easily "pitted" by sparking.

A spark jumps across the gap in the secondary only when the primary circuit is broken. The current in the secondary is then flowing in the same direction as the current flowed in the primary before the circuit was broken. The current in the primary always flows in the same direction, because the source of electrical energy in the primary circuit furnishes direct current. Making and breaking the primary circuit cause a pulsating direct current to flow in the primary. This pulsating current varies the magnetic flux of the electromagnet (primary and core). The variable flux is cut by the turns of the secondary, inducing an E.M.F. first in the opposite direction to that of the primary current and then in the same direction. Because the secondary contains many more turns than the primary, an E.M.F. greater than that in the primary is induced in the secondary. Thus an induction coil is a kind of "voltage changer" that works by mutual induction. Induction coils are used to increase the voltage of a source of direct current.

Ignition system. Probably the commonest use of induction coils is in gasoline engines. Sparks are required inside each cylinder of a gasoline engine in order to set fire to the mixture of gasoline and air in the cylinder and cause the explosions that make the engine run. Every gasoline engine must have an ignition system to provide these sparks, no matter where or for what purpose the engine is used. As you probably know, gasoline engines are used to run automobiles, trucks, tanks, airplanes, and motor boats as well as generators, pumps, air compressors, and various kinds of machinery used on farms and in factories.

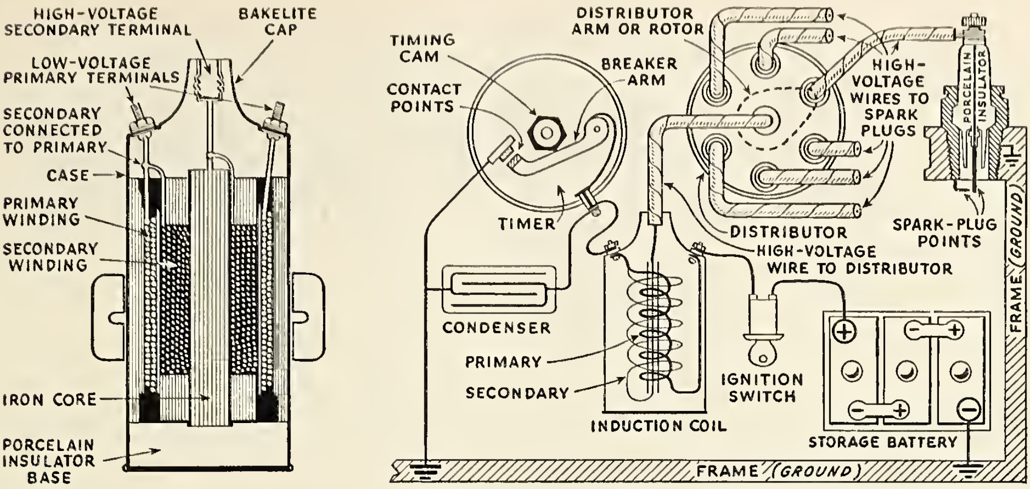


Figure 91. *At the left is a cross-section view of an automobile induction coil. Notice that the primary is wound over the secondary. At the right is a diagram of an automobile ignition circuit. Timer and distributor are usually mounted on one shaft so that the contact points open just as the distributor arm connects the secondary to a spark plug. Note the symbol used to show a connection to "ground," in this case the frame of the car. The new symbol for a condenser is one often used in automobile circuits.*

To provide the sparks needed in the engine, a high voltage is necessary. From 3500 to 15,000 volts may be required to make the spark jump the gap, depending on the size of the gap and the pressure of the mixture of gasoline and air in the cylinder. Since the source of electrical energy in the ignition system is usually a storage battery (6- or 12-volt) connected to a generator, an induction coil is used to increase the voltage of the source. There are other devices that can be used; but induction coils are very cheap to make, fairly reliable in operation, and also compact. Therefore, almost every high-speed gasoline engine used in modern automobiles contains an induction coil in its ignition system. This induction coil is sometimes called a *spark coil.*

Figure 91 shows the important parts of an automobile ignition system. The primary of the induction coil is connected in series with the storage battery. You will notice that the induction coil does not have a magnetic interrupter. Instead, the interrupter is mechanically operated so that the primary circuit is closed and then opened at just the right time to make a spark in a cylinder. For this reason, the interrupter is often called the *timer.* Just as in Figure 90, a condenser is connected across the contacts of the interrupter. To set fire to the gasoline-air mixture, a spark must jump across the gap in the *spark plug.* Each cylinder has a spark plug of its own. (In dual-ignition systems, each cylinder has two spark plugs.) The diagram shows that the secondary is connected to the spark plugs through a device called the *distributor,* which does just what its name suggests. It distributes the sparking current to each of the spark plugs at just the right time to set fire to the gasoline-air mixture in each cylinder. The distributor *arm,* or *rotor,* revolves so that it is opposite the contact point connected to a spark plug at just the instant when the timer contacts break the primary circuit. Thus a spark will occur in each cylinder at the proper time if the distributor and timer are properly adjusted.

Sometimes the adjustment is not quite right. The spark may occur too soon or too late to get the most energy out of the explosions in the cylinders. If this happens, the engine will not operate

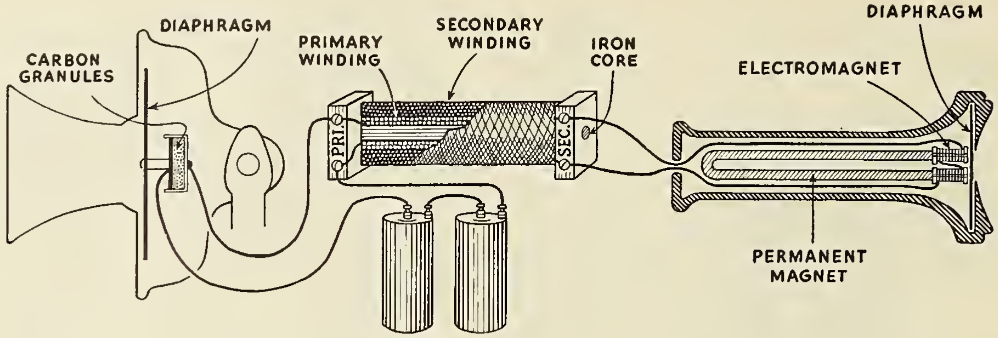
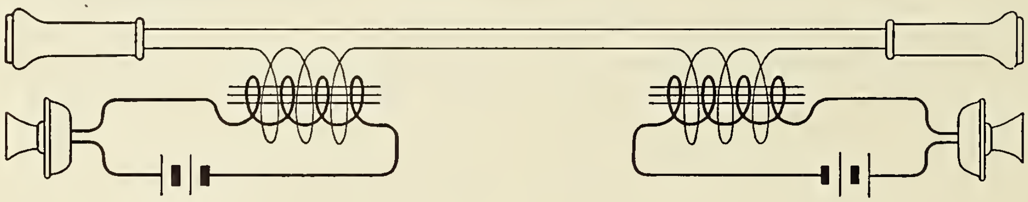


Figure 92. *The upper picture shows a simple one-way telephone circuit with an induction coil. As the transmitter varies the current flowing through the primary, the variation of the magnetic field induces in the secondary a high-voltage current which can be sent over wires for long distances with little loss. The lower diagram shows a simple two-way telephone circuit using induction coils. The primary circuits are shown in heavy lines, while the secondary circuit is shown in lighter lines.*



at its greatest efficiency. The timing cam must be adjusted to get rid of this condition. Another source of trouble is the contact points of the distributor and timer. These may become pitted from sparking and fail to work as they should. Cleaning or replacing the contact points will remedy this condition. A broken spring in the interrupter will also cause trouble. The primary circuit will not be opened and closed as rapidly as it should be. As a result, the spark will not be as strong as necessary. Occasionally, the condenser may break down and "blow out." If this happens, the condenser must be replaced. Probably the commonest cause of trouble is the spark plugs. These become fouled, or dirty, from the explosions in the cylinders. Spark plugs should be cleaned regularly, and the gaps should be checked to see that they are not too great. Sometimes the porcelain insulation around the top of a spark plug cracks. When this happens, the plug should be replaced. Moisture or oil on the tops of the plugs should be wiped off, because it reduces the E.M.F. available at the gaps in the plugs.

Other uses. Induction coils are sometimes used in telephone circuits. Figure 92 shows a telephone circuit in which two induction coils are used. Each transmitter is connected in series with a local battery and the primary of an induction coil. The receivers are connected in series with the secondaries of the induction coils. You will notice that there are no interrupters or condensers used. The pulsating or fluctuating direct current through the primary induces a current in the secondary by varying the magnetic flux. Since the secondary has many more turns than the primary, the secondary current is at a much higher voltage. Thus, it can be sent through a fairly long wire and still cause the receiver to work. Using induction coils in this way makes it possible to carry on telephone conversations over much greater distances than with the simple telephone circuit shown in Figure 76 (page 142).

Transformer: A device used to increase or decrease the voltage of an alternating current by mutual induction between its primary and secondary. A **step-up transformer** has more turns in its secondary than in its primary and thus increases the voltage. A **step-down transformer** has fewer turns in its secondary than in its primary and thus decreases the voltage.

Voltage-turns ratio of a transformer: The ratio of the secondary voltage of a transformer to the primary voltage is the same as the ratio of the number of turns in the secondary to the number of turns in the primary. Or:

$$\frac{\text{Secondary voltage}}{\text{Primary voltage}} = \frac{\text{Secondary turns}}{\text{Primary turns}}$$

Induction coils are sometimes used to operate "neon" signs and X-ray tubes, which require high voltages. An induction coil may be used to supply high voltage from a low-voltage source of direct current if only a small current is needed at the higher voltage. When a large current is needed, induction coils are not satisfactory.

CHECKING WHAT YOU LEARNED

1. State four ways of inducing an E.M.F. in a coil.
2. **a.** How does an induction coil produce an E.M.F.? **b.** Why is an induction coil used?
3. What is meant by the primary of an induction coil? The secondary?
4. Explain why a condenser is usually connected across the contacts of the interrupter of an induction coil.
5. Name the main parts of an automobile ignition system and tell what each part does.
6. What is the advantage of using induction coils in telephone circuits? Explain your answer.

USING WHAT YOU LEARNED

1. The spark produced between the secondary terminals of an induction coil always goes in the same direction. Does this mean that a direct current flows in the secondary? Explain.
2. Why is an interrupter unnecessary in a telephone circuit using induction coils?
3. **a.** If the ignition system of a gasoline engine fails to work properly, what are some possible causes of trouble? **b.** How can each cause be remedied?
4. Both mutual induction and self-induction occur in an induction coil. Tell where and when each occurs.

The Transformer

The induction coil, which you have just studied, is really a kind of **transformer**, or voltage changer. However, the term *transformer* is usually applied to a similar device that differs somewhat from an induction coil in construction and use. Like an induction coil, a transformer has a primary and a secondary wound around a core made from a magnetic substance. The secondary of an induction coil always has many more turns than the primary, because an induction coil is used to increase the voltage of the source of electrical energy. In a transformer, however, the secondary may have more or fewer turns than the primary, depending on whether the voltage is to be increased or decreased. An induction coil has an *open core;* that is, the ends of the core do not form a complete magnetic path. A transformer, on the other hand, has a *closed core;* that is, the core forms a complete magnetic path. If you understand how an induction coil works, it will be easy for you to understand the transformer, since both devices use the same principle—mutual induction. In Experiment 39 you can make and operate a small transformer.

Figure 93 shows a simple transformer consisting of two coils (one of 50 turns and the other of 100 turns) wound around a closed iron core. The coil of 50 turns is connected in series with a dry

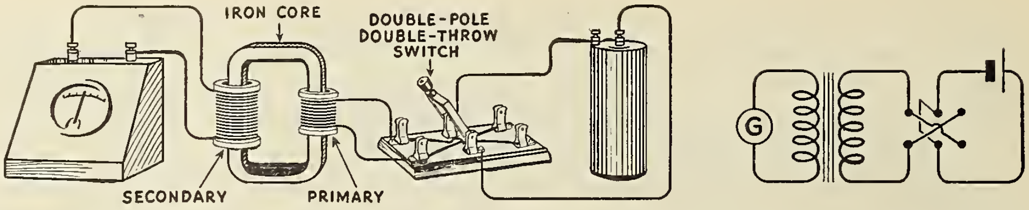


Figure 93. *The picture at the left shows a simple transformer connected to a galvanometer and a reversing switch. Throwing the switch from one side to the other causes the needle of the meter to swing as the current in the primary is reversed. The diagram at the right shows the connections for the double-pole double-throw knife switch. Note also the symbol used in electrical diagrams for a transformer of any kind.*

cell and reversing switch. (The purpose of the switch is to make it easy to reverse the current through the coil without changing the connections at the cell.) The coil of 100 turns is connected to a galvanometer. The 50-turn coil is the primary, while the 100-turn coil is the secondary. If you throw the switch to the left, the galvanometer needle swings to one side and then back to zero, indicating that an induced current flows in the secondary. When the switch is open, the galvanometer needle swings to the other side and then back to zero, showing that an induced current now flows in the opposite direction through the secondary. So far your results are the same as those in Experiment 38.

Now if you throw the switch to the right, the current from the dry cell flows through the primary in the opposite direction. The galvanometer needle swings in the same direction as when you opened the switch before. When the switch is opened this time, the galvanometer needle swings in the same direction as when you threw the switch to the left. *Closing* the primary circuit with the current flowing through it in one way induces a current in the secondary that flows in the same direction as when the primary circuit is *opened* with the current flowing through it in the other way. In other words, the induced current in the secondary changes its direction when the primary circuit is opened or closed and when the current in the primary is reversed. You can easily demonstrate this fact by throwing the reversing switch rapidly back and forth from one side to the other and watching the swing of the galvanometer needle.

The direction of the induced current is in accordance with Lenz's Law. The current in the primary sets up a magnetic flux around the entire iron core; the turns of the secondary cut the lines of force, inducing a current in such a direction that its magnetic field opposes the magnetic field set up by the current in the primary. When the current in the primary is reversed, the direction of the magnetic flux is reversed. The turns of the secondary cut the lines of force in the opposite direction, and the induced current in the secondary flows in the opposite direction. The swing of the galvanometer needle indicates that induced current in the secondary reverses its direction every time the primary current is reversed.

Now let us see what happens when the 50-turn coil is connected to the galvanometer and the 100-turn coil to the dry cell and reversing switch. The 100-turn coil is now the primary, while the 50-turn coil is the secondary. If you throw the switch back and forth as before, the galvanometer needle shows that the induced current in the secondary reverses every time the primary current is reversed. However, the needle does not swing so far to the side as it did before, indicating that the induced E.M.F. is not so great. A current of lower voltage has been induced by using fewer turns in the secondary than in the primary. You already know that a current of higher voltage is induced when the secondary has more turns than the primary. Thus transformers may be used to de-

High on the pole at the left is a distribution transformer—the step-down transformer that reduces alternating current to a safe value for use in the home, usually about 115 volts for two-wire circuits and about 230 volts for three-wire circuits. Some idea of the size and construction of the transformer coils can be had from the picture above, while the picture below shows how the special iron core is fitted around the windings.

Alternating current: An electric current that flows in one direction and then in the other instead of always flowing in the same direction. Often abbreviated **A.C.**

crease as well as increase voltage by mutual induction between the primary and secondary circuits.

Kinds of transformers. A transformer used to increase voltage is called a **step-up transformer,** while a transformer used to decrease voltage is called a **step-down transformer.** The secondary of a step-up transformer has more turns of wire than the primary. As a result, a current of lower voltage in the primary induces a current of higher voltage in the secondary. You can see that an induction coil is really a kind of step-up transformer. On the other hand, the secondary of a step-down transformer has fewer turns of wire than the primary. As a result, a current of higher voltage in the primary induces a current of lower voltage in the secondary. A bell transformer or a toy transformer is a step-down transformer; so is the transformer on the tall wooden pole near your home.

It is a very simple matter to find out the voltage delivered by the secondary of a transformer. The voltage of the secondary has the same ratio to the voltage of the primary as the number of turns in the secondary has to the number of turns in the primary. This may be stated as an equation:

$$\frac{\text{Secondary voltage}}{\text{Primary voltage}} = \frac{\text{Secondary turns}}{\text{Primary turns}}$$

For example, suppose that a transformer has coils of 500 and 1000 turns. If the 500-turn coil is used as the primary and connected to a source that maintains a potential difference of 1.5 volts between the ends of the wire in the coil, the 1000-turn coil used as a secondary will produce a potential difference of 3 volts. The ratio of the secondary turns to the primary turns is 1000 to 500, or 1000/500, or 2. Therefore, the voltage of the secondary is twice that of the primary. However, if the 1000-turn coil is used as the primary and is connected to a source that maintains a potential difference of 1.5 volts, the 500-turn coil used as the secondary will produce a potential difference one-half as great or .75 volt.

It would be very difficult to make the transformer used in Experiment 39 act perfectly as a step-up or step-down transformer. The coils and core built into a transformer must be carefully constructed so that they will have the correct electrical characteristics. The resistance, self-induction, and magnetizing force of the coils must be correct in order to have the transformer operate satisfactorily. Just how these characteristics are all calculated in designing transformers is too complicated to explain in this book.

Do not get the idea that a step-up transformer gives something for nothing because of the increased voltage in the secondary. And do not think that a step-down transformer takes something without giving anything in return because of the decreased voltage in the secondary. In the next chapter you will learn how increasing or decreasing the primary voltage affects the current that can be drawn from the secondary of a transformer.

Alternating current. In this chapter you have learned that an E.M.F. is induced in a conductor (usually a coil) whenever the conductor cuts magnetic lines of force. As you have seen, there are several ways in which this may be done: by moving the magnetic field, by moving the conductor, by closing and opening the circuit through the coil of an electromagnet, by varying the magnetic flux of a core, and by reversing the current in the coil of an electromagnet. The last way, which was used in Experiment 39, is extremely important, because it is the one used in transformers. In every experiment of this chapter you have noticed that the induced current flowed first in one direction and then in the other as lines of force were cut first in one direction and then in the other. A current that flows in one direction and then in the other instead of always flowing in the same direction is called an **alternating current.** You made a crude sort of alternating current flow through the primary of the transformer by throwing the reversing switch back and forth. A transformer ordinarily has an alternating current flowing through its primary; it always has an alternating current induced in its secondary.

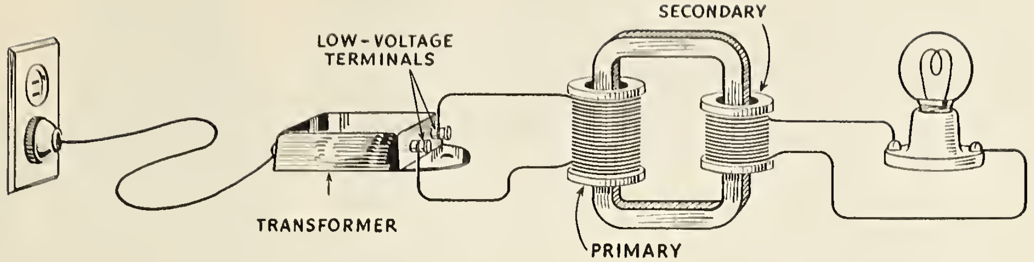


Figure 94 *shows how alternating current can be changed to a higher or a lower voltage by using a transformer. When the small coil is connected to the 2-volt terminals of a toy transformer, the 3-volt bulb connected to the large coil will light up brightly. When the large coil is connected to the toy transformer and the small one to the lamp socket, the 3-volt bulb glows dimly, showing that the voltage is now much less.*

With a pair of headphones (or a telephone receiver) you can actually hear the effect produced by the reversal of an alternating current. If you connect one terminal of the headphones to one terminal of a dry cell and then touch the other terminal of the headphones to the other terminal of the cell, you will hear a click in the headphones but nothing more, since the dry cell furnishes direct current. Now if you connect the headphones to the 100-turn coil of the transformer and attach the 50-turn coil to the low-voltage terminals of a toy transformer (or bell transformer) connected to the 110-volt alternating current circuit, you will hear a steady humming sound, which is produced by the reversal of the current.

A toy transformer or a bell transformer is a step-down transformer. For example, a toy transformer may furnish from about 1.5 to about 30 volts from the secondary when its primary is connected to a source of 110-volt alternating current. When its low-voltage terminals are connected to the transformer made in Experiment 39, alternating current induced in the secondary of the toy transformer induces alternating current in the secondary of the other transformer. You hear the same number of reversals of current per second in the headphones as take place in the primary of the transformer. For each reversal in the primary current of a transformer there is a reversal in the secondary current, as you know.

You have already seen that the transformer made in Experiment 39 can be used to increase or decrease the voltage. If you leave the transformer connected to the toy transformer as shown in Figure 94, you can easily check the facts. If a 3-volt bulb is connected to the 100-turn coil (secondary), it will light up brightly. But if the 100-turn coil is connected as the primary to the toy transformer and the bulb is now connected to the 50-turn coil (secondary), it will not light up as brightly as before. Obviously, the current induced in the secondary of the step-down transformer has a lower voltage than the current induced in the secondary of the step-up transformer.

Alternating current is so important that you must be sure you understand it. Cells furnish direct current, which is also supplied by special generators. Direct current is necessary for communication circuits, for charging storage batteries, for electrolysis and electroplating, and for certain kinds of electric motors. However, alternating current is just as satisfactory for other purposes, such as lighting, heating, and running ordinary motors. The transformer has made it possible to transmit alternating current over long distances at high voltages and then to reduce the voltage for home or factory use. In the next chapter you will see how transformers are used in the transmission of electrical energy.

Figure 95 shows an "electron picture" of an alternating current. Of course such a picture can-

Alternation: Each reversal of an alternating current. During an alternation the current flows in one direction from zero to full amount and back to zero again.
Cycle: A series of two complete alternations of an alternating current.
Frequency: The number of complete cycles per second of an alternating current.

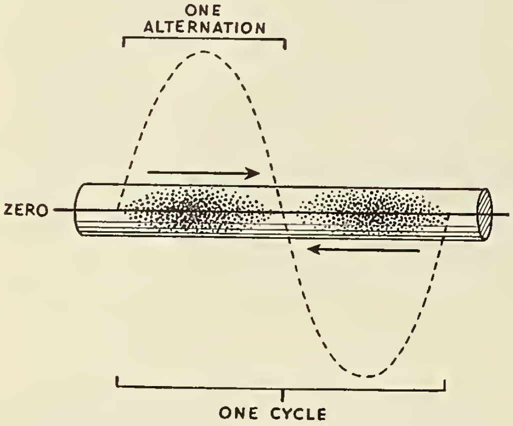


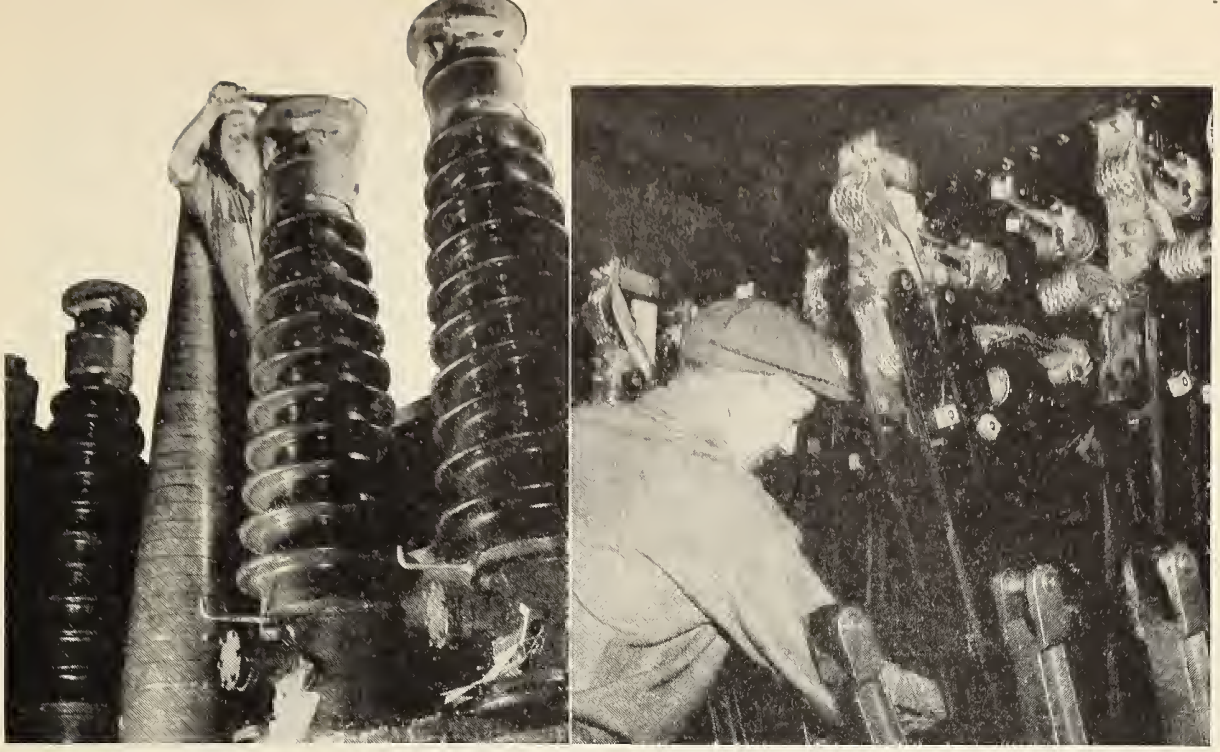
Figure 95 *shows the "electron picture" of an alternating current. Instead of a steady stream of electrons, as in a wire carrying direct current, the electrons flow first one way and then the other in regular alternations. When the current is zero, no electrons flow; when it reaches the peak of its strength, the maximum number of electrons flow. Each two alternations complete a cycle, and the number of cycles per second is the frequency of the current. Thus a 60-cycle current has 120 alternations per second.*

not represent the billions of electrons actually making up the current, but it does give you some idea of how the electrons move back and forth in a conductor carrying an alternating current. A convenient way to show what happens in a circuit is also given in the graph in Figure 95. The broken, curving line represents the current. When the curving line is above the straight center line, the current is flowing in one direction. When the curving line is below the center line, the current is flowing in the opposite direction. The vertical distance from the center line to the curving line represents the size of the current. You can see that the current starts flowing in one direction, gradually reaches its greatest amount (actually this takes only a tiny fraction of a second), and then decreases until it reaches a point where no E.M.F. acts and no current flows. Then the E.M.F. begins to act in the opposite direction, and the current reverses. The current reaches its greatest amount and then decreases as before until no E.M.F. acts and no current flows. Again the E.M.F. begins to act in the opposite direction, and then reverses, and so on—over and over again.

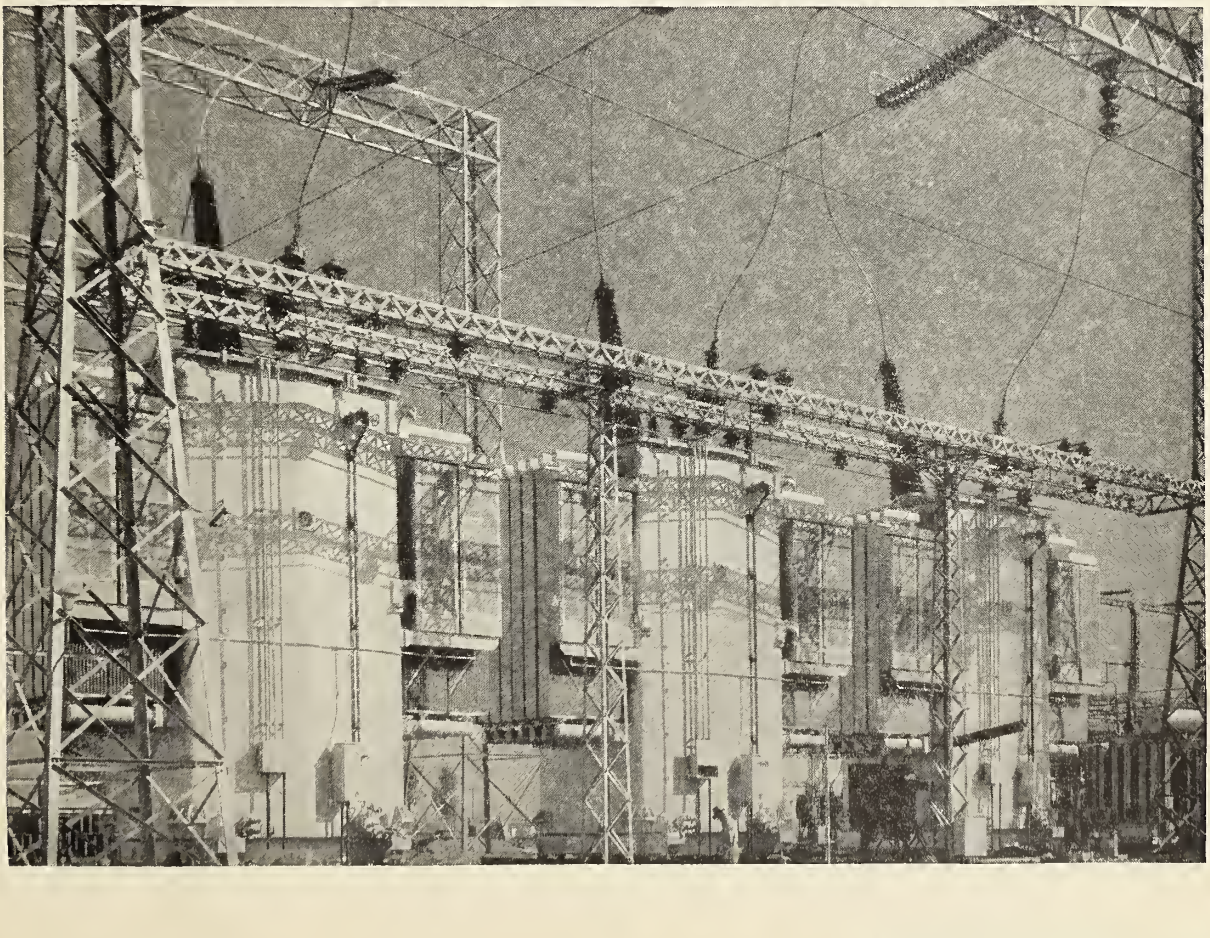
Each reversal of the alternating current is an **alternation.** At the end of two alternations the current has completed a **cycle** and begins to flow in the first direction once more. The number of complete cycles per second is the **frequency** of the alternating current. The ordinary alternating current in a house-wiring circuit has a frequency of 60 cycles. This means that there are 120 alternations, or changes in direction, every second. The current flows 60 times in one direction and 60 times in the other during each second.

CHECKING WHAT YOU LEARNED

1. **a.** What is a transformer? **b.** How does it differ from an induction coil?
2. Tell how an alternating current in the primary of a transformer induces an alternating current in the secondary.
3. **a.** What is meant by a step-up transformer? Step-down transformer? **b.** In what way are they different?
4. How can you determine the secondary voltage of a transformer? Give an example to illustrate your answer.
5. State the difference between an alternating current and a direct current.
6. Explain what is meant by 110-volt 60-cycle alternating current.



The man at the upper left is working on one of the porcelain insulating tubes, or bushings, through which pass the copper cables carrying current to and from the windings of a power transformer. At the right another workman is assembling the special switches needed for controlling large power transformers, such as the three shown in the picture below. The man in the foreground below gives some indication of the size of these devices.



USING WHAT YOU LEARNED

1. How many times does a 60-cycle alternating current change direction in one minute? Explain your answer.
2. A step-down transformer for use on 110-volt alternating current has 990 turns in its primary. To supply current at a pressure of 10 volts, how many turns of wire should be wound on the secondary? Why?
3. A step-up transformer with 160 turns in its primary is connected to 110-volt alternating current. If the secondary has 800 turns, what voltage does it supply? Explain.
4. The voltage of an alternating current transmission line is 2200 volts. In order to reduce the voltage to 110 volts, what must the turns ratio of the secondary and primary of the pole transformer be? Give your reasons.

THINKING OVER WHAT YOU LEARNED

1. After each topic of the chapter write down in complete sentences the big ideas or principles you learned.
2. By using a definition or sentences, show that you understand the meaning of the following: **a.** cycle, **b.** induction coil, **c.** induced current, **d.** alternation, **e.** interrupter, **f.** primary, **g.** inductance, **h.** back E.M.F., **i.** transformer, **j.** alternating current, **k.** secondary, **l.** step-down, **m.** induced E.M.F., **n.** frequency, **o.** step-up, **p.** mutual induction, **q.** self-induction, **r.** spark gap.

Experiment 34: **Using a Permanent Magnet to Induce E.M.F. and Current**

THINGS NEEDED: Coil of 300 or 400 turns of No. 30 cotton-covered or enamel-coated copper wire that will fit between the poles of U-shaped magnet. U-shaped permanent magnet. Sensitive galvanometer. Bar magnet.

WHAT TO DO: **a.** Connect the wires of the coil to the galvanometer. Set the U-shaped magnet so that its poles point upward. (See Fig. 81.) Move the coil edgewise down between the poles of the magnet and watch the galvanometer needle. Stop the coil and look at the needle again. Now move the coil up between the poles and observe the needle. What happens? Try moving the coil down and up as before, stopping it before changing direction. What do you notice by watching the needle? Try moving the coil faster or slower. Notice what happens.

b. Repeat Part **a**, first using a coil of more turns and then one of fewer turns. What do you notice? Then try moving the magnet instead of the coil and observe what happens. Also try a bar magnet in place of the U-shaped magnet. Insert the bar magnet in the coil and then withdraw it. Then turn the bar magnet end for end and repeat with the other pole. What conclusions can you make about inducing an E.M.F. and thus a current in coil by using a permanent magnet?

c. (*Optional*) If a galvanometer sensitive enough to indicate very small currents is available, unwind some of the wire from the coil and repeat Part **a**, using a single wire instead of a coil, as shown in Figure 82. How do the results compare with those in Part **a**? Refer to Figure 83 and compare your results with the illustration.

Experiment 35: **Using an Electromagnet to Induce E.M.F. and Current**

THINGS NEEDED: Coil and galvanometer from Experiment 34. Coil and No. 6 dry cell from Experiment 25. Iron nail or rod that will fit inside the coil. No. 6 dry cell. No. 18 insulated copper wire. Push button (or knife switch).

WHAT TO DO: **a.** Set the two coils end to end, as shown in Figure 84. Close the circuit through the electromagnet coil (solenoid) connected to the dry cell. (If a push button is used, hold it down or remove it from the circuit for this part of the experiment.) Move the solenoid toward the other coil and watch the galvanometer needle. Stop the solenoid and notice what happens to the needle. Now move the solenoid away from the coil connected to the galvanometer and notice what happens. Keep the solenoid stationary and move the coil toward and away from it. How do your results compare with those in Experiment 34? What happens when neither coil nor solenoid is moved? (If you wish, you may try moving the solenoid or coil faster and then slower. Also try adding turns to or removing turns from the coil connected to the galvanometer. Strengthen the electromagnet coil by inserting the iron nail as a core, by adding another dry cell in series with the first one, or by adding more turns to the coil.)

b. Place the coils end to end, as shown in Figure 84. (Do not move either coil in this part of the experiment.) Close the circuit including the electromagnet coil and watch the galvanometer needle. What happens when the circuit is first closed? When the circuit is kept closed? Now open the electromagnet circuit and notice what happens to the needle. (If you wish, you may try using an iron core in the electromagnet coil connected to the dry cell, or you may add more turns to its coil. Also try adding another dry cell to the electromagnet circuit. Open and close the circuit faster and slower and observe what happens. Also try increasing or decreasing the turns of the coil connected to the galvanometer.) What conclusions can you make from Part **b**?

Experiment 36: **Lenz's Law**

THINGS NEEDED: Coil and galvanometer from Experiment 34. Bar magnet. No. 6 dry cell. No. 18 insulated copper wire. Magnetic compass. 3000-ohm resistor.

WHAT TO DO: **a.** (See Fig. 85.) Quickly bring the N pole of a bar magnet near the upper end of the coil and notice the galvanometer needle. Push the bar magnet into the coil. What do you notice as you push the bar magnet into the coil? Now quickly pull the bar magnet out of the coil and notice what happens. What conclusions can you make about the polarity of the coil as the N pole was brought near and then withdrawn from one end? Repeat, using the S pole of the bar magnet.

b. (See Fig. 86.) Connect the coil and galvanometer as in Part **a**. Approach the upper end of the coil with the N pole of a bar magnet. Notice the side to which the galvanometer needle swings. Remove the bar magnet. Connect the galvanometer so that it may be used with 1.5 volts. (If this is not possible, connect a 3000-ohm resistor in series with the galvanometer and dry cell.) Then connect a dry cell in series with the coil so that the galvanometer needle swings in the same direction as when the N pole of the bar magnet was brought near the upper end of the coil. Using the right-hand rule for a coil or using a magnetic compass, find the polarity of that end of the coil. (If you wish, you may prove that the same end of the coil is a S pole when the N pole of the bar magnet is withdrawn.)

Experiment 37: **Self-Induction**

THINGS NEEDED: Coil of many turns having an open or closed iron core, such as a choke coil. 6-volt automobile bulb and socket. Three dry cells. No. 18 insulated copper wire. Push button (or knife switch).

WHAT TO DO: (See Fig. 87.) Connect the coil in series with three dry cells and a push button (or knife switch). Across the coil connect a 6-volt bulb and its socket. Close the circuit and watch the bulb. What happens? Then open the circuit and observe the bulb. What happens now? Explain.

Experiment 38: **Induction Coil**

THINGS NEEDED: Coil and galvanometer from Experiment 34. Iron rod that will fit inside the coil. Bar magnet. Coil and No. 6 dry cell from Experiment 25. Push button (or knife switch). No. 18 insulated copper wire.

WHAT TO DO: **a.** Insert the iron rod in the coil connected to the galvanometer, as shown in the picture at the left in Figure 89. Bring the N pole of a bar magnet near or against one end of the iron rod. What happens to the galvanometer needle? Hold the bar magnet still and observe the needle. Then withdraw the bar magnet and notice what happens. Try the S pole of the magnet and also the other end of the rod. What conclusion can you make?

b. Now slip the other coil over the iron rod. Connect the coil in series with a dry cell and push button (or knife switch), as shown in the picture at the right in Figure 89. Close the circuit through the coil and dry cell by pressing the push button. What happens to the galvanometer needle? Now open the circuit through the coil and dry cell. What happens to the galvanometer needle this time? Try closing the circuit and opening the circuit faster and slower and observe the galvanometer needle. How do your results compare with those in Part **a** and also in Experiment 35?

c. (*Optional*) If a commercial induction coil is available, locate the parts shown in Figure 90. Then connect the coil to a battery and operate it. **Do not touch the secondary terminals while the coil is in operation. You may receive a severe shock.** Also locate the induction coil and other important parts in an automobile ignition system, as shown in Figure 91.

Experiment 39: **Transformers**

THINGS NEEDED: No. 26 cotton-covered or enamel-coated copper wire. Iron rod bent to form a closed core (or coil of stove-pipe wire). Paper. Galvanometer. Reversing switch (double-pole, double-throw). No. 6 dry cell. Headphones (or telephone receiver). Toy transformer (100- or 150-watt). 3-volt bulb and socket.

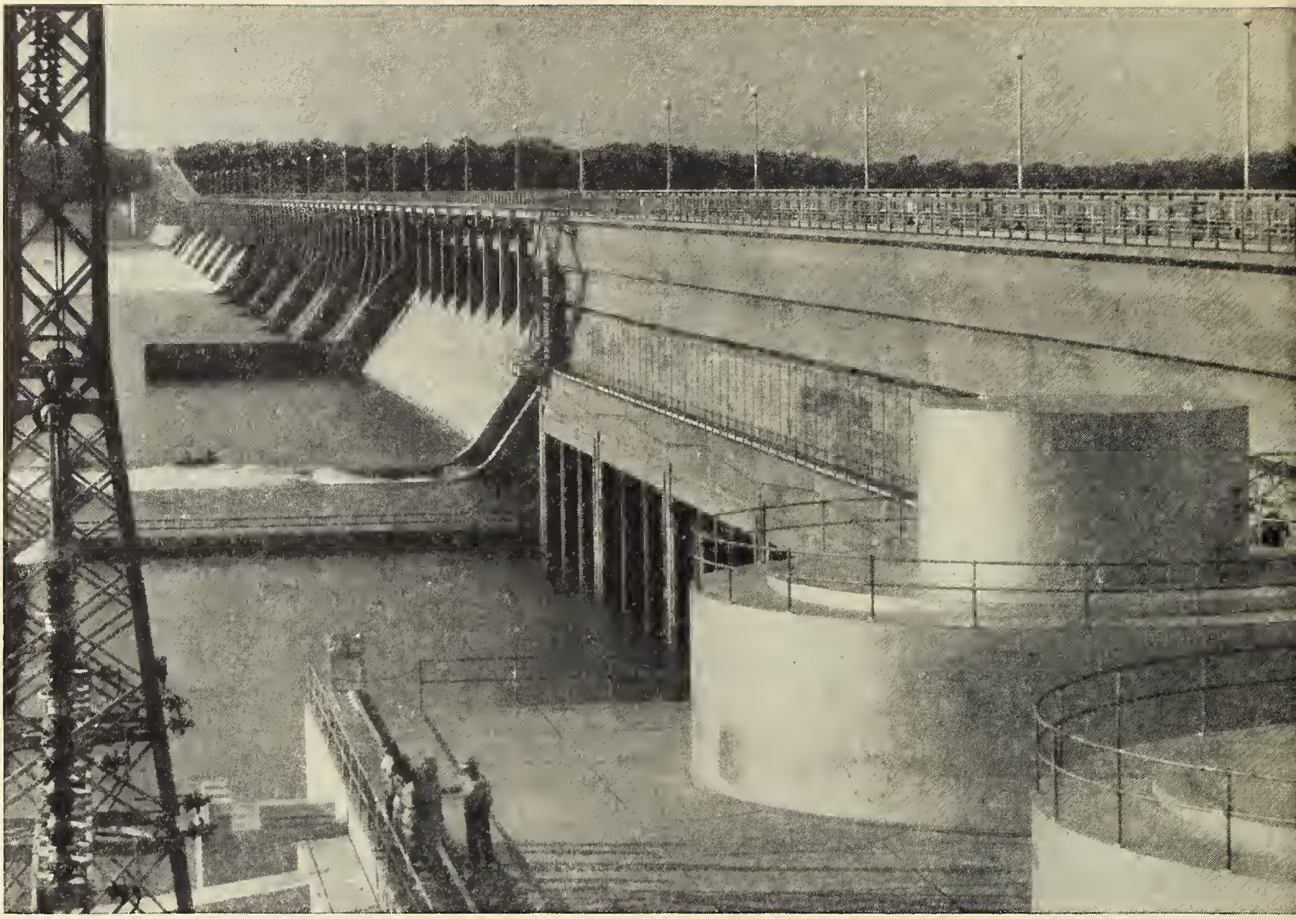
WHAT TO DO: **a.** Make a transformer by winding two coils of wire around an iron core. One coil should have 50 turns and the other, 100 turns.

Insulate the wire from the core with a layer of paper. Connect the 50-turn coil to a reversing switch and dry cell, as shown in Figure 93. Connect the 100-turn coil to the galvanometer. Throw the switch to the left and observe the galvanometer needle. Open the switch and observe the needle again. Now throw the switch to the right and see what happens. Open the switch and notice the galvanometer needle. What conclusion can you make about the effect of reversing the current in the primary on the direction of the current in the secondary?

b. Now connect the 100-turn coil to the reversing switch and the 50-turn coil to the galvanometer. Repeat Part **a** and observe what happens. Does the galvanometer needle swing so far to the side as it did? Why?

c. Connect one terminal of a pair of headphones (or a telephone receiver) to one terminal of a dry cell. Touch the other terminal of the headphones to the other terminal of the dry cell. What do you hear? Now connect the headphones to the 100-turn coil. Attach the 50-turn coil to the low-voltage terminals of a toy transformer. Use the 1.5- or 2-volt terminals. (See Fig. 94.) Connect the toy transformer to the 110-volt alternating-current circuit. What do you hear in the headphones? (Disconnect the toy transformer from the 110-volt circuit.)

d. Now connect a 3-volt bulb and socket in place of the headphones. Connect the toy transformer to the 110-volt circuit again. Notice the brilliance of the bulb. Disconnect the toy transformer as before. Then connect the 100-turn coil to the toy transformer and attach the wires from the 50-turn coil to the bulb and socket. Connect the toy transformer to the 110-volt circuit. Is the bulb as bright as before? Explain.



8. Energy, Work, and Power

FINDING OUT WHAT YOU KNOW

1. What is energy?
   How is energy different from matter?
2. Name as many different forms of energy as you can.
3. Does a magnet have energy?
   Give reasons for your answer.
4. Tell when and where you have noticed one form of energy changing into another form.
   Give at least three examples.
5. What is meant by force?
   Give as many examples of forces as you can.
6. How do scientists define work? Power?
7. In what unit is electrical energy measured and sold?
   Explain what the unit means.
8. Tell why transformers are so useful in the transmission of electrical energy.

YOU HAVE NOT OFTEN MET the word "electricity" in this book. Instead of that misused and misunderstood word, "electric current," "electrical charge," and "electrical energy" have been used. In Chapter 3 you learned that there is a definite relation between the rate of current flow, the electromotive force that causes the current to flow, and the resistance in the circuit. As you know, the electromotive force is the result of a difference in potential. In Chapter 2 you learned that potential difference actually refers to a difference in electrical charges, that is, a difference in potential energy. From your study of Chapter 4 you found that chemical energy could be changed into electrical energy. Then in Chapter 6 you learned that electromagnetism provided a means of changing electrical energy into mechanical energy. Before we go on with the study of electricity, let us go more deeply into the facts about energy. Then you will be able to understand the relation between energy, work, and power in electrical devices and electric circuits.

Energy

Every day we see changes going on in the materials that make up everything in the world about us. Even the materials that make up our bodies change. There must be something that causes these changes in materials, or matter. This "something" is called **energy**; it can make things happen to matter. It takes energy to wind a watch, to turn a wheel, to move a muscle, to produce light or heat, or to make a sound—just to mention a

Energy: The ability to do work. The energy of matter in motion is called **kinetic energy.** The energy stored in matter is called **potential energy.**

few things that require energy to accomplish them. Although matter has energy, matter and energy are not the same. Matter takes up space, while energy does not. For example, a ball has energy when it is thrown; it can break a windowpane. Yet when the ball is moving through the air, it is no larger or smaller than before it is thrown. From this and other similar examples we conclude that energy does not take up space. At least we cannot prove that it does. And yet we are sure that energy exists, because we can sometimes feel what it does and because we see that it makes matter change. As scientists define it, energy is the ability to do work; but the meaning of work in the sense that scientists use it is not quite the same as the meaning of work in ordinary use. Later on in this chapter you will learn the scientific meaning of work.

Kinds of energy. The electrons and protons, which with other tiny particles make up the atoms in the molecules of all materials, are bits of matter. As you know, each electron or proton has an electrical charge. The charge of an electron or proton is energy; but when electrical energy is mentioned, we ordinarily mean the energy of an electron or of many electrons. When electrons move from one place to another, they do so as the result of the repulsion of like charges. The moving electrons that form a current have energy just as any moving material does. For example, a bullet shot from a gun and a falling weight both have energy because of their motion; so has a moving automobile or airplane. The kind of energy that matter has because of its motion is called **kinetic energy**.

However, matter that is not moving from one place to another also has energy. Protons have energy; yet they are supposed not to move as electrons do. And electrons will not move from one object to another unless there is a difference of potential and a path between the objects; yet electrons have energy even when they do not move from one place to another. This energy is stored in the electrons as negative electrical charges, just as energy is stored in the protons as positive electrical charges. The kind of energy that is stored in matter because of its position or condition is called **potential energy.**

Of course electrons are not the only bits of matter that may have potential energy. For example, a package on a closet shelf has potential energy because of its position, as you will discover if it falls on your head. The coiled spring of a watch or the stretched spring of an open door has potential energy because of its condition. The wound-up watch spring will turn the wheels of the watch, while the stretched spring will close the door after you have passed through. The powder used to shoot a bullet from a gun barrel has potential energy because of its chemical composition. When the powder catches fire and explodes, it undergoes a chemical change, and its stored energy is released. The same thing is true of coal, wood, oil, gasoline, and other fuels; they have potential energy because of their chemical composition, and this energy may be released by burning them. You recall that cells have chemical energy stored in them; the energy is released when the cells are connected in a closed circuit.

Forms of energy. As you have learned, there are two kinds of energy: potential and kinetic. There are also various forms in which these kinds may be observed. In this book we are especially interested in the form called electrical energy, but other forms of energy have already been mentioned. For example, heat and light are forms of energy. Two other forms are chemical energy and mechanical energy. Sound and magnetism illustrate other forms. All about us we see evidence of the various forms of energy. There is heat energy from a flame or from friction, light energy from the sun or a lamp, chemical energy in the baking powder that makes biscuits rise, mechanical energy in a stretched rubber band or a moving car, and

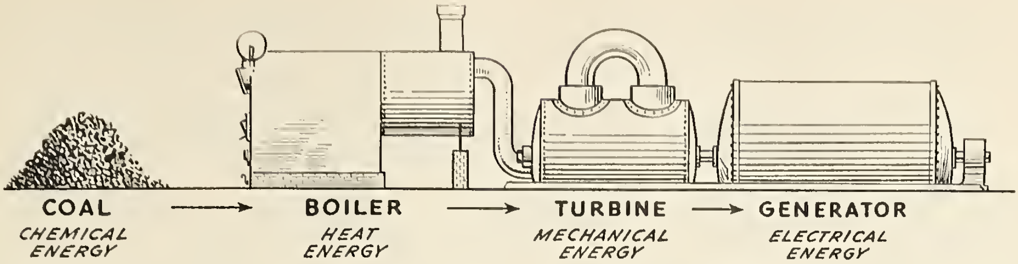


Figure 96 *shows one of the ways in which power stations convert the chemical potential energy of coal into electrical kinetic energy. When coal is burned in the boiler, the chemical energy stored in the coal is released as heat energy and used to change water to steam. By means of the turbine the mechanical energy of expanding steam is used to turn the shaft of the generator, thus producing electrical energy.*

sound energy in a scream or the bang of a hammer. Energy takes different forms, but every form has the same characteristic—the ability to make something happen to matter.

Electrical energy may be either kinetic or potential. An electric current is an example of kinetic energy, while a stationary electrical charge is an example of potential energy. Heat is always kinetic energy, since it is actually the motion of molecules. The form of energy known as light is really just the visible part of the form called radiant energy, which includes infrared rays, ultraviolet rays, X-rays, radium rays, and radio waves in addition to light. Curiously enough, radiant energy consists of equal quantities of potential energy and kinetic energy. Chemical energy is stored energy, while mechanical energy may be either potential or kinetic. Sound is both kinetic energy and potential energy.

A detailed discussion of the various forms of energy is far beyond the scope of this book. However, the important thing for you to remember is that there are various forms of energy which may be observed.

Transformation of energy. You already know that one kind or form of energy may be changed into another, though you have probably not thought much about the change. When mechanical kinetic energy is used to lift a weight, the energy is stored in the lifted weight as potential energy. When the lifted weight falls, its mechanical potential energy is changed back to kinetic energy. In Chapter 3 you learned that electrical energy can be changed into heat energy. Whenever a current flows through a wire, some heat is produced. The heating element in an electric toaster, iron, stove, or other heating device is a specially designed wire or rod that will change

---

Thermocouple: A loop made of two pieces of different metals joined together. If one of the joints is heated, an electric current will flow through the loop. Only a low voltage can be produced in this way, but good use is made of it in **pyrometers, thermopiles,** and alternating-current meters. A pyrometer is used to measure high temperatures in furnaces and ovens, where ordinary thermometers are not satisfactory. A thermopile is simply a number of thermocouples connected in series so as to increase the E.M.F. and thus the current. By means of a thermopile very sensitive scientific instruments can measure extremely small variations in temperature. Astronomers use thermopiles to measure the temperatures of the sun, moon, planets, and even stars billions of miles away from the earth. Thermocouples used in alternating-current meters will be discussed again in Chapter 11.

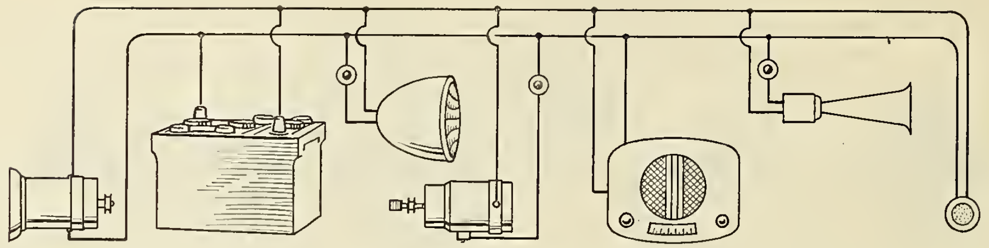
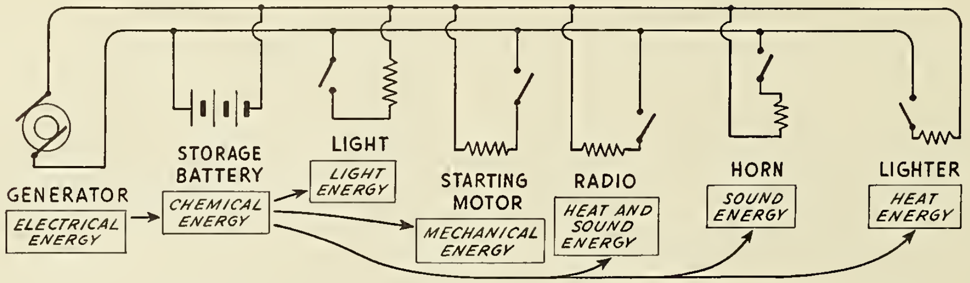


Figure 97. *The picture above shows some of the ways in which electrical energy is used in an automobile. In the diagram below, the electrical energy produced by the generator is stored in the battery as chemical energy. When the switch of an electrical device is closed, the battery transforms some of its stored chemical energy into electrical energy so that the device can produce light, motion, sound, or heat.*



a great deal of electrical energy into heat. You may be surprised to learn that heat can be changed into electrical energy by a device called a *thermocouple* (Figure 100). In Experiment 40 (page 200) you can make a thermocouple and use it to cause a current to flow.

An electric lamp changes electrical energy into light energy. Of course, most of the electrical energy is changed into heat, whether the lamp uses a filament or vapor to produce light. Light energy can be changed into electrical energy by means of a device called a *photoelectric cell,* or "electric eye," as shown in Figure 100. In Experiment 40 you can use a light meter, which is simply a photoelectric cell connected to a sensitive galvanometer. In Chapter 4 you learned that chemical energy stored in the electrodes and electrolyte of a cell is changed to electrical energy when the cell is used to supply current in a circuit. When a storage cell is charged, electrical energy is changed to chemical energy, which is stored in the electrodes and electrolyte until needed to produce a current. If you do Experiment 41, you can change electrical energy to chemical energy in electrolysis and electroplating.

Electrical energy may be used to produce magnetism, or magnetism may be used to produce electrical energy. In an electric bell or buzzer, telephone receiver, telegraph sounder, relay, or magnetic circuit breaker, electrical energy is changed into mechanical energy by using magnetism. The mechanical energy produced in an electric bell or buzzer, telephone receiver, and telegraph sounder is then changed into the form of energy we call sound. The first telephone transmitter was very much like the receiver; it changed sound energy into electrical energy by using magnetism. An electric motor changes electrical energy into mechanical energy by using magnetism, as you will see in Chapter 10. Mechanical energy is changed to electrical energy by using magnetism in a generator. You will see how this is done when you study Chapter 9. It is even possible to change mechanical energy directly into electrical energy by means of pressure on crystals, such as quartz. For example, the crystal pickup of an electric phonograph changes the mechanical energy of the moving needle into electrical energy without using magnetism. In a similar way, electrical energy can be changed directly to mechanical energy.

Not all transformations of energy are as simple as those mentioned. Sometimes many changes of energy take place in between. For example, a generator changes mechanical energy to electrical energy by means of magnetism. The mechanical energy is supplied in various ways: by water wheels or water turbines, by steam turbines, by gasoline or Diesel engines, and even by windmills. The energy of running water, expanding steam, exploding gas, or moving air is used to turn a wheel, which makes part of the generator revolve. As this part of the generator revolves, mechanical energy is changed to electrical energy by means of magnetism. But where does the energy of the water, steam, gas, or air come from? Strangely enough, the energy in all of them comes from the same place—the sun.

First let us see how running water gets its energy. Water in the oceans is warmed when it changes radiant energy from the sun into heat. Some of the water evaporates into the air. When the water vapor in the air is cooled, it falls to earth as rain or snow. Water from the rain or melted snow flows downhill on its way back to the oceans. The running water has energy that can be used to turn a wheel, which makes a generator revolve, thus producing electrical energy.

If the generator is run by steam, the steam is supplied by heating water in a boiler. To furnish the heat, a fuel such as coal or oil is burned. Burning the fuel changes the chemical energy stored in the fuel to heat energy. The heat changes the water to steam. When water becomes steam, it expands about 1600 times. The mechanical energy of the expanding steam then turns a turbine attached to a generator, thus producing electrical energy, as shown in Figure 96. The fuel used to produce the steam got its chemical energy from the sun millions of years ago. Coal was formed from plants, which use the sun's energy to grow and make food. Oil was formed from plants or from animals that ate plants. In either case, the energy stored in the fuel came from the sun.

When a Diesel engine is used to turn a generator, oil is also used as fuel. And when a gasoline engine is used, gasoline is the fuel; it is made from oil or sometimes coal. The moving air, or wind, that turns a windmill also gets its energy from the sun. Radiant energy from the sun is changed to heat by the earth. Different parts of the earth's surface are heated more than others. This unequal heating causes air currents that result in winds. Thus no matter which of the different ways is used to turn a generator, the energy comes originally from the sun.

Conservation of energy. For many years scientists have studied the transformation or conversion of energy from one form to another. They have concluded after extremely careful and accurate experiments that energy can be changed from one kind or form to another but that it is not ordinarily created or destroyed. Whenever one form or kind of energy appears, a certain amount of some other form or kind disappears. When a cell furnishes electrical energy, no new energy is created. Some chemical energy stored in the cell disappears when the electrical energy is

---

Photoelectric cell: There are several different types of photoelectric cells in common use. One type consists of a wire, plate, or other surface made of or covered with a light-sensitive metal or chemical compound in a glass bulb. The metal is usually caesium, potassium, sodium, or lithium. Most of the air may be removed from the bulb to form a partial vacuum, or gases such as neon, argon, or helium may be put in the bulb. Another type of cell uses selenium, a light-sensitive non-metal. When light falls on the light-sensitive material, electrons flow through the space in the bulb. This flow of electrons can be used to operate or control many kinds of electrical devices too numerous to mention here. Photoelectric cells are used in recording and reproducing sound in talking motion pictures, in television, in measuring light, in turning lights or machinery on and off automatically, in comparing colors, and in burglar and fire alarms—just to mention a few common uses.

Law of Conservation of Energy: Energy can be changed from one form or kind to another, but it cannot ordinarily be created or destroyed.

Force: A push or pull. The amount of force can be measured in pounds.

produced. For example, in a simple cell the zinc and sulphuric acid are used up. While the cell is operating, the electrolyte becomes warmer, although the heat is scarcely noticeable. Some heat energy is produced along with the electrical energy when the chemical energy is transformed. The amount of chemical energy that disappears is exactly equal to the electrical energy produced plus this heat energy. No energy is gained or lost in the transformation or conversion.

The fact that energy can be changed but not ordinarily created or destroyed is known as the **Law of Conservation of Energy**. It is one of the most important scientific laws because it explains so many different facts. For one thing, it explains why "perpetual motion" is impossible. You cannot get more energy out of a machine or other device than was put in. As a matter of fact, you cannot get out quite so much useful energy because some of the original energy is always changed into heat that cannot be used.

CHECKING WHAT YOU LEARNED

1. **a.** Tell what is meant by energy. **b.** Is energy the same as matter? Explain.
2. What are the different kinds of energy called? Give an example of each kind.
3. List as many forms of energy as you can and give an example of each one.
4. **a.** Into what forms of energy can electrical energy be changed? **b.** Tell how each change may be accomplished.
5. What forms of energy can be changed into electrical energy? Give an example for each form.
6. State the real source of the electrical energy furnished by a generator. Explain your answer.
7. What happens whenever a new form of energy appears? Explain.
8. State the Law of Conservation of Energy and tell what it means.

USING WHAT YOU LEARNED

1. What form (or forms) of energy is produced in each of the following? **a.** An electric iron, **b.** a mercury-vapor lamp, **c.** a circuit breaker, **d.** an electrically operated phonograph, **e.** a charging storage cell.
2. How does the electrical energy in a closed circuit differ from that in an open circuit?
3. Name the energy changes that take place when a generator is run by **a.** steam, **b.** water. Be sure to tell where the steam or water got its energy.
4. Why will an electrical device or appliance stop working if the current is turned off?

Force

Energy has already been defined as the ability to do work. But before you can understand the scientific meaning of work, you must know what is meant by a **force**. Let us start with some common examples. Every time you open a door, pick up a book, put your feet on the floor, or steer a car, you are using a force. If you will stop and think about what happens in each case, you will find that you do one of two things: You either push or pull some object. In steering a car you may do both if you pull on the steering wheel with

Matter and Energy: Scientists formerly thought that matter and energy were completely distinct. Now it appears that the sun's energy results from the destruction of matter in the sun. Under very special conditions matter may be changed into energy, or energy into matter.

one hand as you push on it with the other. Whenever you push or pull on something, you are using a force. Therefore, we can say that a force is a push or pull.

Whenever something moves, a force must be used to make it move. But a force can be used without causing anything to move, as when you push or pull some heavy object without being able to make it budge. Regardless of whether the object moves, you exert a force when you push or pull the object. The amount of force can be measured in pounds.

The examples given have to do with the force you exert with your muscles, but there are other forces in action around you at all times. You have probably felt the push of the wind against your body as you walked or the push of water if you tried to swim against the current of a stream. If you fall off a ladder or a chair, the force of gravity pulls you down. When you try to slide something across a floor, a force due to friction resists your efforts. If you try to break a piece of wood or separate glued papers, you must overcome the forces that hold materials together. Of one thing you can be sure: Whenever anything starts to move, it is pulled or pushed by some force.

In Chapter 2 you learned that like charges repel each other, while unlike charges attract each other. There is thus a force between electrical charges; for repulsion is a push, and attraction is a pull. The same thing is true of magnetic poles. Like poles repel, or push, each other, while unlike poles attract, or pull, each other. The poles of a magnet obviously exert a force. The force between electrical charges results in electromotive force, while the force between magnetic poles determines the magnetizing force, or field strength. You recall that a magnet seems to exert its force along invisible lines of force, which pull lengthwise and push sidewise. You also know that a current-carrying conductor is surrounded by lines of force. In the field of an electromagnet the lines of force are very close together; the result is a very strong field of force around the electromagnet. (If you do Experiment 42, you can measure the force exerted by a solenoid when a current flows through its coil.) In Chapter 7 you learned that an electromotive force is induced in a conductor when the conductor cuts lines of force. If the conductor forms part of a closed path, the induced electromotive force causes a current to flow.

The examples we have mentioned show what is meant by force. They also show that no force is exerted unless there is a source of energy. Electrons exist in all parts of a circuit, but they will not move around the circuit unless there is a source of energy to provide an electromotive force that will drive them around the circuit. A cell connected in the circuit supplies electrical energy by chemical action. There is a difference in electrical charge between the two electrodes of the cell. This difference in electrical charge, or potential difference, results in the electromotive force that drives current through the circuit against the resistance of the conductors in the circuit.

CHECKING WHAT YOU LEARNED

1. Tell what is meant by a force. Give at least three examples to show that you understand the meaning of force.
2. If an object does not move, are you sure that no force is being exerted on it? Explain.
3. Why is a source of electrical energy an essential part of every complete circuit?
4. What causes the electromotive force in a circuit that includes a cell?

USING WHAT YOU LEARNED

1. What force turns a compass needle so that it points as it does?
2. The paper insulation between tin foil strips in a condenser sometimes breaks down. Why does this happen?
3. Resistance is sometimes called electrical friction. Do you think that this is a good name for resistance? Explain your answer.
4. How do you know that a magnet has energy?

Work

When a force accomplishes something, we say that **work** is done. Or as scientists put it, when a force moves something through a distance and overcomes a resistance, work is done. You might struggle for an hour and be all tired out from trying to move a big rock, but a scientist would say that you had done no work, because the rock was not moved. However, if you brushed a leaf

Work: The use of a force to overcome a resistance and thus move something through a distance. The amount of work done can be measured in foot-pounds.

Foot-pound: A unit for measuring work. When a force of one pound moves an object through a distance of one foot in the direction of the force, one foot-pound of work is done. Often abbreviated **ft.-lb.**

Efficiency: The ratio of the work out to the work in. It is usually shown as a percentage for a machine or other device. $\text{Efficiency } (\%) = \frac{\text{Work out}}{\text{Work in}} \times 100$

or feather aside, the scientist would say that you had done some work, because the leaf or feather moved. Whenever you lift a book, pedal a bicycle, push a lawn mower, or climb stairs, you are doing work. In each case, you exert a force and something moves. Work is done when a force is used to overcome a resistance and thus move something through a distance.

So far nothing has been said about *how much* work is done. In other words, we need some unit of measurement to tell how much work is done under certain conditions. Force can be measured in pounds. If a stone weighs 10 pounds, you must use a force of 10 pounds to lift it. According to the definition of work, a force must move something or act through a distance. Distance can be measured in feet. Therefore, a convenient way to measure the amount of work done is to multiply the distance in feet by the force in pounds. The unit used to measure work in this way is appropriately called the **foot-pound.** If a force of one pound is used to move an object through a distance of one foot in the direction of the force, one foot-pound of work is done. When a stone weighing 10 pounds is lifted to a height of 3 feet, the work done is found by multiplying the distance by the force, or 3 feet × 10 pounds = 30 foot-pounds. This may be stated as a formula:

$$\textbf{Work} \text{ (ft.-lb.)} = \textbf{Distance} \text{ (ft.)} \times \textbf{Force} \text{ (lb.)}$$

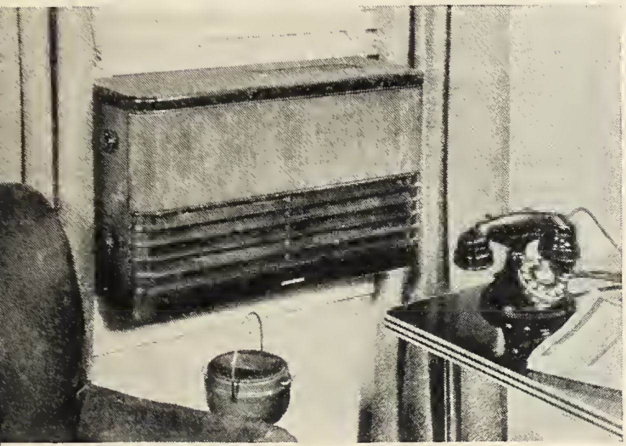
The speed at which the object is moved does not affect the use of the formula. If a man weighing 200 pounds runs up a stairway 30 feet high or walks up slowly to the same height, the amount of useful work done is the same in either case. Of course, he may feel more tired if he runs upstairs instead of walking, but the amount of useful work done does not change. Through a distance of 30 feet 200 pounds are lifted. Work = 30 feet × 200 pounds, or 6000 foot-pounds. The man thus did 6000 foot-pounds of useful work in going upstairs. Actually, he did more work than that, because he became very warm and probably did a lot of puffing and blowing, especially if he ran upstairs. He used up energy that did not help in lifting his body upstairs. In other words, the man was not particularly efficient.

When scientists talk about **efficiency,** they mean the ratio of the useful work got out to the work put in, or as they usually say, the ratio of the *work out* to the *work in.* Efficiency is calculated by dividing work out by work in and then multiplying by 100 to change to per cent. This method of calculating efficiency can be shown in a formula as follows:

$$\text{Efficiency } (\%) = \frac{\text{Work out}}{\text{Work in}} \times 100$$

Of course, you know that you cannot get more work out of a machine or device than you put into it. Actually, you never get quite so much out as you put in, because there are various losses from heat. You recall that an incandescent lamp at best changes about 5 per cent of the electrical energy it uses into light; the other 95 per cent is wasted as heat. A storage battery gives back only part of the energy used to charge it; for example, a lead-acid battery is about 75 to 85 per cent efficient. If 100 units of work are put into a device and only 85 units of work are got out, the device is 85 per cent efficient, since 85 divided by 100 equals .85, or 85 per cent. Efficiency is always less than 100 per cent.

Energy cannot be measured directly; we can only measure the work it does or the work re-



Electrical energy is used in many interesting ways. For example, it melts metals in the small laboratory furnace shown at the upper left. It lifts scrap metal from freight cars by means of powerful overhead cranes and electromagnets, as at the upper right. It heats or cools the air passing through the air conditioner in the office window at the left. And as shown below, it scoops up dirt—thirty yards of it at a bite—with an enormous dipper that is raised, lowered, and swung by means of five motors totaling 875 horsepower.

Power: The rate of doing work or expending energy. $\text{Power} = \frac{\text{Work}}{\text{Time}}$ or $P = \frac{W}{t}$

quired to produce it. This situation causes no difficulty, because work and energy are really two different ways of thinking about the same thing. We never have one without the other. To produce energy, work must be done. Whenever work is done, energy is expended. Work is simply energy in use. Electrical energy does work when it heats a toaster, lights a lamp, rings a bell, magnetizes a piece of iron, charges a storage battery, or induces a current. Since a force must move something through a distance and overcome a resistance in order to do work, you can see that kinetic energy is the only kind that actually does work. Potential energy must first be changed to kinetic energy before it can do work.

CHECKING WHAT YOU LEARNED

1. **a.** Explain what is meant by work. **b.** In what unit is work measured?
2. If you hold a 25-pound weight 2 feet above the ground, how much work are you doing? Why?
3. **a.** A 60-pound weight is raised 20 feet in 10 seconds. How much work is done? **b.** The same weight is lifted to the same height in 5 seconds. How much work is done? **c.** Explain your answers.
4. **a.** What is efficiency? **b.** A water-driven turbine connected to a generator has an efficiency of 80 per cent. Explain what this means.

USING WHAT YOU LEARNED

1. Which one does the greater amount of work: a man who lifts ten 100-pound weights in five minutes or a man who lifts twenty 50-pound weights in ten minutes? Why?
2. Make up a problem to show that you understand the meaning of foot-pound.
3. A 75-pound weight is raised 6 feet. **a.** How much work is done in raising the weight? **b.** How much work can the weight do when it falls 6 feet?
4. If 16 foot-pounds of useful work are obtained from a device, into which 40 foot-pounds of work were put, what is the efficiency of the device? Explain your answer.

Power

We often use the word *power* without any exact idea of what we mean. For example, we speak of water power or of getting power from an engine. Used in this way, power means about the same thing as mechanical energy or kinetic energy. When we say that more power is needed to move a heavy object than to move a lighter one, we are using power to mean about the same thing as force. But power, like work, has a different meaning to scientists and engineers. In order to understand the scientific meaning of power, let us go back to the man climbing the stairs.

According to the work formula, a 200-pound man who climbs to a height of 30 feet does 6000 foot-pounds of useful work. No matter whether he walks or runs upstairs, the amount of useful work done is the same. But we know that the time he takes to reach the top does make some difference. If he runs up the steps two at a time and gets to the top in one minute, he may be completely exhausted. On the other hand, if he takes it easy, one step at a time, he may need three minutes to reach the top. To do the same amount of work in one minute as done in three minutes, the man must expend, or use, his energy three times as fast. In other words, his rate of working must be three times as fast as when he takes three minutes to do the work. The rate of doing work or expending energy is called **power.** The formula for power is as follows:

$$\text{Power} = \frac{\text{Work}}{\text{Time}} \quad \text{or} \quad P = \frac{W}{t}$$

The man going upstairs has done 6000 foot-pounds of useful work when he reaches the top.

Horsepower: A unit for measuring power. It is equal to 33,000 foot-pounds per minute, or 550 foot-pounds per second. Often abbreviated **H.P.**

$$\text{Horsepower} = \frac{\text{Foot-pounds per min.}}{33{,}000} = \frac{\text{Foot-pounds per sec.}}{550}$$

Watt: A unit for measuring power, especially electric power. One watt is the power of a current of one ampere flowing under a pressure of one volt. A watt is also equal to about 44 foot-pounds per minute.

$$\text{Watts} = \text{Volts} \times \text{Amperes} \quad \text{or} \quad P = EI \qquad 746 \text{ watts} = 1 \text{ horsepower}$$

Kilowatt: A unit for measuring power equal to 1000 watts. Often abbreviated **Kw.**

$$\text{Kilowatts} = \frac{\text{Watts}}{1000} \qquad 1 \text{ kilowatt} = 1.34 \text{ horsepower}$$

If it takes him one minute, the power needed is 6000 foot-pounds divided by 1 minute, or 6000 foot-pounds *per minute*. But if he takes three minutes, the power required is 6000 foot-pounds divided by 3 minutes, or 2000 foot-pounds *per minute*. Since power is the rate of doing work or expending energy, it must be stated in terms of so much work in a certain time, that is, a certain number of foot-pounds in a minute or a second.

Power can be measured in a unit called the **horsepower.** One horsepower is equal to 33,000 foot-pounds per minute, or 550 foot-pounds per second, which amounts to the same thing (33,000 ft.-lb. ÷ 60 sec. = 550 ft.-lb. per sec.). The term was first used by James Watt, a British engineer, who wanted to sell his new steam engine to the mine owners in England. Since horses were used to run the pumps in the mines and do other work, Watt needed some way to show how many horses his steam engine would replace. He calculated the amount of work that a strong horse could do in one minute if it worked at an average rate. The result of his calculations is the unit called the horsepower, which has been in common use for measuring power ever since Watt's day. We can apply this unit to the man climbing the stairs. If he works at the rate of 6000 foot-pounds per minute, he delivers about .18 horsepower (6000 ft.-lb. per min. ÷ 33,000 ft.-lb. per min.). If he works at the rate of 2000 foot-pounds per minute, he delivers about .06 horsepower (2000 ft.-lb. per min. ÷ 33,000 ft.-lb. per min.).

If you examine an electrical device, such as a light bulb, toaster, iron, or motor, you may find a label indicating the voltage required to operate the device properly and also the power needed. The label on an electric light bulb may read "110 volts, 60 watts." There are other sizes of 110-volt bulbs, such as 7 watts, 15 watts, 25 watts, 40 watts, 100 watts, and so on; but the bulb of 60 watts is probably commonest. The label on an electric toaster may indicate 110 volts, 600 watts, while that on an electric iron may show 110 volts, 1000 watts. The number of watts marked on the label tells how fast the device or appliance uses electrical energy. Is there any connection between watts and volts?

When scientists selected the various electrical units of measurement, they deliberately planned a convenient relation between them. As you know, the formulas of Ohm's Law express the relation between rate of current flow, pressure, and resistance. A similar relation exists between power, pressure, and rate of current flow. One **watt** is the power of a current of one ampere flowing under a pressure of one volt. The power in watts of any electrical device using energy or doing work is found by multiplying the pressure in volts by the current in amperes. Expressed as a formula, this relation is as follows:

$$\text{Watts} = \text{Volts} \times \text{Amperes} \quad \text{or} \quad P = EI$$

If 5 amperes of current flow through an electric toaster at a pressure of 110 volts, the toaster uses

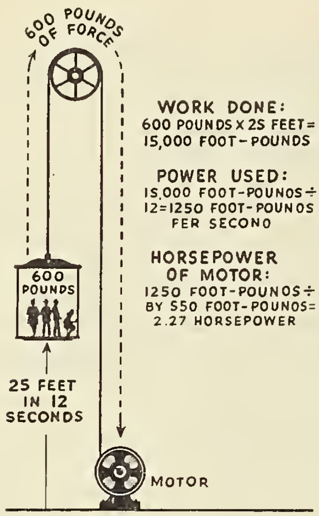
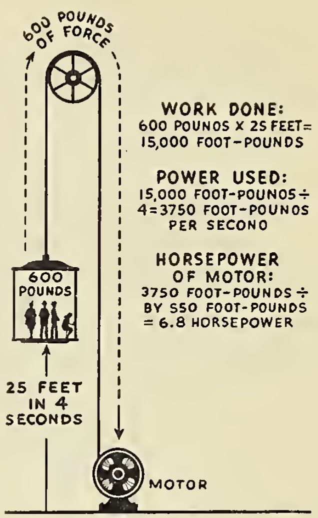


Figure 98 *will help you remember the relationship between force and work and power. In both diagrams the force needed to raise the elevator is the same; and since the distance in each case is the same, equal amounts of work have been done. At the right, however, where the work was done in one third the time, three times as much power was required to do the same amount of work as at the left.*



electrical energy at a rate of 550 watts (110 volts × 5 amperes). The power required to operate the toaster at 110 volts is thus 550 watts. In Experiment 43 you can find the wattage of light bulbs.

When you know the relation between power, pressure, and rate of current flow, you can solve other types of problems. Just as with the Ohm's Law formulas, if you know any two of the elements, you can always find the other. For example, a large light bulb is labeled 110 volts, 300 watts. How many amperes of current flow through the bulb when it is lighted? Using the formula $P = EI$, we substitute 300 for P and 110 for E: $300 = 110 \times I$

Dividing both sides of the equation by 110 and canceling, we get

$$\frac{300}{110} = I \quad \text{or} \quad I = 2.7 \text{ amperes}$$

Of course, the formula can also be used to find the pressure in volts if the power in watts and the current are known.

One watt is equal to about 44 foot-pounds per minute. Since the watt is such a small unit, a larger unit of power called the **kilowatt** is sometimes more convenient to use. One kilowatt equals 1000 watts. The power of electric motors is often stated in horsepower; therefore, it is sometimes necessary to change horsepower to watts or kilowatts in order to use the formula: $P = EI$. One kilowatt equals 1.34 horsepower (a little more than 1⅓ horsepower). One horsepower equals 746 watts, or .746 kilowatt (a little less than ¾ kilowatt).

CHECKING WHAT YOU LEARNED

1. What is the scientific meaning of power?
2. **a.** Name the units in which power is measured. **b.** State the relationship between the various units.
3. How can you find the power required by an electrical device?
4. What is the difference in the rate of using energy between a 500-watt electric iron and a 1000-watt electric iron?

USING WHAT YOU LEARNED

1. A 3-volt flashlight bulb draws .5 ampere. How much power is required to operate it properly?
2. How many watts are needed to run a ¼-horsepower electric motor? How many kilowatts?
3. A current of 4.5 amperes at 110 volts flows through an arc lamp. At what rate does the lamp use electrical energy?
4. A 6-volt automobile headlight bulb requires 24 watts. How much current flows through the bulb when it is lighted?
5. **a.** How much current flows through a 60-watt light bulb operated at 110 volts? **b.** What is the resistance of the bulb when it is lighted?

Watt-hour: A unit for measuring electrical energy or the work done by electrical energy. One watt-hour equals one watt for one hour. Often abbreviated **Wh.**

$$\text{Watt-hours} = \text{Watts} \times \text{Hours} \quad \text{or} \quad Wh = Pt = EIt \qquad (t \text{ is the time in hours.})$$

Kilowatt-hour: A unit for measuring electrical energy or the work done by electrical energy. One kilowatt-hour equals 1000 watt-hours. Often abbreviated **Kwh.**

$$\text{Kilowatt-hours} = \frac{\text{Watt-hours}}{1000} = \text{Kilowatts} \times \text{hours} \quad \text{or} \quad Kwh = \frac{Wh}{1000} = Kwt$$

(t is the time in hours.)

6. An electric toaster has a resistance of 22 ohms. How many watts are required to operate the toaster at a pressure of 110 volts?
7. How many 100-watt bulbs can be connected in parallel in a 110-volt lighting circuit without melting the 15-ampere fuse? Explain your answer.
8. If the resistance of a circuit is increased or the voltage is decreased, what happens to the current and the power? Why?

Work Done by Electrical Energy

Electrical energy is measured and also sold by the **kilowatt-hour.** One kilowatt-hour is equal to 1000 **watt-hours.** A watt-hour is the amount of energy used at the rate of one watt for one hour. For example, a 60-watt light bulb uses 60 watt-hours of energy in one hour. In 24 hours it will use 1440 watt-hours (24 × 60), or 1.44 kilowatt-hours. If electrical energy costs 6 cents a kilowatt-hour, the cost of using a 60-watt light bulb for 24 hours is 8.64 cents (1.44 × 6). Since energy and work are measured in the same units, the watt-hour and, more commonly, the kilowatt-hour are also used to measure the work done by electrical energy.

Losses and efficiency. The efficiency of an electrical device is found in the same way that efficiency is usually calculated: The work out is divided by the work in, and the result is multiplied by 100 to change to per cent. Work done by electrical energy is measured in watt-hours (or kilowatt-hours). When watt-hours out are divided by watt-hours in, the hours cancel out. Therefore, the efficiency of an electrical device can be determined by dividing the watts out by the watts in. The formula is as follows:

$$\text{Efficiency } (\%) = \frac{\text{Watts out}}{\text{Watts in}} \times 100$$

As you know, machines and other devices do not give out as much useful energy as is supplied to them. In other words, their efficiency is always less than 100 per cent. Even in such a simple device as a wheel, some of the energy furnished is wasted by friction. Part of the energy put in is changed into an unwanted kind of energy, usually heat. In an incandescent bulb, at least 95 per cent of the electrical energy is transformed into heat; the remaining 5 per cent or less is changed into light. In all electrical devices there are similar losses, though the losses may not be so great. Since most of the wasted energy is changed into heat, the losses are called *heat losses.* There are two main kinds of heat losses: losses due to resistance and losses due to induction.

Losses due to resistance. The amount of power lost as the result of heating due to resistance can be calculated for a circuit or any part of a circuit if the resistance and rate of current flow are known. A formula for this calculation can easily be worked out from the power formula $P = EI$ and the Ohm's Law formula $E = IR$. If IR is substituted for E in the power formula, the result is $P = IR \times I$ or $P = I^2R$. This is the formula for the **power loss.** If we want to find the **energy loss,** we multiply the power loss by the time just as we multiply power by time to get the energy used or the work done. The energy loss is $Wh = Pt = I^2Rt$. From Chapter 3 you recall that heat produced by an electric current doubled

Losses due to resistance: The **power loss** is equal to the square of the current multiplied by the resistance. $P = I^2R$ The **energy loss** is equal to the power loss multiplied by the time. $Wh = Pt = I^2Rt$ (**t** is the time in hours.)

if the resistance was doubled but quadrupled if the current was doubled. The formula for the heat in calories produced by a current is therefore $H = .24\ I^2Rt$, in which I^2R is the same as in the formulas for power loss and energy loss.

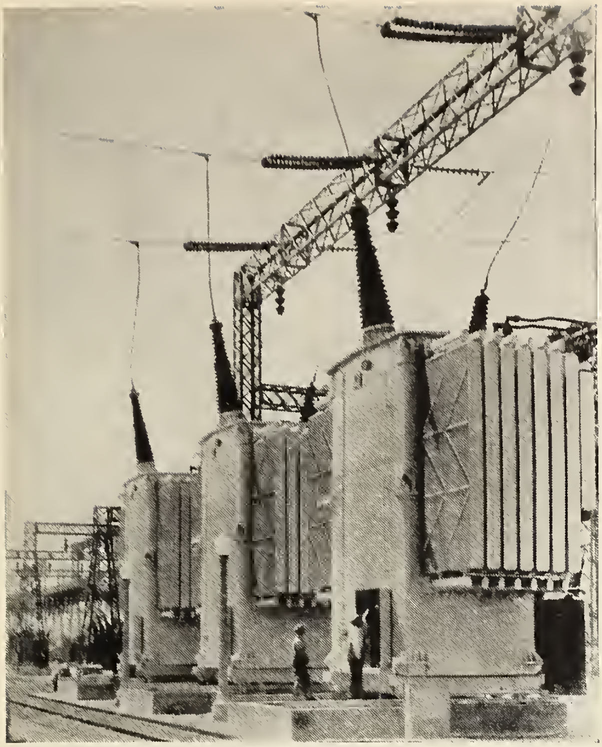
When an electric motor is used, there is loss of power and also energy. The motor will not deliver as much power as was put into it. Suppose that the power input of a large motor is 40 kilowatts, while the power output is only 30 kilowatts. What becomes of the other 10 kilowatts of power? The motor and connecting wires offer resistance to the flow of current. According to the formula $P = I^2R$, a certain number of watts is lost as a result of the resistance of the circuit. This is the power loss. The energy lost appears in the conductors as heat, which is wasted. In addition to the losses due to resistance, there is a loss caused by friction between the moving parts of the motor. This loss reduces the power still more by wasting more energy as heat. In the motor, 10 kilowatts of power are lost as a result of resistance and friction. The efficiency of the motor can be calculated as follows:

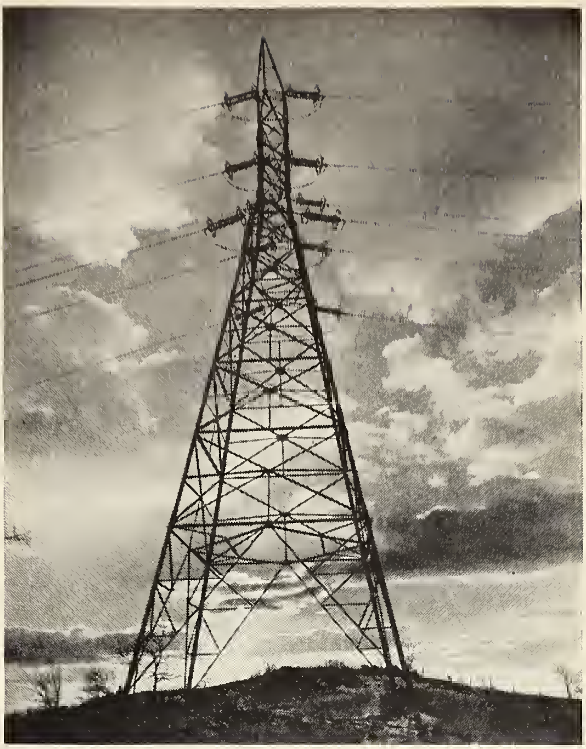
$$\text{Efficiency} = \frac{\text{30 kilowatts out}}{\text{40 kilowatts in}} \times 100 = 75\%$$

Losses due to induction. Besides the losses due to resistance, there are likely to be losses due to induction in certain kinds of electrical devices. When a conductor in a closed circuit cuts lines of force, an induced E.M.F. makes a current flow through the conductor. In transformers, induction coils, generators, and motors, a path for the useful induced current is provided by copper conductors. These electrical devices operated by induction have cores made of iron or some other magnetic substance, and the cores are also conductors. A current is induced not only in the copper conductors around the core but also in the core itself. Such a current induced in a core or other conductor that is not part of the circuit is called an *eddy current,* or *Foucault current.*

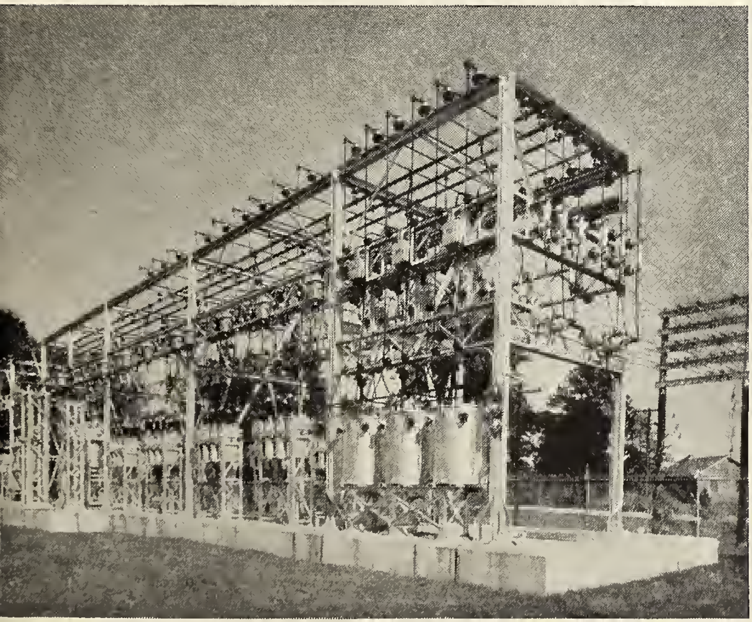
Eddy currents heat the cores and, in motors and generators, act as a brake on the moving parts. To reduce these wasteful eddy currents, the cores of induction coils are made of iron wires tied together in a bundle instead of being made of solid pieces. For the same reason, transformer cores are made up of thin sheets of special steel, called *laminations.* The armature cores of generators and motors are often made in a similar way from thin sheets of iron or steel bolted together to make a solid piece. The wires or metal sheets are insulated from one another by a coating of shellac, enamel, or other insulating material. This insulation cuts across the path in which the eddy currents flow and thus greatly reduces them. Because of the insulation between wires or sheets, the eddy currents are deprived of a closed path in which to flow all around the core.

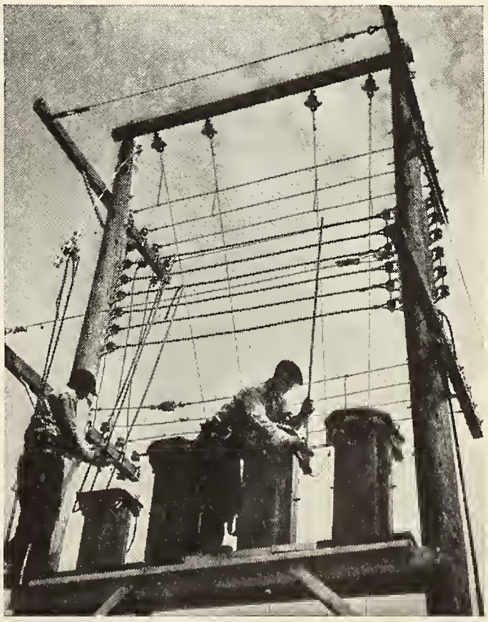
Magnetic speedometer. Sometimes eddy currents are put to good use. For example, one type of automobile speedometer operates by means of eddy currents. A permanent magnet is attached to a flexible shaft connected to one wheel or the drive shaft of the car, so that it revolves when the wheel or shaft turns. The magnet is placed inside a drum, usually made of aluminum. The drum is delicately balanced so that it can turn in the same direction as the revolving magnet. The speed of the car determines the speed of the revolving magnet. As the magnet turns, it sets up eddy currents in the drum. These induced currents produce a magnetic field that tries to oppose the moving field of the revolving magnet. As a result of the magnetic "drag," the drum moves. The faster the magnet revolves, the stronger the eddy currents and the magnetic field they set up, and the farther the drum moves against the opposition of a spring that pushes it back. A pointer attached to the drum indicates





Whether produced by steam or water power, electrical energy from big generators, such as those shown at the beginning of this chapter, is seldom of high enough voltage for transmission. Hence, large transformers like those at the upper left increase the voltage many times. From these transformers electrical energy travels for miles across country over wires supported by high transmission towers, as shown at the upper right. Near a city, however, other large transformers in a sub-station such as that at the lower left reduce the voltage to about 2200 before the electrical energy is sent through the city to transformers like those the men are installing at the lower right in the neighborhood of homes or factories, where the electrical energy is changed into other forms of energy.





the speed on a dial. Another practical use of eddy currents in certain types of electrical meters will be discussed in Chapter 11.

In addition to the loss caused by eddy currents, there is another loss in electrical devices operated by induction. Magnetic substances have reluctance; in other words, they resist magnetization. They also have retentivity; that is, they resist a loss of magnetization. Energy is required to magnetize a magnetic substance and also to demagnetize it. Induction-operated electrical devices contain electromagnets. The cores of the magnets are magnetized and then demagnetized. If an alternating current is used, as in a transformer, the core may be magnetized, demagnetized, then magnetized in the opposite direction, and so on, many times each second. As a result, the core becomes heated. Electrical energy is changed into heat and thus wasted. Iron and certain special steels are used for cores, because they have low reluctance and low retentivity. Comparatively little energy is lost in magnetizing or demagnetizing cores made of these substances.

With the exception of electric lights, electrical devices are very efficient compared with most other devices. A steam engine wastes at least 80 per cent of the energy in the fuel used to operate it. A steam turbine is less than 30 per cent efficient. Gasoline engines are about 30 per cent efficient, while Diesel engines are somewhat less than 40 per cent efficient. Small electric motors have an efficiency of from 35 to 60 per cent, while larger motors may be from 75 to 95 per cent efficient. Generators have about the same efficiency as motors, depending on their sizes. Even electric cells are fairly efficient sources of energy.

CHECKING WHAT YOU LEARNED

1. What is a watt-hour? A kilowatt-hour?
2. How is the efficiency of an electrical device calculated?
3. Why is the efficiency of an electrical device always less than 100 per cent?
4. **a.** In order to calculate the power loss in a circuit, what must you know? **b.** How is the energy loss in a circuit calculated?
5. What are the two main kinds of losses in electrical devices or circuits? Give an example of each kind.
6. Are eddy currents induced only in magnetic substances? Explain.

USING WHAT YOU LEARNED

1. A 1000-watt electric iron was used for three and one-half hours. How many watt-hours of electrical energy did the iron use? How many kilowatt-hours?
2. **a.** A 600-watt electric toaster is used for 15 minutes. How many kilowatt-hours of electrical energy does it use? **b.** If electrical energy costs 6 cents a kilowatt-hour, how much does it cost to use the toaster?
3. Six 110-volt bulbs, each drawing .5 ampere, are used to light a room for three hours. How many kilowatt-hours of electrical energy are used?
4. When all its heating elements are turned on, an electric stove for use at 220 volts has a resistance of 11 ohms. How many kilowatt-hours of electrical energy does the stove use in one and one-half hours?
5. A current of 2 amperes flows through a circuit including a 6-ohm resistor for one-half hour. **a.** What is the power loss due to the resistor? **b.** What is the energy loss?
6. If you know the voltage drop and the current through an electrical device, how can you find the power loss due to the device? Give an example to illustrate your answer.

Transmission of Electrical Energy

In transmitting electrical energy, losses become extremely important. The power available in a direct-current circuit is equal to the voltage multiplied by the amperage, or $P = EI$. The power loss, on the other hand, is equal to the square of the current multiplied by the resistance, or $P = I^2R$. When electrical energy is transmitted over long distances, it is desirable to keep the resistance of the connecting wires small; but it is even more important to keep the current as small as possible. As you can see from the power-loss formula, an increase in resistance or current will cause an increase in the loss of power. However, an increase in the current causes a much greater loss, because in the formula the current is squared (multiplied by itself).

In order to understand what this means, let us see what the power loss in a circuit is when a current of 2 amperes at a pressure of 100 volts is sent through connecting wires having a resistance of 4

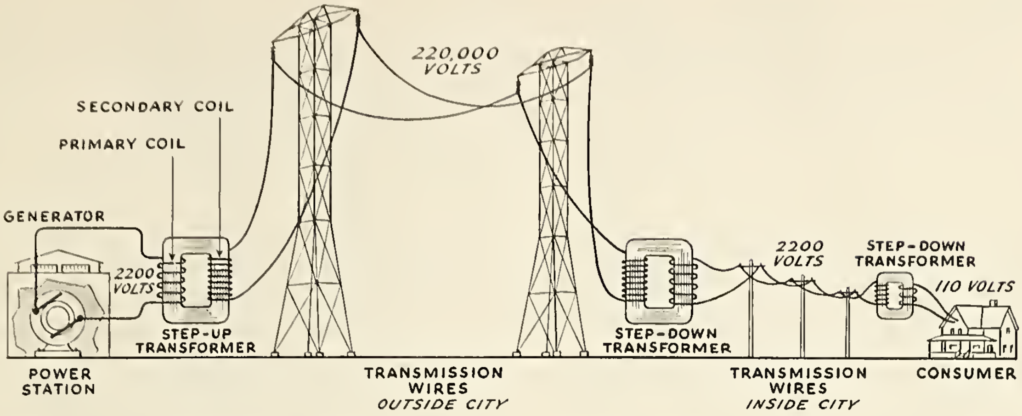


Figure 99. *This simplified diagram shows how electrical energy is carried for long distances by transmission wires. Notice that high voltages are used as much as possible in order to keep the power loss at a minimum. As the step-up transformer increases the generator voltage to one hundred times as much, the current is correspondingly reduced, so that the power loss is decreased to one ten-thousandth.*

ohms. (About 1600 feet of No. 14 copper wire has this resistance.) From the formula $P = EI$ we can calculate the power input. Substituting 100 for E and 2 for I, we get $P = 100 \times 2$, or **200 watts.** The power loss in the connecting wires can be calculated by using the power-loss formula. Substituting 2 for I and 4 for R, we get $P = 2 \times 2 \times 4$, or **16 watts.** Of the original power input of 200 watts, only 184 watts remain (200 − 16). The other 16 watts of power are lost due to the resistance of the connecting wires.

Now suppose that we transmit electrical energy at the same rate of 200 watts through the same wires but increase the pressure to 1000 volts. Using the formula $P = EI$, we substitute for P and E to find I.

$$P = EI \quad 200 = 1000 \times I$$

$$\frac{200}{1000} = I \quad \text{or} \quad I = .2 \text{ ampere}$$

Decreasing the current reduces the power loss. Using the power loss formula, we find that the power loss is now only .16 watt ($P = I^2R = .2 \times .2 \times 4 = .16$ **watt**). Of the original power input of 200 watts, 199.84 watts now remain. By using ten times as much voltage, electrical energy can be transmitted at the same power with one tenth as much current. As a result, the power loss is only one hundredth of the power loss when the lower voltage and larger current are used.

When electrical energy is transmitted over long distances, high voltage and low amperage are used to keep the power loss as small as possible. Generators ordinarily do not furnish current at a high enough voltage for efficient transmission. But if a step-up transformer is connected to a generator that furnishes alternating current, the voltage can easily be increased. As you know, the increase in voltage depends on the voltage-turns ratio of the transformer. If a step-up transformer has a voltage-turns ratio of 10 to 1, the secondary voltage will be ten times the primary voltage. However, the current supplied by the secondary is only one tenth as large as that in the primary. From the Law of Conservation of Energy, you know that no more work can be obtained from a device than was put into it. The power output of a transformer cannot be greater than the power input. Although well-designed transformers are extremely efficient devices, losses due to resistance and induction keep them from being 100 per cent efficient. These losses are usually small compared with those in other electrical devices. Well-designed transformers operated under the proper

Wattage output and wattage input of transformers: The power in watts in the secondary of a transformer is equal to the power in watts in the primary (less the losses in power due to resistance and induction). **Watts output = Watts input**

conditions may be from 93 to 98 per cent efficient. In other words, only from 2 to 7 per cent of the **wattage input** is lost; the **wattage output** is thus very high. In Experiment 44 you can determine the efficiency of transformers.

In order to understand the relation of wattage output to wattage input, let us see what happens in a step-up transformer with a voltage-turns ratio of 10 to 1. (We will ignore the transformer losses, because they are so small.) If the primary voltage is 100, we know from the voltage-turns ratio that the secondary voltage will be ten times as great as the primary voltage, or 1000 volts. If a current of 20 amperes flows through the primary, the wattage input of the transformer is 2000 watts (100×20). The formula for wattage output and wattage input is as follows:

$$\text{Watts output} = \text{Watts input}$$

We can find the current supplied by the secondary by using the formula $P = EI$. Substituting 2000 for P and 1000 for E, we can find I.

$$2000 = 1000 \times I \quad \text{or} \quad I = 2 \text{ amperes}$$

The secondary current of 2 amperes is only one tenth as large as the primary current of 20 amperes. Thus you can see that while the step-up transformer increases the voltage in the secondary, the current in the secondary is reduced. As you might suppose, just the opposite thing takes place in a step-down transformer. The secondary voltage decreases, but the secondary current increases. With either kind of transformer, the relation of wattage output to wattage input determines the current that can be supplied at the voltage of the secondary.

Both step-up and step-down transformers are used in the transmission of electrical energy. A step-up transformer increases the voltage of the alternating current produced, as shown in Figure 99. The high-voltage current is carried by the transmission lines to the outskirts of a city. Here a step-down transformer decreases the voltage so that the current can be safely transmitted through the lines within the city. Another step-down transformer on a pole near your home reduces the voltage still further so that the current can be safely used inside the house or other building. An alternating current at about 110 volts is usually supplied to homes, although 220-volt alternating current is ordinarily provided in a special circuit if an electric stove is used. The transmission lines connected to the pole transformer usually furnish current at about 2200 volts, while the transmission lines outside a city may carry alternating

Impedance is the total opposition to the flow of an alternating current. Impedance (**Z**) is made up of ordinary resistance (**R**) and what is called **reactance** (**X**). $Z = \sqrt{R^2 + X^2}$

Reactance is the opposition to the flow of an alternating current, caused by capacity and inductance in a circuit.

Power factor: The power of an alternating current is not quite the same as that of a direct current if there is reactance in the circuit. To use the formula for power in alternating-current circuits, a correction must be applied. This correction is called the **power factor.** The formula for power in alternating current is as follows: $P = EI \times \text{power factor}$

Since each alternating-current circuit has its own power factor, the apparent power is sometimes indicated on alternating-current devices in **volt-amperes** or **kilovolt-amperes** (often abbreviated **Kva**) instead of **watts** or **kilowatts.** In a direct-current circuit, a volt-ampere is the same as a watt, and a kilovolt-ampere is the same as a kilowatt.

current at 220,000 volts or even more. By the use of such high voltages, the power loss may be kept very low.

Step-up transformers make possible the high voltages used in long-distance transmission of electrical energy, while step-down transformers reduce the high voltages so that we can use the current at a lower, safer pressure. Of course, transformers operate only on alternating current. Since they do not work on direct current, alternating current is always used whenever electrical energy must be transmitted over long distances. For most purposes, alternating current is just as satisfactory as direct current. Since it can be transmitted more efficiently than direct current, alternating current is ordinarily used when electrical energy is supplied by generators. However, alternating current has certain peculiarities. Some of the formulas you have learned for direct current must be changed somewhat before they can be applied to alternating current. For example, when Ohm's Law is applied to alternating-current circuits, the symbol **R** is no longer used to show opposition to current flow in ohms; instead, the symbol **Z**, standing for what is known as *impedance*, is used. Like resistance, impedance is measured in ohms. Its effect on the current is similar to that of resistance. It includes the opposition to current flow resulting from resistance and also the opposition resulting from inductance and capacity. A detailed discussion of impedance is beyond the scope of this book.

CHECKING WHAT YOU LEARNED

1. Why is the voltage increased while the amperage is decreased when electrical energy is transmitted over long distances?
2. When a step-up transformer is used to increase the voltage, what happens to the current? Explain.
3. Tell why step-down transformers are used in the transmission of electrical energy.
4. Transmission lines ordinarily carry alternating current. Explain why this is done.

USING WHAT YOU LEARNED

1. What is the wattage output of a transformer that is 95% efficient if the input is 20,000 watts?
2. A step-up transformer has a voltage-turns ratio of 20 to 1. If a current of 10 amperes at 110 volts flows through the primary, what are the amperage and voltage of the secondary? (Neglect losses.)
3. A 220-volt alternating current is supplied by a 6600-watt step-down transformer whose voltage-turns ratio is 1 to 10. What are the amperage and voltage of the primary? (Neglect losses.)
4. The connecting wires in a circuit have a resistance of 2 ohms, and a current of 15 amperes flows through the circuit. **a.** What is the power? **b.** The power loss in the connecting wires? **c.** How much power is left after the loss?

THINKING OVER WHAT YOU LEARNED

1. After each topic of this chapter write down in complete sentences the big ideas or principles you learned. Be sure to give only the big ideas or principles.
2. By using a definition or sentence, show that you understand the following: **a.** horsepower, **b.** eddy current, **c.** foot-pound, **d.** efficiency, **e.** kilowatt-hour, **f.** potential energy, **g.** watt, **h.** heat losses, **i.** kilowatt, **j.** work in, **k.** power loss, **l.** thermocouple, **m.** watt-hour, **n.** energy loss, **o.** photoelectric cell, **p.** kinetic energy, **q.** work out.

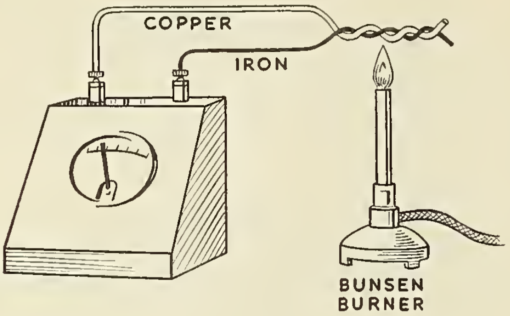
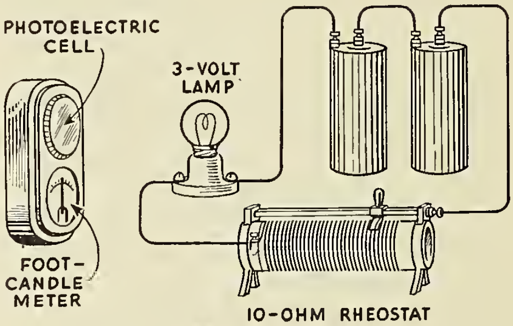


Figure 100. *Experiment 40 shows two ways in which heat and light energy can be transformed directly into electrical energy. At the left is a thermocouple made by twisting together a piece of copper wire and a piece of iron wire as shown. When the twisted joint is heated, the galvanometer indicates that an electric current is flowing in the circuit.*



The foot-candle meter shown at the right indicates the intensity of light by means of a photoelectric cell and a sensitive meter with a special scale. As the rheostat handle is moved so that the small lamp increases in brilliance, the photoelectric cell transforms more light energy directly into electrical energy, and the meter needle moves upward.

Experiment 40: **Thermocouple and Photoelectric Cell**

THINGS NEEDED: Pieces of copper and iron wire about 1 foot long. Galvanometer. Bunsen burner or other source of heat. Light (or exposure) meter. 3-volt bulb and socket. 10-ohm rheostat. Two No. 6 dry cells. No. 18 insulated copper wire.

WHAT TO DO: **a.** (See Fig. 100.) Connect a copper wire to one terminal of a galvanometer and an iron wire to the other. Twist the loose ends of the wires together. Then heat the twisted joint with a Bunsen burner or other source of heat. What happens to the galvanometer needle? Reverse the connections on the galvanometer and heat the joint again. What happens now? Can heat be changed into electrical energy?

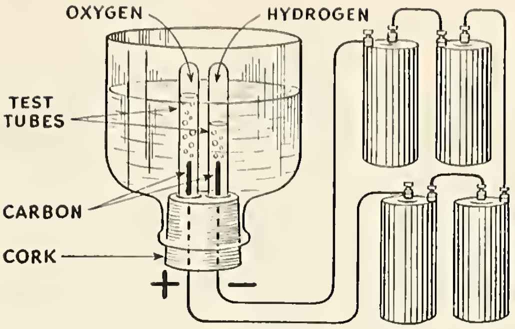
b. (See Fig. 100.) Connect the 3-volt bulb and socket in series with two dry cells and a 10-ohm rheostat. Move the slider of the rheostat to the OFF position. Now place a light meter about 6 inches from the bulb. (The light-sensitive part of the meter should face the bulb.) Move the slider of the rheostat slowly so that the bulb lights up. Notice the reading of the light meter as the brightness of the bulb increases. Can light be changed into electrical energy?

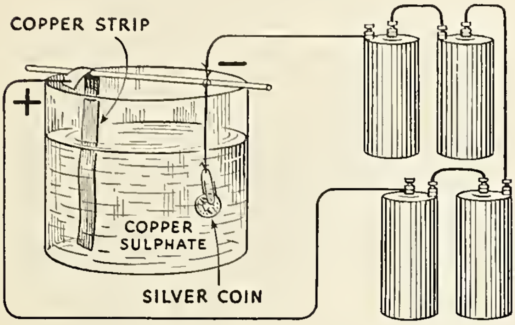
Experiment 41: **Electrolysis and Electroplating**

THINGS NEEDED: Electrolysis apparatus (or apparatus shown in Figure 101 consisting of half-gallon bottle cut in two, large cork, two carbons from old flashlight batteries, and two test tubes). Four No. 6 dry cells. No. 18 insulated copper wire. Concentrated sulphuric acid. Tap water. Matches. Wood splinters. Glass tumbler or beaker. Copper sulphate crystals. Copper strip. Silver coin. Paper clip. Glass rod. Soap. Brush.

WHAT TO DO: **a.** Using the apparatus shown in Figure 101, fill the cut-off bottle about half full of water to which a little sulphuric acid has been put. (One part of acid to about 40 parts of water will make the water conduct a current.) Fill two test tubes with this acid-water solution and place them over the carbons. Connect four dry cells in series. Then attach a wire from the outside post (negative) of the battery to one carbon and

Figure 101. *Experiment 41 shows two ways in which electrical energy can be used to produce certain chemical changes. At the right is shown a simple electrolysis apparatus you can make to change water into oxygen and hydrogen. Notice that the oxygen collects in the test tube set over the positive carbon, while the hydrogen collects in the test tube set over the negative carbon.*





The picture at the left shows how electroplating can be done with simple equipment. A glass rod supports the strip of copper and the wire fastened to the silver coin with a paper clip. Notice that the wire from the positive terminal of the battery is connected to the copper strip, while the wire from the negative terminal is connected to the article being plated.

another wire from the center post (positive) to the other carbon. Watch what happens in the tubes as the gas bubbles rise. Is there the same amount of gas in each tube? When the first tube is filled with gas, put your thumb over the open end and remove the tube from the water. Bring a lighted match near the open end of the tube. What happens? The gas is hydrogen. In the same way remove the other tube of gas. Test it with a glowing wood splinter. What happens this time? The gas is oxygen. What energy change has taken place?

b. Dissolve as many copper sulphate crystals as you can in a glass tumbler or beaker of water. Add a few drops of sulphuric acid to the solution. Clean a silver coin with soap and water, using a brush. Rinse the coin in clear water. Without touching the surface of the coin with your fingers, slip the coin in a paper clip. Attach a wire from the negative terminal of the battery used in Part **a** to the paper clip. Wind a few turns of the wire around a glass rod, as shown in Figure 101. Connect a wire from the positive terminal of the battery to a copper strip. Lower both coin and strip into the solution without letting them touch each other. After a few minutes lift out the coin. What has happened? (You can remove the copper from the coin by reversing the connections to the battery.) What change of energy takes place in electroplating?

Experiment 42: **Force of a Solenoid**

THINGS NEEDED: Solenoid and iron core (coil from Experiment 34 and iron rod that fits inside). Pan balance and weights (or spring balance). String. Two No. 6 dry cells. Knife switch.

WHAT TO DO: Set up the apparatus as shown in Figure 102, on the next page. Fasten a string from the core of the solenoid to one side of the balance. Adjust the length of the string so that the core is only one third of the way inside the coil of the solenoid. Add weights to the other side of the balance until the pointer is at zero. Notice how much weight is required to balance the weight of

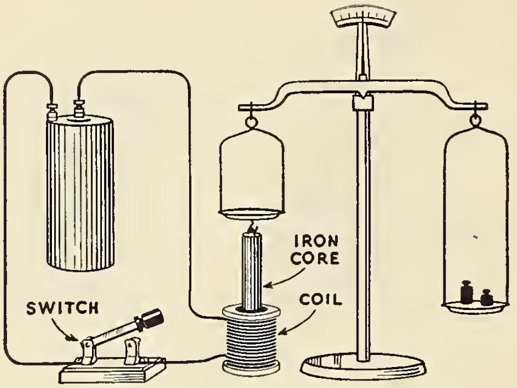


Figure 102 *shows how the force of a solenoid-plunger type of electromagnet can be measured. If the special balance shown is not available, use a regular pan balance and fasten the core to the balance arm with a piece of string. With the switch open, add weights to the right-hand pan until the pointer is at zero. Be sure to note the weight used, so that you can subtract it from the total weight needed to bring the pointer back to zero after the switch is closed.*

the core. Throw the knife switch, closing the circuit. What happens? Add weights to the balance until the pointer returns to zero. How much additional weight must be added? What is the pull of the solenoid? (If you wish, you may repeat the experiment, adding one or more cells in series with the first one, using a larger solenoid, or varying the length of core in the solenoid.)

Experiment 43: **Wattage of Electric Light Bulbs**

THINGS NEEDED: 3-volt flashlight bulb and socket. Two No. 6 dry cells. No. 18 insulated copper wire. Knife switch. Voltmeter reading to at least 3 volts. Ammeter reading to at least 1.5 amperes.

WHAT TO DO: **a.** Connect the apparatus as shown in Figure 103. Close the switch and take the meter readings. Then open the switch. From the voltage and amperage, calculate the wattage of the flashlight bulb, using the formula you learned on page 191.

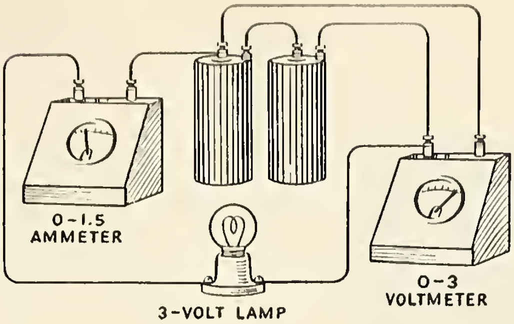
b. (*Optional*) If an alternating-current voltmeter and ammeter are available, repeat Part **a**, using various sizes of 110-volt bulbs (25-, 40-, 60-watt bulbs, etc.). Connect the circuit as in Part **a**, but use 110-volt alternating current and insulated wire and a socket intended for use with this voltage.

Experiment 44: **Efficiency of Transformers**

THINGS NEEDED: 32-candle power automobile headlight bulb and socket. Bell transformer. Toy transformer. No. 18 insulated copper wire. Alternating-current voltmeter (7.5-volt and 150-volt scales). Alternating-current ammeter (5-ampere scale).

WHAT TO DO: Connect the headlight bulb and socket to the 6-volt terminals of a bell transformer, as shown in Figure 104. Attach the other terminals to the 110-volt alternating-current circuit. Take the meter readings and calculate the wattage output of the transformer. Disconnect the transformer. Then connect the automobile bulb and socket directly to the 6-volt terminals of the transformer. Place the meters in the primary circuit, as shown in Figure 104. Connect the ammeter in series with the primary and connect the voltmeter across the primary. Be sure to use the 150-volt terminals of the voltmeter. Use well-insulated wire to connect the meters in the primary circuit, and check all connections carefully before you insert the plug into the outlet. Again attach the primary terminals to the 110-volt circuit and take the meter readings. Calculate the wattage input of the transformer. Then from the wattage output and wattage input find the efficiency of the transformer. Repeat the experiment, using a toy transformer. Which transformer is more efficient?

Figure 103 shows how you can measure the voltage and the amperage of light bulbs in order to calculate their wattage. Notice that the ammeter is connected in series with the lamp, while the voltmeter is connected across the two dry cells. Be sure to connect the wires from the center post of the dry cell to the positive (+) terminals of the meters so that the needles move in the right direction.



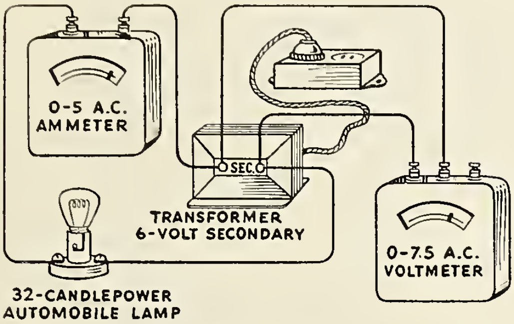
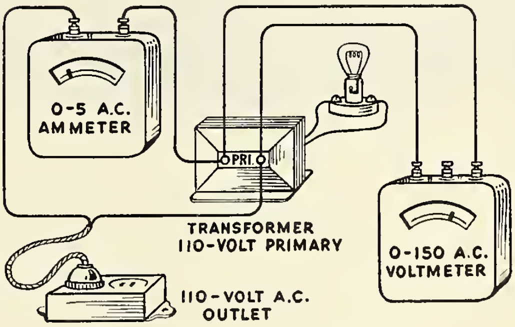


Figure 104 shows how to measure the output and input of a transformer in order to calculate its efficiency. At the left is the arrangement for measuring the amperage and the voltage of the secondary. Notice that the ammeter is connected in series with the automobile lamp, while the voltmeter is connected across the secondary terminals of the transformer.

At the right is shown the arrangement for measuring the amperage and the voltage of the primary. Notice that the automobile bulb is connected directly to the secondary while the primary is being measured. Remember that the primary wires carry about 110 volts. Be sure to use the correct terminals on the voltmeter and check all connections carefully before inserting the plug in the outlet.



9. Generators

FINDING OUT WHAT YOU KNOW

1. What two sources of electrical energy do we commonly use?
   State the energy change that takes place in each one.
2. Tell what a magneto is and name its main parts.
3. Explain how a simple alternating-current generator works.
4. What kind of current is produced in all generators?
   How is a generator made to furnish the other kind of current?
5. On what does the electromotive force of a generator depend?
   How can it be increased?
6. What is the main reason for using alternating current?
   Why must direct current sometimes be used?

In the very first chapter of this book you learned that there are only two important sources of electrical energy: cells and generators. Cells are very convenient for many purposes, and we use them a great deal. But, as you know, the electrodes and electrolytes of cells are so expensive that it is not practical to use cells to supply current for lighting houses and streets, for heating purposes, and for running large motors. When large amounts of current are needed for a considerable length of time, generators are used. There are large generators run by steam or moving water in electric power plants all over the world. Every automobile, airplane, modern ship, and nearly every factory has one or more generators run by an engine or motor. Almost all locomotives and many railroad passenger cars have their own generators. The Diesel engines on streamlined trains and the steam turbines on many ships drive generators whose current transmits energy to the driving wheels or propellers.

As you learned in Chapter 1, generators are machines for producing electrical energy. In other words, a generator changes mechanical (kinetic) energy into electrical energy. To do this, a generator makes use of the principles of magnetism and induction you learned in preceding chapters; it is usually nothing more than a machine for moving wires rapidly through a magnetic field, thus cutting lines of force and inducing an E.M.F. in the wires. If a closed circuit is provided, the induced E.M.F. will cause a current to flow. Much of what you have already learned about magnets, electromagnets, induction coils, and

Magneto: A generator in which an E.M.F. and thus a current are induced by using one or more permanent magnets and a coil. Lines of force are cut by rotating either the coil or the magnetic field.

Field magnet: A magnet used to provide a magnetic field in a generator or motor. It may be a permanent magnet, as in a magneto; but it is usually an electromagnet, as in most generators and motors.

Collector: The part of a generator that connects the rotating coil (or coils) to an external circuit. In a magneto or alternating-current generator, it consists of stationary contacts called **brushes** that touch rotating contacts called **slip rings,** which are connected to the rotating coil (or coils).

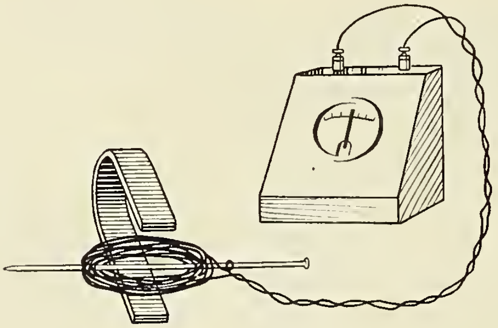


Figure 105. *At the left is shown a very simple magneto, consisting of a coil of wire that can be rotated between the poles of a permanent magnet. As the coil is rotated in one direction, the needle of the galvanometer swings first to one side of the center zero mark and then to the other side, indicating that an alternating current is being induced by the motion of the wire.*

transformers applies equally well to generators. In Experiments 34 and 35 a crude sort of generator was actually made when a moving coil cut lines of force in a magnetic field. Before going on with this chapter on generators, you will do well to review Chapters 5, 6, and 7, looking at the diagrams and reading over the definitions.

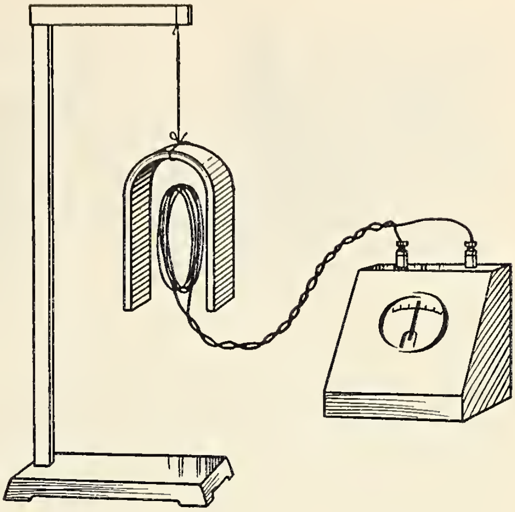
The Magneto

Perhaps the simplest kind of generator is the **magneto.** You can see how a magneto works by doing Experiment 45 (page 228). A coil of many turns of small wire is rotated rapidly between the poles of a U-magnet, as shown in Figure 105. The ends of the wire are connected to a galvanometer. As the coil is rotated, the galvanometer needle swings from one side to the other, indicating that an alternating current is induced in the coil. When the rotating coil cuts lines of force in the magnetic field, an E.M.F. is induced in the coil. The lines of force are cut first in one direction and then in the other. As a result, the induced E.M.F. acts first in one direction and then in the other. Since the coil is connected in a closed circuit, a current flows. The current alternates as the direction of the induced E.M.F. changes. In accordance with Lenz's Law, the induced current has such a direction that its magnetic field opposes the motion which induced the current.

If you wish, you may add another U-magnet alongside the first one, being sure that like poles are placed next to each other. You will find that strengthening the magnetic field increases the induced E.M.F. and thus the current. You may also try rotating the coil faster or slower, or using more or fewer turns in the coil. Just as in Experiments 34 and 35, you will find that the induced E.M.F. is increased by moving the coil faster and by using more turns. That is what you should expect, because more lines of force are cut in a certain time if the magnetic flux, the speed of cutting, or the number of turns is increased.

Another thing you may wish to try is keeping the coil stationary while rotating the U-magnet. If the magnet is hung by a string over the coil, as

Figure 106 *shows a simple experimental magneto in which the poles of the magnet can rotate around the coil of wire. If the magnet is balanced carefully so that it does not wobble as the string untwists, the magnet will continue to spin for some time with one "winding." Since the motion of the rotating magnet is regular, it is possible to compare meter readings with different amounts of the coil in the magnetic field and at different speeds of turning. A magneto in which the magnetic poles turn instead of the coil is said to have a rotating field.*



shown in Figure 106, you can do this by twisting the string and then letting it unwind. As the magnet spins, its lines of force will be cut first in one direction and then in the other by the coil. As before, the galvanometer needle will swing from side to side, thus indicating that an alternating current is induced in the coil.

Commercial magnetos. Of course commercial magnetos are not so crude as the one made in the experiment. In one type of magneto, the magnetic field is provided by several U-magnets placed next to one another so that all like poles are together. Curiously enough, several **field magnets**, as they are called, arranged in this way have a greater magnetic flux than one large magnet as big as all the separate magnets put together. Between the poles of the U-magnets there is an *armature*, which has many turns of small wire wound about a laminated iron core. From Chapter 6 you recall that an armature is the part of an electrical device acted on by a magnetic field. The laminations in the core reduce eddy currents and thus heat losses due to induction, as you learned in Chapter 8.

If you did Experiment 45, you found that the wires from the coil connected to the galvanometer became twisted as the coil was rotated. Obviously, some better way must be used to connect the armature coil to the external circuit. For this purpose a device called a **collector** is used. It consists of one or two **brushes** and one or two **slip rings**. The brushes are stationary, but they touch the slip rings attached to the rotating shaft. Each slip ring is connected to one end of the coil. (If the collector has only one brush and one slip ring, as is usually the case in magnetos of this type, the other end of the coil is connected to the metal shaft, which serves as one conductor.) Of course, the brushes and slip rings are conductors. The brushes are usually made of a form of carbon called *graphite*, while the slip rings may be made of hard copper. If a demonstration magneto is available, do Experiment 46 in which you can examine and operate one type.

Figure 107 shows how one type of magneto is constructed and what its parts are. Notice that the field magnets have curved parts, called *pole pieces*, attached to their poles. There is only a small space between the pole pieces and the armature. The pole pieces, which are made of iron, conduct lines of force to and from the poles of the field magnets. Since lines of force pass more readily through iron than through air, the pole pieces help concentrate the magnetic flux near the armature and thus increase the induced E.M.F. When the armature is rotated rapidly by turning a crank or otherwise spinning its shaft, its coil cuts lines of force between the pole pieces.

In Experiment 46 a galvanometer is connected to the armature of the magneto, and the crank is turned slowly. Just as in the preceding experi-

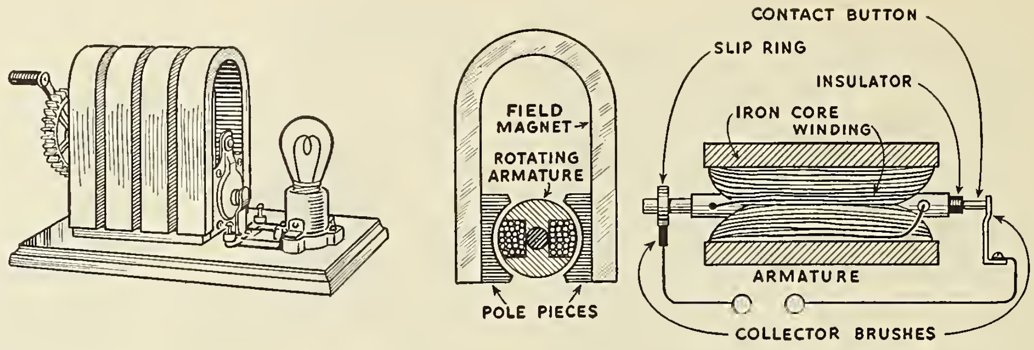


Figure 107. *At the left is shown a telephone-ringer magneto with four separate field magnets. The small bulb lights when the magneto crank is turned. The center picture shows how the armature rotates between the concave pole pieces, to which the field magnets are clamped. At the right is shown an armature in which one end of the coil winding is fastened to a slip ring, while the other end is fastened to an insulated contact button.*

ment, the galvanometer needle swings first to one side and then to the other, indicating that an alternating current is induced. If you connect headphones to the armature and then turn the crank, you hear a sound each time the current is reversed. By turning the crank at various speeds, you find that the induced current reverses its direction more often as the speed of turning increases. As the crank is turned faster and faster, the sounds indicating reversal of the alternating current come faster and faster until they make a humming sound. In other words, increasing the number of alternations per second increases the frequency of the alternating current induced in the coil.

If a suitable bulb is connected in place of the headphones, you can see that it lights up brighter as the crank is turned faster. Obviously, the induced E.M.F. increases as the armature rotates faster, thus driving more current through the filament of the bulb. You may also try removing one or more of the field magnets. As the field strength is reduced, the brightness of the bulb decreases. Thus the results in Experiment 46 agree with those in the preceding experiment.

In Chapter 7 you learned that the induced E.M.F. is determined by the number of lines of force cut in a certain time (usually one second). The number of lines of force cut in one second depends on (1) the field strength of the magnet, (2) the speed of cutting, and (3) the number of turns in the coil. In a magneto or other generator (or any induction machine), there is one other thing that affects the number of lines of force cut per second, which you should now add to the three you have already learned. This is the angle at which the lines of force are cut by the coil, as shown in Figure 113. Later in this chapter you will find out just why this makes a difference in the induced E.M.F. and thus the current.

Operation. Since a magneto or any other generator is simply a device for obtaining induced E.M.F. and thus current rapidly and continuously, it operates in accordance with Lenz's Law. In other words, the induced current has such a direction that its magnetic field opposes the motion which induced the current. By using the right-hand rule for induced current (also called the *right-hand rule for generator*), you can determine the direction of the induced current supplied by a magneto or similar generator. (If you turn back to Figure 83, page 154, you can see how this is done.)

When an E.M.F. is induced by moving a conductor across lines of force in a magnetic field, the induced current sets up its own magnetic field around the conductor. One result of this is to

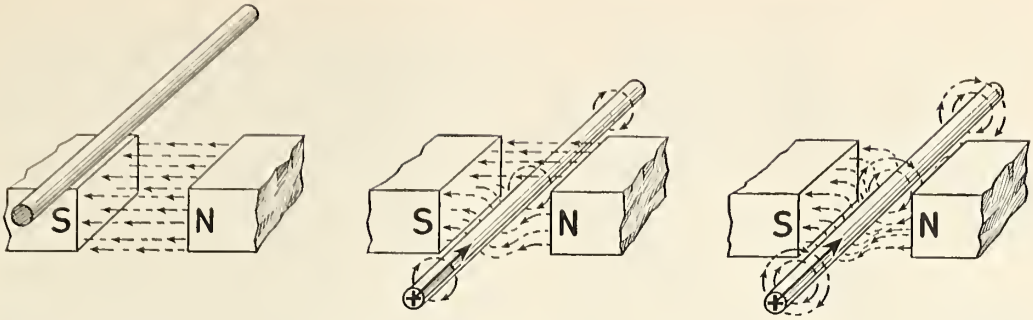


Figure 108 *shows why a conductor meets opposition in moving through a magnetic field. At the left the conductor moves easily toward the pole pieces, since no current has been induced in it. The center diagram shows a small current flowing through the conductor, causing an opposing magnetic field that bends a few lines of force, while the heavy current in the conductor at the right causes much more opposition as many lines of force are bent. (In all three diagrams, the conductor is part of a closed path.)*

increase the lines of force on the side of the conductor toward which it is moving. Since lines of force act somewhat like stretched rubber bands, they tend to pull back on the conductor around which they are looped. Figure 108 shows that there are more lines of force in the direction toward which the conductor moves.

If you did Experiment 46, Lenz's Law explains something you must have noticed. There was quite a difference in the ease with which you could turn the crank under different conditions. If the magneto was not connected to any device, the crank turned easily at almost any speed. Just as with most machines, once the magneto was turning rapidly, little effort was required to maintain the speed. The armature coil was part of an open circuit. Although an E.M.F. was induced in the coil, no current flowed because there was no complete path through which it could flow. But when the bulb was connected to the armature coil, the more current that was supplied to the bulb, the harder the crank turned. The induced current set up its own magnetic field, which opposed the motion that induced the current. In other words, the magnetic field set up by the induced current acted like a brake on the armature and thus retarded its motion.

If you keep this fact in mind, you will have no trouble in understanding why large amounts of energy are needed to turn any generator that is furnishing a large current. Some people see no reason why a generator turns harder when supplying current than when running idle and supplying no current. Of course, if more electrical energy could be obtained without putting in more mechanical energy, the generator would be a "perpetual motion" machine. From the Law of Conservation of Energy, you know that no machine can give out more energy than was put into it. Actually, when more electrical energy is supplied by a magneto or other generator, more mechanical energy must be supplied to turn it. As more current flows through the armature coil, the strength of the magnetic field set up by the induced current increases. Since this magnetic field opposes the motion that induced the current (in accordance with Lenz's Law), the crank is harder to turn.

Other types. The magneto shown in Figure 107 is not the only type in use. In another type the armature is stationary, while the pole pieces are turned to produce a rotating magnetic field. A third type has a stationary coil over a rotating core. Still another has a stationary armature coil and rotating field magnets. Alnico, the magnetic alloy which can lift 50 times its own weight, is often used for the field magnets in this type of magneto. If you did Experiment 45, you can prob-

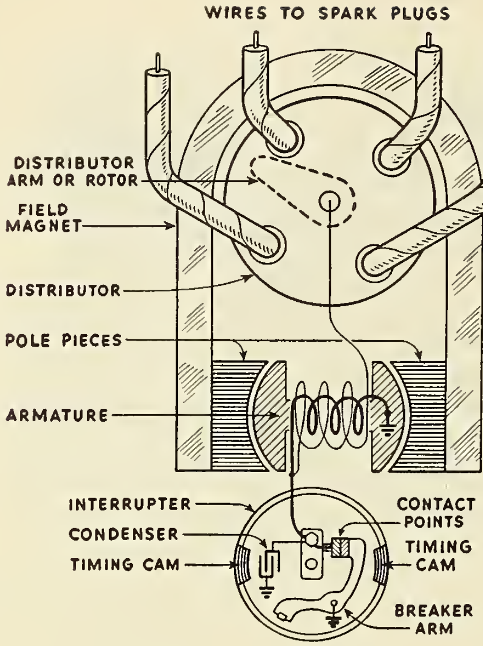


Figure 109. *Gasoline engines designed for use in airplanes and motorcycles often have high-voltage magnetos that supply the ignition spark. In the ignition magneto shown at the left the armature has two windings—a low-voltage primary of fairly heavy wire and a high-voltage secondary of many turns of fine wire. Turning with the armature is the interrupter, so arranged that the contact points separate when the induced voltage in the primary becomes greatest. Also geared to the armature shaft is the distributor arm, which makes contact with the wire to the proper spark plug so that as the induced E.M.F. becomes great enough to cause a spark, the mixture of gasoline and air will be exploded in the right cylinder at the right time.*

ably guess the reason for using a stationary coil: No collector with its brushes and slip rings is required. Since brushes and slip rings wear out from rubbing and sparking, they must be replaced. Getting rid of the collector by using a stationary coil eliminates any trouble that might be caused by worn, pitted, or dirty brushes and slip rings.

Uses. Because they are simple and reliable, magnetos are used to supply the sparking current in the ignition systems of some gasoline engines, particularly those used in airplanes and motorcycles. There is very little that can go wrong with a magneto, especially if it has a stationary coil. Most airplane engines have dual-ignition systems with two spark plugs in each cylinder and two separate magnetos. One of the spark plugs is connected to one magneto, while the other spark plug is connected to the other magneto. The two sparks supplied to each cylinder increase the efficiency of the engine, because the gasoline-air mixture in the cylinder is more completely burned. Using dual ignition also increases the reliability of the engine, since both ignition systems are unlikely to fail at the same time.

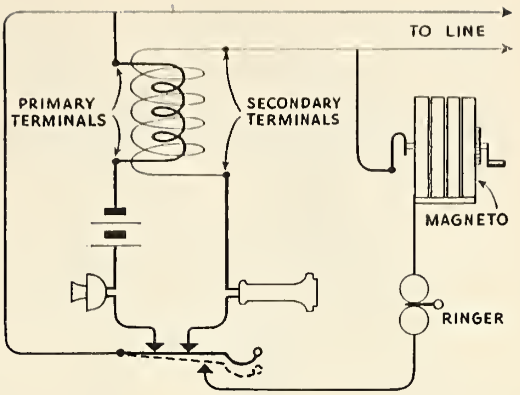
If a magneto supplies only a low voltage, it is usually connected to the primary of an induction coil so as to increase the voltage in the secondary connected to the spark plugs. In a high-voltage magneto, a separate induction coil is not needed because the voltage produced is high enough to make a good spark. By getting rid of the induction coil another possible source of ignition trouble is eliminated. In a high-voltage magneto used for ignition, the interrupter and the distributor are also included, as shown in Figure 109. The interrupter is usually mounted on the same shaft as the rotating coil or magnet, thus simplifying the connections and reducing the number of moving parts in the ignition system.

Another use of the magneto is to supply the ringing current in certain telephone circuits, as shown in Figure 110. Turning the crank induces an alternating current that will ring a bell at the other end of the line. Telephones used in rural districts usually have magnetos to supply the ringing current. Army field telephones are also equipped with magnetos for this purpose.

CHECKING WHAT YOU LEARNED

1. Explain why generators instead of cells are used to supply large quantities of electrical energy.

Figure 110. *At the right is shown a diagram of a telephone set using a magneto. When the receiver is on the hook, the magneto and the ringer are connected to the line so that the central station can be called by turning the crank or so that the ringer will operate when the crank at another station is turned. When the receiver is off the hook, the transmitter and receiver are connected to the line through an induction coil, and the magneto and ringer are disconnected.*



2. Does a generator make electrical energy? Give reasons for your answer.
3. **a.** Name the main parts of a simple magneto and tell what each part does. **b.** Which parts are not used in certain types of magnetos? Why?
4. Experiment 45 shows the only two really different ways of inducing a current in a generator, such as a magneto. **a.** What are these two ways? **b.** Tell what happens when either of them is used.
5. **a.** What determines the strength of the E.M.F. induced in a generator? **b.** In what ways can the induced E.M.F. be increased?
6. How does the speed of turning affect the frequency of the induced current? Explain.
7. What kind of current is produced when a coil is rotated in a magnetic field? Why?
8. **a.** Tell why magnetos are used in certain ignition systems. **b.** What other common use is made of magnetos?

USING WHAT YOU LEARNED

1. A magneto supplying current to an external circuit suddenly begins to turn very easily. What has happened?
2. A coil of wire is connected to a galvanometer and rotated between the poles of two U-magnets placed side by side; but the galvanometer needle does not move although the circuit is closed, the magnets are magnetized, and the galvanometer is in working order. Why does the needle fail to move?
3. Explain why more energy must be supplied to a generator when more current is drawn from it, using Lenz's Law and the Law of Conservation of Energy.
4. A large coil is rotated very rapidly on a shaft placed in an east-west direction. A galvanometer connected to the coil by means of a collector indicates that a current is flowing, although no magnets are near the coil. What causes the induced current?
5. In an ignition system, the E.M.F. of a magneto is 60 volts when the armature is turning at full speed. **a.** To furnish a 9000-volt sparking current, how many times must the magneto voltage be increased by an induction coil? **b.** If the interrupter and condenser increase the voltage 25 times, what is the voltage-turns ratio of the secondary to the primary of the induction coil?

The Alternating-Current Generator

A magneto is a simple and reliable generator, but it will not furnish a large enough current at a voltage sufficient to operate lights, heating devices, large motors, and other devices that require large amounts of electrical energy. A more powerful generator is needed for such purposes. You know that a higher voltage is induced when more lines of force are cut each second and that the rate of cutting lines of force can be increased by strengthening the magnetic field, moving the coil or magnetic field faster, or using more turns in

Alternating-current generator: A generator in which the magnetic field provided by electromagnets is used to induce an alternating current. In most large generators of this kind, the field magnets rotate while the armature is stationary. Stationary field magnets and a rotating armature are used in smaller generators. Also called **alternator** or **A.C. generator.**

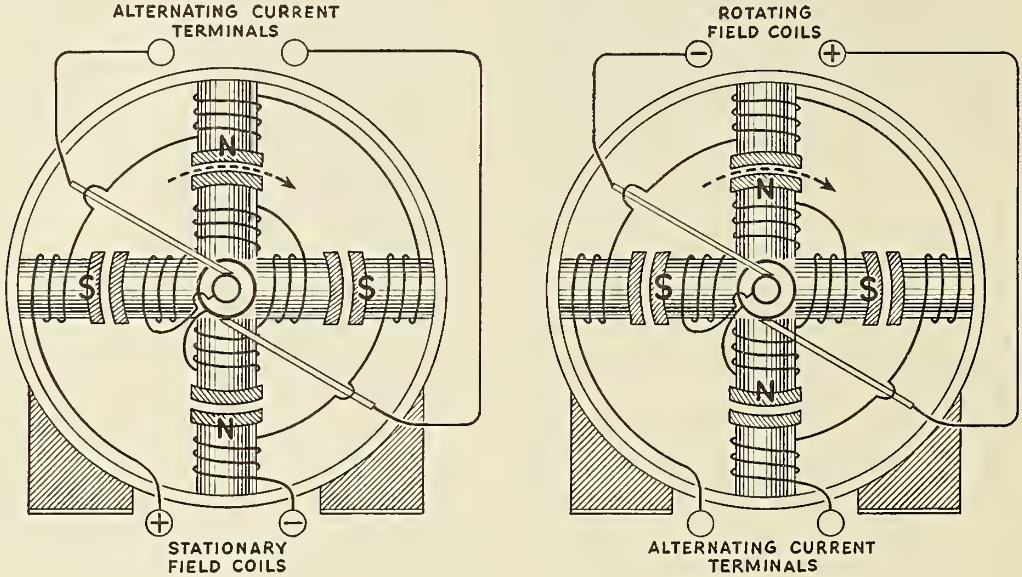


Figure 111. *At the left is a diagram of an alternating-current generator with a stationary field and a rotating armature. Notice that the alternating current induced in the armature is collected by means of brushes and slip rings. At the right is a diagram of a similar generator with a rotating field and a stationary armature. Notice that the field coils receive direct current by means of the brushes and slip rings.*

the coil. Reducing the internal resistance of the coil by using larger wire will increase the current that can be supplied to an external circuit.

Construction. One kind of generator designed to furnish large amounts of electrical energy is called the **alternating-current generator**, or **alternator.** We often call it the **A.C. generator**, for short. In one sense, a magneto is an alternating-current generator, because it produces an alternating current. However, the term *alternating-current generator* is usually applied to the kind whose magnetic field is provided by electromagnets instead of permanent magnets. As you know, electromagnets are not only stronger than permanent magnets, but their magnetism can also be controlled. The essential parts of an A.C. generator are the same as those of a magneto: field magnets, armature, and collector with brushes and slip rings. The electromagnets providing the magnetic field are supplied, or, as we say, *excited,* by direct current. Alternating current would cause an undesirable reversal of polarity in the field magnets. The armature is wound with many turns of wire, which increases the induced E.M.F. and thus the current.

Like a magneto, an A.C. generator may have either a rotating armature and a stationary field, or a rotating field and a stationary armature. For reasons of economy and better construction, most A.C. generators furnishing large amounts of elec-

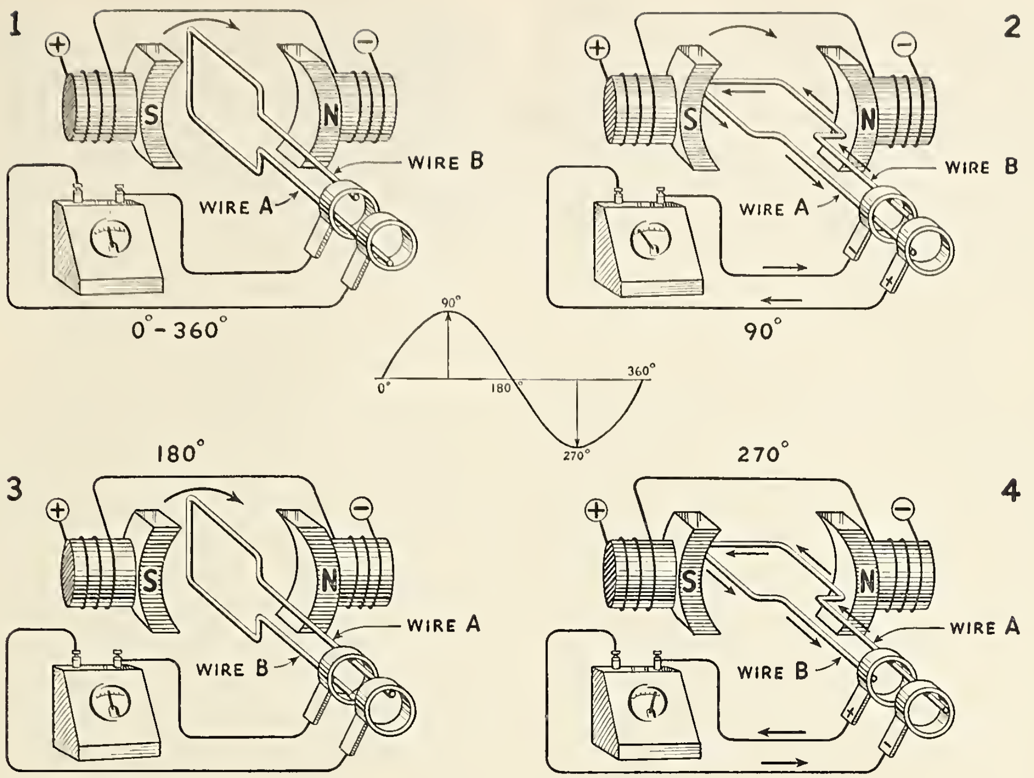


Figure 112. *The diagrams above show how an alternating current is induced in a loop of wire rotating in a magnetic field. In diagram 1 no current flows, because no lines of force are being cut. In diagram 2 a maximum number of lines of force is being cut, and so maximum current flows. In diagram 3 no current flows. In diagram 4 maximum current flows again but in the opposite direction, as shown by the graph in the center.*

trical energy have rotating fields and stationary armatures. Whichever arrangement is used, brushes and slip rings connect the rotating coil to the rest of a circuit. If the field rotates, the collector carries direct current into the field coils and back again. If the armature rotates, the collector carries alternating current into the rest of the circuit and back again. The rotating armature or the rotating field is made to turn at high speed. To do this, a water wheel, water turbine, steam turbine, gasoline engine, Diesel engine, or electric motor attached to the shaft of the generator is used. The faster lines of force are cut, the greater will be the induced E.M.F. Thus you can see that everything possible is done to increase the induced E.M.F. and the current. If a demonstration A.C. generator is available, you can examine its parts and see how it works.

Operation. To understand how an A.C. generator works, look at Figure 112, which shows the type using a rotating armature and a stationary field. The diagrams are very simple, since they show only one turn of wire and no core in the armature. Actually, a generator has many turns of wire wound around the iron core of the armature. One end of the coil is connected to one slip ring, and the other end to the other slip ring. Brushes pressing against the slip rings connect the coil to the external circuit. The field magnet is an electromagnet connected to a source of direct current. One pole piece is opposite to the other, so that there is a magnetic flux from the N pole to the S pole. As the armature coil rotates in the magnetic field, one side of the coil cuts down through the lines of force while the other side cuts up through the lines of force. The currents induced in the two sides of the coil flow in opposite directions, in accordance with Lenz's Law. Since the two sides are part of a turn of wire, the current flowing in one side joins the current flowing in the other side. Then the current flows out through one slip ring and brush, around the external circuit, and back through the other brush and slip ring.

Let us follow the coil through one complete rotation in the magnetic field. The first diagram in Figure 112 shows the coil in a vertical position. Since both sides of the coil are moving parallel to the lines of force, no lines of force are cut by the coil, and no E.M.F. or current is induced. As the coil rotates toward the horizontal position shown in the second diagram, lines of force are cut by both sides of the coil. Side A cuts upward as side B cuts downward, and an E.M.F. is induced in the coil. The arrows show the direction of the induced current. As the coil keeps on turning, the current continues to flow in this direction until the vertical position shown in the third diagram is reached. At this point the sides of the coil are again moving parallel to the lines of force. As a result, no lines of force are cut, no E.M.F. is induced, and no current flows. The coil continues to turn until it reaches the position shown in the fourth diagram. As it does so, the current in the coil reverses, because side A now cuts downward through the lines of force and side B now cuts upward. The current continues to flow in this direction until the coil returns to the position shown in the first diagram. When this point is reached, no E.M.F. is induced, and no current flows. A cycle with two alternations has now been completed in one rotation of the coil.

As the coil continues to turn, the same cycle takes place all over again. This goes on as long as the coil is kept turning. Thus the generator produces an alternating current such as shown by the curving line in Figure 95 (page 174) and in Figure 112. The alternating current starts from zero when the coil is vertical and cutting no lines of force. It increases to a maximum, or *peak*, when the coil is horizontal. Then it decreases to zero again when the coil is vertical. At this point the current reverses. Once more it increases to a maximum and then decreases to zero.

Wave form of alternating current. In Figure 112 is a graph showing the wave form of the cur-

---

Rotating vector in graph form: The strength of the induced E.M.F. can be represented graphically. In the diagram at the left on page 215 the head of the rotating arrow shows a wire cutting lines of force as it moves in a circle through a magnetic field. The rotating arrow is called a **vector,** that is, it represents a quantity of a certain value in a certain direction. The length of the arrow indicates the value, while the arrow head indicates the direction. The vertical distance from the tip of the arrow to the horizontal line represents the strength of the induced E.M.F., because it is proportional to the number of lines of force cut per second. As the arrow moves through a complete circle, or 360°, the length of the vertical line increases to a maximum at 90° and then decreases to zero at 180°. The length again increases to a maximum (below the horizontal line) at 270° and then decreases to zero at 360°. This completes one rotation. You can see that the movement of the arrow head represents what happens when a wire moves in a circle through a magnetic field.

The movement of the rotating vector can be shown graphically, as in the diagram at the right. Along the horizontal line intervals of 30° are measured off equal to distances through which the tip of the arrow moves. The length of the horizontal line is equal to the circumference of the circle. Above and below the horizontal line a curving line is drawn through points whose vertical distances from the horizontal line are equal to the vertical distances of the tip of the arrow from the horizontal line in the circle at the left.

A curving line drawn in this way is called a **sine curve,** or **sine wave,** because it represents the changing values of the **sine** of the angle of rotation. The sine of an angle is a ratio used in trigonometry. In the diagram at the left, the sine of the angle between the rotating arrow and

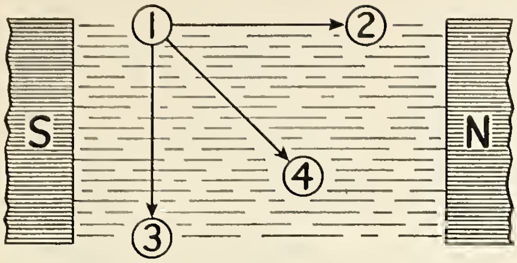
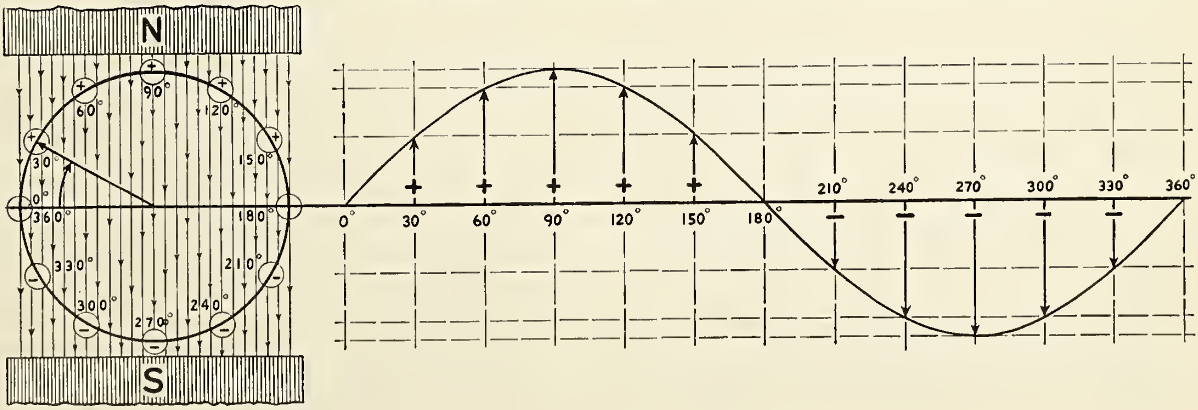


Figure 113 *shows that the E.M.F. induced in a conductor depends on the angle at which it cuts the lines of force. From 1 to 2 no lines are cut, and no E.M.F. is induced. From 1 to 3 a maximum number of lines is cut, and maximum E.M.F. is induced in the conductor. At intermediate positions, such as 1 to 4, the E.M.F. is less than maximum.*

rent produced in an alternating-current generator. The straight center line is zero, that is, where the curving line cuts the center line, no E.M.F. is induced and no current flows. Above the center line the curving line indicates a current flowing in one direction, while below the center line the curving line indicates a current flowing in the opposite direction. The direction of the current above the line is thought of as positive, while below the line the direction is considered to be negative. The strength of the E.M.F. is shown by the distance of the curving line above or below the center line. If you examine the curving line, you see that the current rises from zero to a maximum, then dies down to zero, and reverses its direction. Again it rises to a maximum (but in the opposite direction from the first maximum), then dies down to zero, and reverses its direction.

Now let us see why the current produced by an alternating generator has this wave form. You already know that the strength of the induced E.M.F. depends on the rate at which lines of force are cut. Figure 113 shows a single wire moving through a magnetic field in several directions. If the wire moves from position 1 to position 2, no lines of force are cut, because the wire moves

the horizontal line is equal to the vertical distance from the tip of the arrow to the horizontal line divided by the length of the arrow. If the length of the arrow, which is the radius of the circle, is given the value of 1, the vertical distance may be considered equivalent to the sine of the angle. The sine of the angle represents what is called the **vertical component,** or part, of the vector. The changing values of the voltage or the current produced by an alternating current generator approximate the points on the curving line at the right. However, in actual practice the true values of the voltage or the current make a somewhat different curve, or, as usually happens, two curves—one for the voltage and one for the current. The differences between these curves and a sine curve are caused by resistance, inductance, and capacity in the circuit.



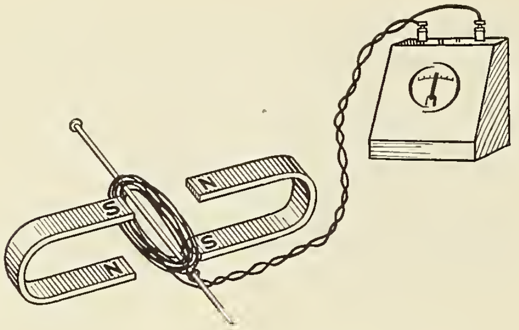


Figure 114. *Rotating a coil of wire in one direction between the poles of two U-magnets arranged as shown at the left will cause the needle of the galvanometer to swing back and forth twice during each rotation of the coil. This indicates that, at the same speed, doubling the number of field poles doubles the frequency of the alternating current induced in the armature coils.*

parallel to the lines of force. Therefore, no E.M.F. will be induced. However, if the wire moves from position 1 to position 3, many lines of force will be cut, and an E.M.F. will be induced in the wire. Now suppose that the wire moves from position 1 to position 4. Lines of force will also be cut, and an E.M.F. will be induced.

Notice that the distances from position 1 to positions 2, 3, and 4 are equal. When the wire is moved horizontally through this distance, no lines of force are cut. And when the wire is moved vertically through this distance many lines of force are cut. However, when the wire is moved obliquely through this distance, more lines are cut than in the horizontal movement but fewer than in the vertical movement. Therefore, a greater E.M.F. will be induced than when the wire moves horizontally but a smaller E.M.F. than when the wire moves vertically. The angle at which the lines of force are cut thus makes a difference in the number of lines cut in one second. If the angle is zero degrees, the wire moves parallel to the magnetic field, and no lines of force are cut. If the angle is 90 degrees, the wire moves straight across the magnetic field, and many lines of force are cut. However, if the wire moves at an angle somewhere between zero and 90 degrees, a lesser number of lines of force will be cut. Just how many depends on the angle; the nearer the angle is to 90 degrees, the more lines of force that will be cut. Now let us see how this applies to a generator.

As the coil of the generator rotates, its turns cut lines of force at various angles from zero to 90 degrees. The induced E.M.F. and thus the current reach their greatest amounts when lines of force are cut straight across, or at an angle of 90 degrees. This happens twice in each cycle, or once in each alternation. Just before the current reverses, no lines of force are cut, because the turns of coil move parallel to the lines of force, or at an angle of zero degrees. This happens at the beginning, middle, and end of each cycle, or at the beginning and end of each alternation. (Of course, the end of one cycle or alternation is actually the beginning of another.) At all other points in the rotation, the induced E.M.F. and thus the current are either increasing from zero to a maximum or decreasing from a maximum to zero, since lines of force are cut at various angles greater than zero but less than 90 degrees. If the coil rotates at a constant speed, more lines of force are cut per second as the angle of cutting approaches 90 degrees.

Bipolar and multipolar types. The A.C. generator shown in Figure 112 is *bipolar,* that is, its field magnet has only two poles. The poles of the armature coil are not shown, but the armature is also bipolar. If you use the right-hand rule for a coil, you can see that the armature coil has its two poles perpendicular to the turn of wire. In such a generator, there are large areas in which the armature coil cuts few, if any, lines of force. As a result, the average E.M.F. is rather low. The single pair of *field poles,* as they are called, produces two alternations for each complete rotation. Thus, with a single pair of field poles a complete cycle occurs once in each rotation.

If you do Experiment 47, you can see how using more pairs of field poles increases the in-

Frequency of alternating current: The frequency of an alternating current supplied by a generator is equal to the number of pairs of field poles multiplied by the number of rotations per second.

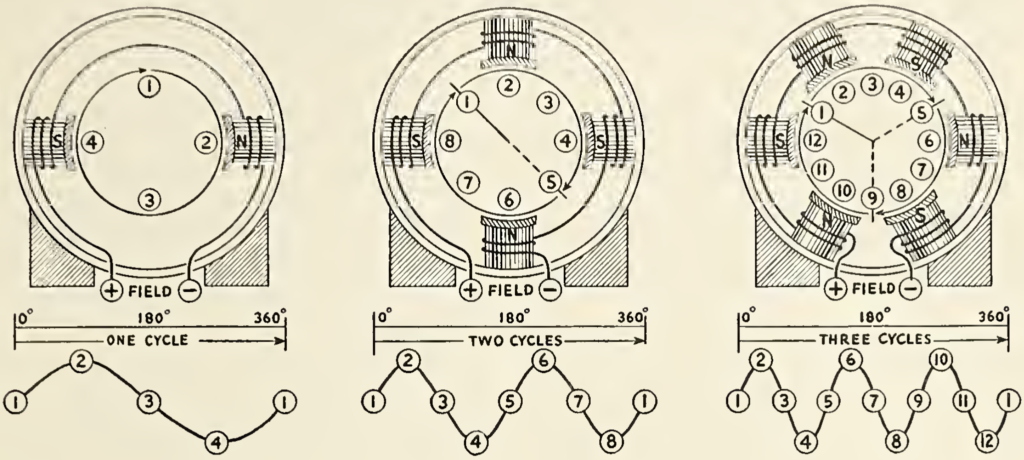


Figure 115 *shows why the number of field poles determines the frequency of the alternating current induced at a certain speed. One complete rotation of a conductor in fields of two, four, and six poles produces one, two, and three cycles, respectively, as shown above. In each case the graph shows the E.M.F. induced at each of the numbered points.*

duced E.M.F. and also the number of alternations for each rotation. Figure 114 shows a coil being rotated between the poles of two U-magnets that face each other. Notice that the poles alternate. Each pole has an unlike pole on either side of it. Lines of force extend between the unlike poles. As the coil rotates, the lines of force are cut first by one side of the coil and then by the other. Each side of the coil cuts lines of force in opposite directions *four* times in each rotation. As a result, each rotation produces four alternations or two cycles. The induced E.M.F. is increased because more space around the coil is filled with lines of force to be cut by the rotating coil.

For most purposes the standard 60-cycle alternating current is used. The flickering in light bulbs produced by frequencies less than 60 cycles per second causes eyestrain. In order to produce 60-cycle current, a bipolar generator must rotate 60 times each second, or 3600 times each minute (60 × 60). (The speed of a rotating part of a machine is usually indicated in *revolutions per minute*, often abbreviated as *r.p.m.* A revolution is the same as a rotation.) A speed of 3600 r.p.m. is very high. If the shaft of a generator turns at this speed, special construction must be used for the coil. Besides this, other engineering problems are encountered. To avoid such a high speed and also to increase the average strength of the induced E.M.F., engineers have designed *multipolar* generators, which have several pairs of poles in the field and also in the armature. Figure 115 shows how using several pairs of field poles fills more of the space in a generator with magnetic fields whose lines of force can be cut by the turns of the armature coils. As you know, cutting more lines of force per second increases the induced E.M.F.

Using more pairs of field poles also makes it possible to run the generators at slower speeds. For example, if an A.C. generator has six pairs of field poles, each rotation produces six cycles of alternating current. In order to produce 60-cycle alternating current, only 10 rotations per second are necessary. The generator can thus turn at the reasonable speed of 600 r.p.m. (10 × 60). You can find the **frequency of alternating current** supplied by a generator if you multiply the number of pairs of field poles by the number of complete rotations per second. Practically all generators used to supply large amounts of alternating current are multipolar.

CHECKING WHAT YOU LEARNED

1. Is a magneto the same as an alternating-current generator? Explain.
2. **a.** What are the essential parts of an alternating-current generator? **b.** State the use of each part.
3. Why is it incorrect to say that the armature is always the rotating part of a generator?
4. Describe one complete rotation of an alternating-current generator having two field poles and a single armature coil. Tell what happens to the induced current and why it happens.
5. **a.** In the graph of an alternating current or its E.M.F., what is represented by the curving line above the horizontal line? By the curving line below the horizontal line? By both curving lines together? **b.** What does the curving line show about an alternating current? Give at least two different things.
6. **a.** Explain how increasing the number of field poles increases the E.M.F. induced in a generator. **b.** What determines the frequency of the alternating current supplied by a generator?

USING WHAT YOU LEARNED

1. Three wires move through a magnetic field for the same distance and at the same speed. If they move at different angles to the lines of force, in which wire is the greatest E.M.F. induced? Why?
2. Why does an alternating-current generator need an outside source of direct current for its field magnets?
3. Does an alternating-current generator with a stationary armature have a collector? Explain your answer.
4. What are the advantages of using electromagnets in a generator? What are the disadvantages?
5. Refer to Figure 112. Draw simple diagrams of one rotation of an alternating-current generator like the ones shown there but reverse the direction of the magnetic flux and also the direction of rotation. Indicate the direction of the magnetic flux, rotation, and current with arrows.
6. To produce 60-cycle alternating-current, how many revolutions per minute must a generator with eight field poles make? Explain your answer.

The Direct-Current Generator

For some purposes, such as electrolysis, electroplating, charging storage batteries, and communication work, direct current is needed. Cells supply direct current, but they are too expensive to use when large currents must be provided for a considerable length of time. Therefore, a **direct-current generator,** or **D.C. generator,** is ordinarily used to supply large amounts of direct current. You know that an alternating current is induced in the armature coil of a generator, whether the armature or the field rotates. How, then, is it possible to get direct current from a generator?

The parts of a direct-current generator are the same as those of an alternating-current generator, with one exception: The collector contains a device called a **commutator** instead of slip rings.

Phase of alternating current: Any point on a curving line, such as that used to represent an alternating current, is called a **phase.** An A.C. generator with a bipolar armature is called a **single-phase** generator, because each point on the curving line is the same for every cycle. A.C. generators may have multipolar armatures and thus several sets of armature coils that provide additional circuits for induced currents. The result is several currents changing direction at different times. Generators supplying such currents are said to be **polyphase** generators. If two different currents are supplied, the generator is **two-phase.** A **three-phase** generator supplies three different currents. Polyphase generators are more efficient than single-phase generators, but some of them require extra wires to carry the additional currents.

Direct-current generator: A generator that supplies direct current by means of a switching device called a commutator, which changes induced alternating current into pulsating direct current. Also called **D.C. generator.**

Commutator: A switching device used to reverse the flow of an alternating current. It is used in direct-current generators and motors.

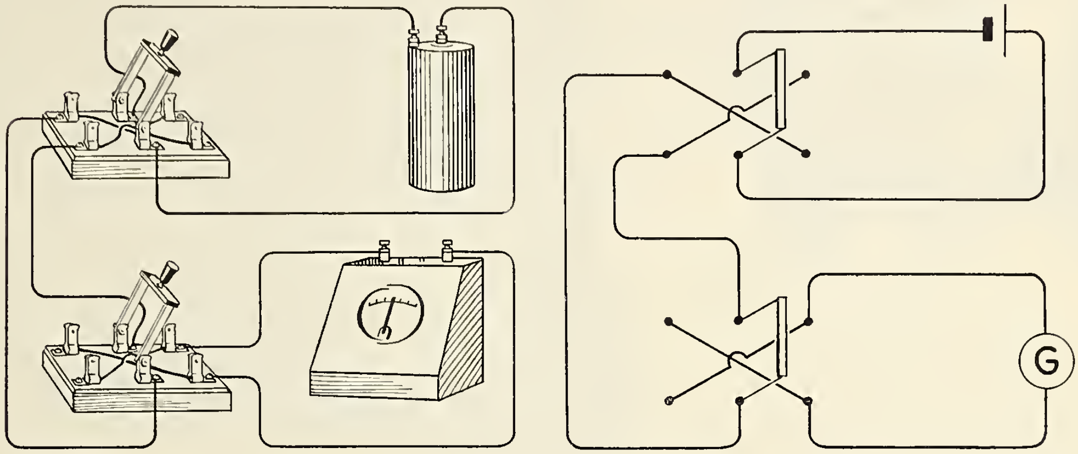
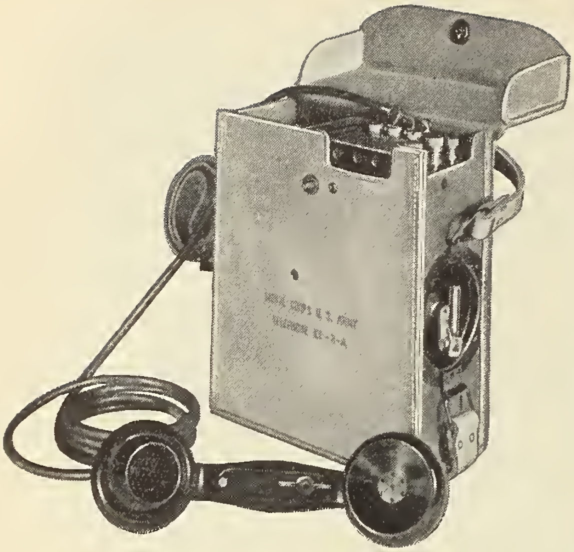


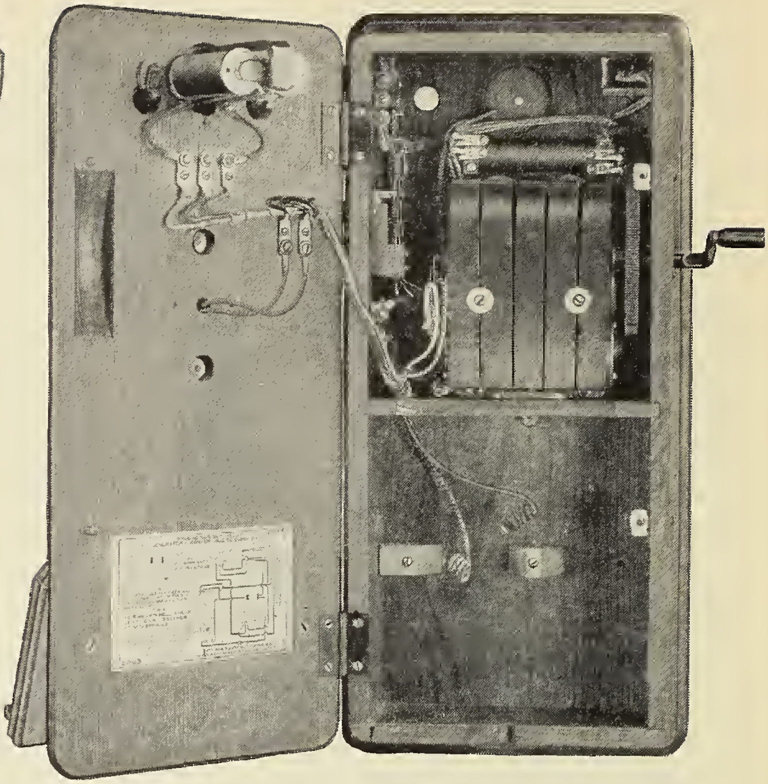
Figure 116 *shows how a commutator changes alternating current to direct current. The dry cell and upper switch at the left represent a generator, while the lower switch represents a commutator. When both switch levers are moved from side to side at the same time, the direction of the current through the 1.5-volt galvanometer does not change. The diagram at the right shows how the two reversing switches are connected.*

The commutator is a switching device that reverses the flow of current induced in the armature coil at just the right times to make a direct current flow through the external circuit. It is called a commutator, because it *commutes*, or changes, the direction of the current. You can understand why a commutator is needed and how it works if you do Experiment 48.

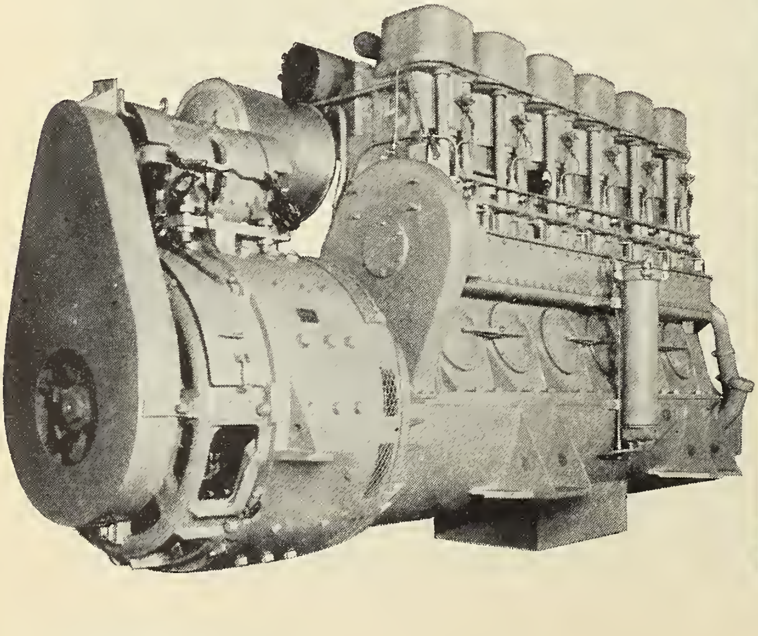
Commutation. Figure 116 shows a galvanometer connected to a reversing switch that is connected to another reversing switch attached to the terminals of a dry cell. The galvanometer and its wires represent the external circuit connected to a direct-current generator. The reversing switch connected to the galvanometer corresponds to a commutator. The other reversing switch and dry cell represent the armature coil. If you close the circuit by throwing both switches to the right, the galvanometer needles will swing to one side. Then if you throw the reversing switch connected to the dry cell to the left, the galvanometer needle will swing to the other side. In other words, by throwing this switch back and forth, you can produce a crude sort of alternating current, just as you did in Experiment 39.

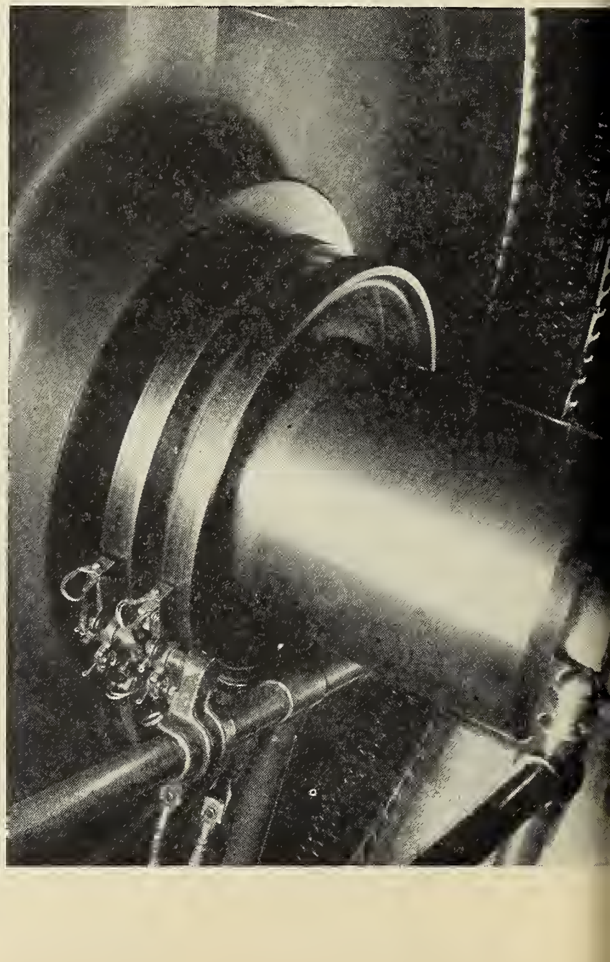
Now if you also throw the other reversing switch to the left, the needle will swing to the same side as it did at first. Thus you can use one reversing switch to cancel out the reversal of current caused by the other. When you throw both switches from side to side at the same time, the galvanometer needle swings to one side only, indicating that a direct current is flowing. The current is not steady, for the needle swings back to zero (or a little beyond) every time the circuit is opened. In other words, using a switch to reverse an alternating current produces a *pulsating* direct current. You will see that this is quite similar to

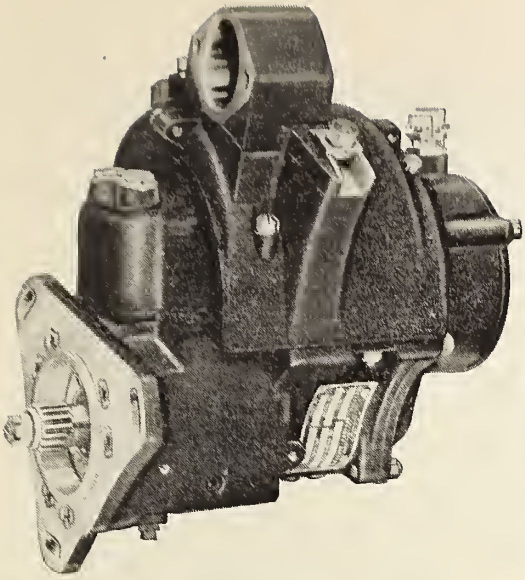




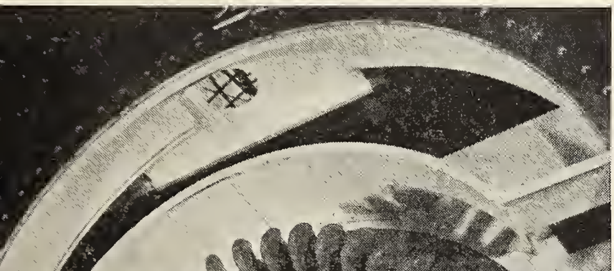
Across the top of these two pages are shown four kinds of magnetos. The Signal Corps telephone at the upper left has a small built-in magneto for calling other stations; the folded hand crank can be seen at the side of the leather case. Next is shown the inside of a wall telephone in which a magneto with five field magnets is used to call the central station; two No. 6 dry cells supply current for talking. Third from the left is a modern ignition magneto designed for use on large, high-speed airplane engines. And last, at the far right, is a two-crank magneto that delivers current at both high and low voltages to portable radio transmitters, such as those used by the Army.

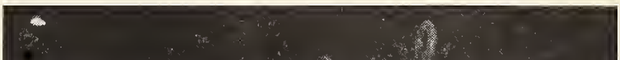






Across the bottom *of these two pages are shown four generators. The 660-horsepower generator unit at the extreme left supplies current for the Diesel-electric switching locomotive shown on page 245. Next is a close-up view of the slip rings and brushes that supply direct current to the rotating field of a large alternating-current generator. Third from the left are shown the stator and armature windings of a high-speed, turbine-driven alternator. And at the far right is a direct-current generator of medium size. Notice the many sets of brushes needed to collect the heavy current from the whirling commutator.*





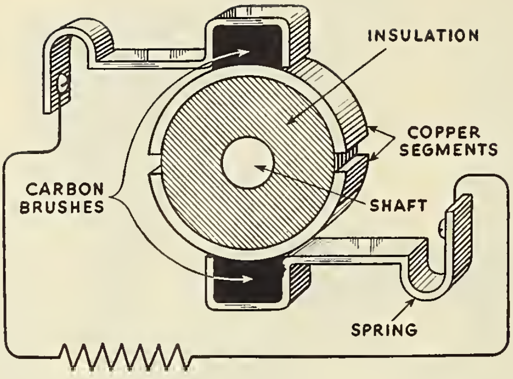


Figure 117 *shows the parts of a simple commutator suitable for one rotating loop or coil. Each end of the loop or coil is connected to a segment, and the two segments are fastened to the shaft so that they rotate with it. Carbon brushes, held against the copper segments by springs, slide on the segments and provide a path for the current. Additional coils require more segments. When the armature coils are connected in series, there are as many segments as coils.*

what happens when a commutator is used in a direct-current generator.

Operation. Like A.C. generators, D.C. generators usually have electromagnets to provide a magnetic field, though it is possible to use permanent field magnets, as in a magneto. In fact, a magneto equipped with a commutator is used by the Army to furnish small amounts of direct current for field radio sets. Unlike A.C. generators, however, D.C. generators always have rotating armatures and stationary field magnets. It is theoretically possible to make a D.C. generator with a stationary armature and a rotating field, but for engineering reasons this is not done. For one thing, the commutator must be mounted on the rotating shaft. Since the commutator is connected to the armature, it would be very awkward to have one rotate without the other. The main thing for you to learn about the operation of a direct-current generator is how the commutator is connected to do its work. You already know how current is induced in the armature.

Figure 117 shows a commutator in its simplest form. Instead of a continuous band like a slip ring, it is split into two parts, called *segments* or *sectors*. Each end of the coil is connected to a segment, and one brush is provided for each segment. Figure 118 shows how a commutator works during one rotation of the coil. In the first diagram the sides of the coil are moving parallel to the lines of force. No lines of force are cut, and no E.M.F. is induced. Just as in an A.C. generator, no current flows. Each brush touches both commutator segments. In the second diagram side A of the coil cuts upward through the magnetic field as side B cuts downward. An E.M.F. is induced, and a current flows in the coil and through the circuit. Notice that at this point each segment is in contact with only one brush. The third diagram shows the sides of the coil moving parallel to the lines of force as in the first diagram. No E.M.F. is induced, and no current flows. Again notice that each brush touches both commutator segments. The fourth diagram shows side A cutting downward through the magnetic field as side B cuts upward. Lines of force are cut in the opposite direction by the sides of the coil. An E.M.F. is induced, and a current flows but in the opposite direction to that shown in the second diagram. However, the commutator segments have rotated until each one touches the other brush. Current flows through the external circuit in the same direction as before.

By means of a commutator, the generator thus supplies a direct current to the external circuit. The curving line in Figure 118 shows that the E.M.F. increases from zero to a maximum and then decreases to zero, just as in an alternating current. However, instead of reversing, the E.M.F. again increases to a maximum and then decreases. The commutator keeps the current in the external circuit flowing in the same direction. Another thing to notice in the diagrams is that when a current is induced, the positive (+) brush is connected to the side of the coil moving upward, while the negative (—) brush is connected to the

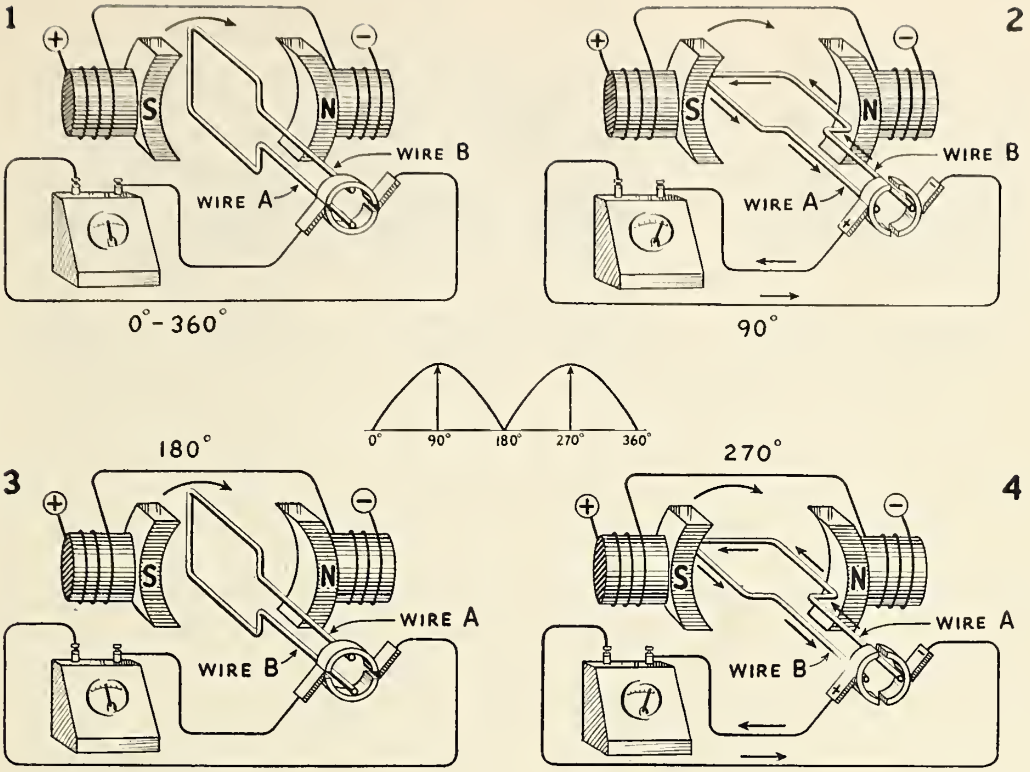


Figure 118 *shows how direct current is obtained from a generator. In diagram 1 no current flows, because no lines of force are being cut. In diagram 2 wire A is connected to the positive brush, and wire B to the negative one. In diagram 3 no current flows as the commutator reverses connections. In diagram 4 wire B is connected to the positive brush, wire A to the negative one, and the graph shows a pulsating direct current.*

side of the coil moving downward. The positive brush of a D.C. generator is always the one from which current flows out to the external circuit; the negative brush is always the one to which current flows back from the external circuit. If a demonstration D.C. generator is available, you can examine its parts and see how it works.

Bipolar and multipolar types. Like an A.C. generator, a D.C. generator may be either bipolar or multipolar. Figure 118 shows how the E.M.F. and thus the current supplied by a bipolar D.C. generator fluctuate as the generator turns. The reason for this, of course, is the same as for the fluctuations in E.M.F. and current supplied by a bipolar A.C. generator. For some purposes, the pulsating direct current furnished by a bipolar generator is not particularly objectionable. This current can be made to pulsate more rapidly by rotating the armature faster or using more pairs of field poles. Either of these things increases the frequency of the induced alternating current. As a result of the increased frequency, the pulsations are more rapid. The average E.M.F. of the current is greater, and the current appears to be somewhat smoother. Figure 119 shows a D.C. generator with one pair of field poles and another with two pairs of field poles. Notice that the poles of the field magnets are arranged like the spokes of a wheel and that there is always an even number of poles. Each pole has an unlike pole on either side of it. Multipolar generators may have four, six, eight, or even more poles.

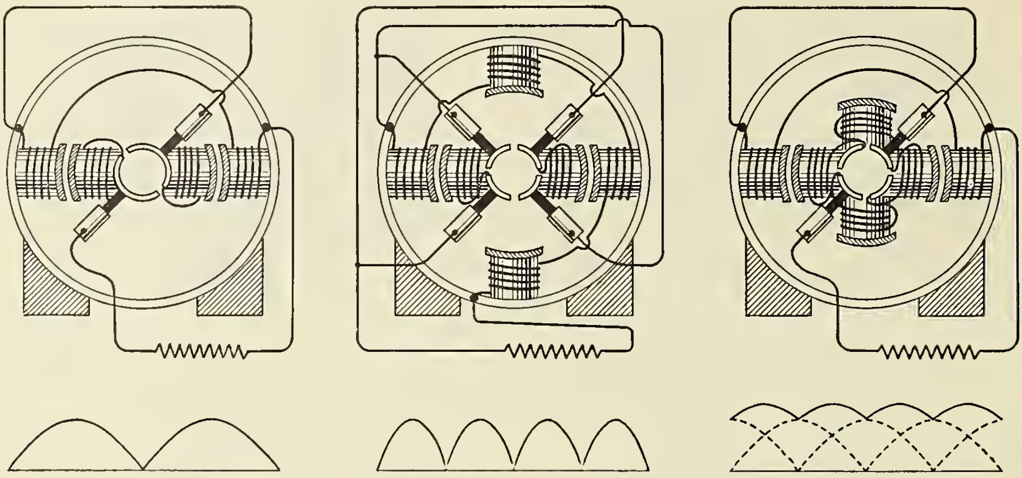


Figure 119 *shows that increasing the number of field poles increases the frequency of a pulsating direct current, while increasing the number of armature coils produces a smoother, stronger current that never drops to zero, as shown by the solid line in the graph at the right. Multipolar generators have many poles and many armature coils.*

Figure 119 shows another thing about direct-current generators. The curving line under the bipolar generator is similar to the curving line in Figure 118. If four poles (two pairs) are used, the curving line under the second generator shows what happens. The pulsations are more frequent, and the average E.M.F. is greater. An even better way to smooth out the direct current is illustrated by a generator with one pair of field poles and four armature coils. The curving lines under the generator shows how the direct current supplied by this multipolar type is made up from the currents induced in the various coils. The four coils are connected in series. When two of the coils are going through one part of the cycle, the other two are going through another part of the cycle. As a result, the E.M.F. never drops to zero in both pairs of coils at the same time, and some current always flows. You can see that the curving lines overlap and partly fill in the valleys between the curves. The other curving line indicates the current that flows through the commutator and external circuit. Notice that only the tops of the curves are shown, because the E.M.F. in the external circuit never falls to zero. Thus you can see that multipolar generators produce a smoother and stronger direct current than bipolar generators. Where large, even direct currents are required, multipolar generators must be used.

As you might suppose, the greatest source of difficulty in both types of D.C. generators is in the commutator. Generators with more than one armature coil must have at least one commutator segment for each coil; some generators have two segments for each coil. The commutator segments are ordinarily made from hard copper. Springs press the brushes against the segments. The brushes are usually made of graphite, a form of carbon. The resistance of the carbon brushes reduces sparking at the commutator caused by making and breaking the circuit. Since graphite is also a lubricant, the brushes slide smoothly over the commutator segments. Of course the brushes and commutator segments are carefully insulated from the rest of the generator. Mica, or other non-conductors, are used to insulate the commutator segments from one another and from the shaft.

Self-excited types. Unless the magnetic field of a generator is provided by permanent magnets, direct current must be furnished to the field coils. In an alternating-current generator, a small direct-current generator mounted on the same shaft is ordinarily used to supply the current to the field magnets. The A.C. generator is said to be *separately excited.* D.C. generators for special work in laboratories, for electroplating, and for testing may be separately excited by cells or by a smaller D.C. generator. However, practically all D.C. generators used to supply current commercially are of the *self-excited* type. Part or all of the direct current produced by the generator is sent through the coils of the field magnets to excite them.

Perhaps you are wondering how a self-excited generator can start producing current, since no current is induced in the armature until the field magnets are excited, and the field magnets are not excited until a current is induced in the armature. Actually, however, the cores of the field magnets never become completely demagnetized while the generator is stopped. A little magnetism (called *residual magnetism*) always remains in the cores. Even when the generator is standing idle, this magnetism produces a weak magnetic field. When the armature begins to rotate, its turns cut lines of force in this weak field, and a very weak E.M.F. is induced. The weak current that flows excites the field magnets a little more, and a somewhat stronger magnetic field is produced. This induces a greater E.M.F., and thus a larger current flows. The larger current strengthens the magnetic field, and so on until the field strength is built up to the point where the generator supplies the voltage for which it was designed. For this to happen, 20 to 30 seconds may be required.

There are three main kinds of self-excited D.C. generators: (1) the series-wound generator, (2) the shunt-wound generator, and (3) the compound-wound generator. Each kind is named from the way in which its armature and field coils are connected.

As the name suggests, the armature coil, field coils, and external circuit of a *series-wound* generator are all in series. Figure 120 shows this kind of generator. The series connection usually supplies the field coils with a large current. Therefore, only a comparatively small number of turns of wire are needed to produce the required magnetic field. As you recall from Chapter 6, the magnetizing force, or field strength, of an electromagnet is determined by the ampere-turns as well as by the permeability of the core. The larger the current flowing through the series circuit, the greater the field strength of the electromagnets, and the greater the induced E.M.F. will be. Since the external circuit usually includes a number of devices in parallel (not series), turning on more devices increases the current flowing in the entire circuit; the induced E.M.F. will be increased. On the other hand, turning off devices reduces the current flowing in the entire circuit; the induced E.M.F. will be reduced. For this reason, series-wound generators are ordinarily used in circuits where the external resistance and thus the current are kept constant. An automobile has a series-wound generator to charge the storage battery.

In *shunt-wound* generators, the field coils are connected in parallel with the armature coil and also the external circuit, as shown in Figure 120. (*Shunt* means the same thing as parallel connection.) Part of the current supplied by the generator flows through the field coils, and the rest flows through the external circuit. Thus the same current does not flow through the field coils and the external circuit. The resistance of the wire in the field coils is usually calculated so that from 1 to 5 per cent of the current induced in the armature flows through the field coils. Since the

Commutating poles are small magnetic poles set in the spaces between the field poles to counteract self-induction in the armature coil, thus reducing the sparking at the commutator as well as the braking effect on the shaft. Also called **interpoles.**

Armature wiring: In open-coil wiring, each end of the wire in every armature coil is connected to a separate segment of the commutator. In closed-coil wiring, the coils are connected in series, and the connection between each two coils is connected to a segment. Because closed-coil wiring provides a smoother current with less sparking at the commutator, it is now more commonly used.

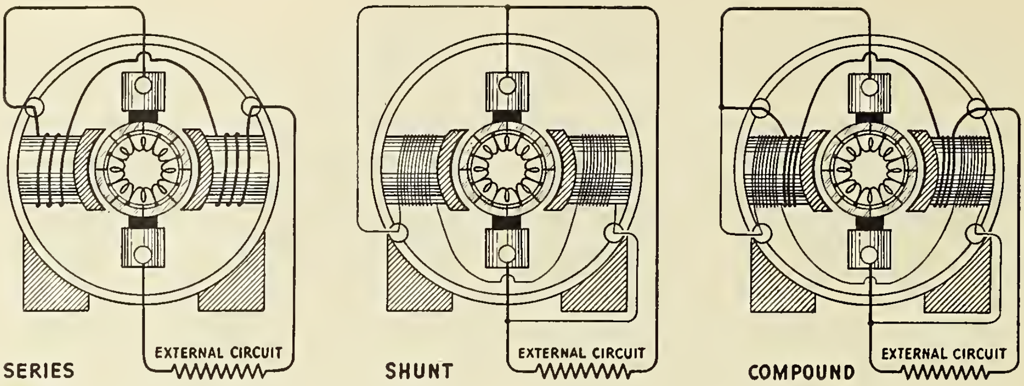


Figure 120 *shows three types of self-excited generators. In the* SERIES *generator the field coils are in series with the armature coils. In the* SHUNT *generator the field coils are in parallel with the armature coils. The* COMPOUND *generator has two sets of field coils, one set in series with the armature coils and one set in parallel with them.*

current in the field coils is comparatively small, a large number of turns are required to provide a field strength of sufficient ampere-turns.

When more devices are connected in parallel in the external circuit, more current flows through this part of the circuit, and less current flows through the field coils. As a result, the field is weakened, and the E.M.F. is reduced. Thus, in a shunt-wound generator, an increase in the current drawn by the external circuit causes a decrease in the E.M.F. (This is just the opposite to what happens in a series-wound generator.) However, under normal operating conditions the decrease in voltage is not great.

The field coils of a *compound-wound* generator have two sets of windings, as shown in Figure 120. One set is in series with the entire circuit, as in a series-wound generator. The current flowing in this winding increases when the current in the entire circuit increases. The other set of windings is connected in parallel with the armature coil, as in a shunt-wound generator. The current in this winding decreases as the current in the external circuit increases. In this way, the field magnets are strengthened by an increase of current through the series winding but at the same time are weakened by the decrease in current through the shunt winding. One effect counteracts the other. Thus compound-wound generators maintain a constant E.M.F. even when there is a wide variation in the current supplied to the external circuit.

Voltage control in series-wound and shunt-wound generators: Since generators are usually run at a constant speed, to control the voltage it is necessary to control the rate at which lines of force are cut. This can be done in a series-wound generator by connecting a rheostat across (in parallel with) the field coils. When the rheostat is off, the total current flows through the field coils, and the magnetic field reaches its greatest strength. However, if the rheostat is turned on, some of the current then flows through the rheostat, thus reducing the current through the field coils. As a result, the magnetic field is weakened, and the voltage is reduced.

In a shunt-wound generator, a rheostat is connected in series with the field coils. By increasing the resistance of the rheostat, the current through the coils can be reduced. This weakens the magnetic field and thus reduces the voltage.

Uses of direct current and alternating current. As mentioned before, direct current is required to produce chemical changes, such as electrolysis, electroplating, and charging storage cells. For example, the generator in an automobile supplies direct current for charging the storage battery. Direct current is also used for communication purposes. One use, the field radio set operated by a D.C. magneto, has been mentioned. Arc lights and arc welding require direct current for good results, although spot welding can be done with alternating current. But the main advantage of direct current over alternating current is that it can be more easily used to control motors. For example, the speed of a motor using direct current, as in a streetcar or electrically driven train, is more easily regulated than if alternating current is used. This is particularly true when motors must start with a large load. In areas where large motors are used, the transmission lines often supply direct current.

However, direct current is costly to transmit, because its voltage cannot be raised and its amperage lowered by transformers. Large conductors are required, and the power losses are high. In Chapter 8 you learned why high-voltage currents can be transmitted with much less loss than low-voltage currents of the same power. Smaller conductors can be used with high-voltage currents, because their amperage is lower than for the same amount of power at a lower voltage. By means of a step-up transformer, the voltage of an alternating current can be easily increased while its amperage is decreased. The high-voltage alternating current can then be transmitted over long distances with much less loss than with low-voltage current of the same power. Because of the economy of transmission, alternating current has replaced direct current in many places. Users who require direct current must then install their own direct-current generators run by constant-speed alternating-current motors.

The development of different types of alternating-current motors and the rapid progress in making devices to control such motors are also responsible for the shift from direct current to alternating current. In the next chapter you will learn about direct-current and alternating-current motors.

CHECKING WHAT YOU LEARNED

1. Name the main parts of a direct-current generator and tell what each part does.
2. Describe one complete rotation of a direct-current generator having two field poles and a single moving coil. Tell what happens to the induced current and explain why it happens.
3. Why does using more pairs of field poles or more armature coils produce a smoother current from a direct-current generator?
4. **a.** What is meant by a separately excited generator? By a self-excited generator? **b.** Name the three kinds of self-excited generators and explain what each name means.
5. Explain how it is possible for a self-excited generator to induce a current as it starts to turn.
6. **a.** Why is alternating current replacing direct current in many places? **b.** Give some reasons for using direct current instead of alternating current.

USING WHAT YOU LEARNED

1. Is it correct to say that the same kind of current is produced in all generators? Why?
2. How can you easily tell which kind of current a generator furnishes without testing the current? Explain.
3. A generator is described as being self-excited. What kind of current will it supply? How do you know?
4. How does the direct current furnished by a generator differ from that supplied by a storage battery? Why?

THINKING OVER WHAT YOU LEARNED

1. After each topic in this chapter state the big ideas you learned, using complete sentences.
2. By using a definition or sentence, show that you understand the following: **a.** field magnet, **b.** series-wound, **c.** bipolar, **d.** commutator, **e.** brush, **f.** magneto, **g.** pole piece, **h.** separately excited, **i.** shunt-wound, **j.** field pole, **k.** alternator, **l.** multipolar, **m.** slip ring, **n.** compound-wound, **o.** self-excited, **p.** collector, **q.** armature.

Experiment 45: **Inducing a Current in a Rotating Coil**

THINGS NEEDED: Steel knitting needle (or stiff wire at least 6 inches long). No. 30 cotton-covered or enamel-coated copper wire. Thread. Two U-magnets. Sensitive galvanometer. Two bar magnets. String. Overhead support.

WHAT TO DO: **a.** Wind an oval coil of about 100 turns of wire and fasten the turns of the coil with thread. Carefully push the knitting needle through the length of the coil so that you can rotate the coil by twirling the needle between your fingers. Connect the ends of the wire to the galvanometer. Hold the coil between the poles of a U-magnet, as shown in Figure 105. Rotate the coil rather rapidly and watch the galvanometer needle. What happens? Does the needle indicate a reversal of current? What difficulty would you have in keeping the coil turning in one direction all the time?

b. Repeat Part **a**, using two U-magnets. First try like poles together and then try unlike poles together, placing the magnets alongside each other. Also try rotating the coil faster or slower, using first one and then both magnets. If you wish, you may use a coil with more or fewer turns. Then use two bar magnets in place of the U-magnets. Rotate the coil between the N pole of one magnet and the S pole of the other magnet.

c. Set the coil in an upright position between the poles of a U-magnet suspended from an overhead support, as shown in Figure 106. Twist the string and then let it unwind. As the magnet spins about the coil, watch the galvanometer needle. What happens? What difficulty encountered in Part **a** is eliminated? If you wish, you may try using two U-magnets tied together with like poles touching.

Experiment 46: **Examining and Operating a Magneto**

THINGS NEEDED: Demonstration magneto. 15-watt bulb and socket. Galvanometer. Headphones (or telephone receiver). No. 18 insulated copper wire.

WHAT TO DO: Find the various parts of the magneto shown in Figure 107. Then connect the galvanometer to the terminals of the magneto and turn the crank very slowly. Watch the galvanometer needle and notice what happens. How does this compare with your results in Part **a** of Experiment 45? Connect the headphones in place of the galvanometer. Again turn the crank slowly. Listen to the sound produced in the headphones. How does this compare with the results of Experiment 39? Try turning the crank faster and then slower. What do you hear? Explain what this indicates. Now connect a 15-watt bulb to the terminals of the magneto. Try turning the crank at various speeds and observe what happens to the brilliance of the bulb. Explain the results. (If possible, try removing one or more of the field magnets.) Then disconnect the bulb and turn the crank at various speeds. What do you notice? Explain.

Experiment 47: **Bipolar and Multipolar Field Magnets**

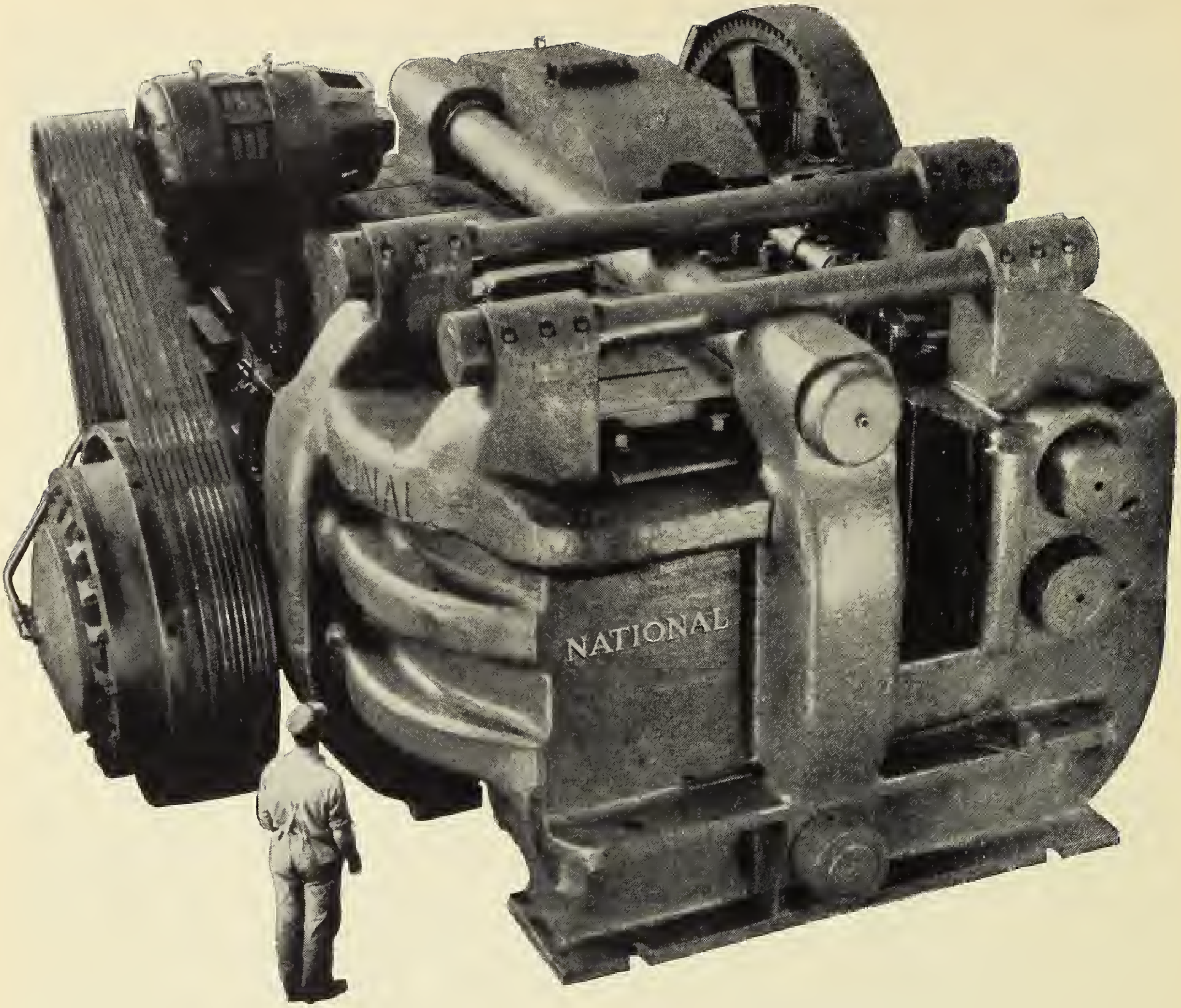
THINGS NEEDED: Coil, knitting needle, two U-magnets, and sensitive galvanometer from Experiment 45.

WHAT TO DO: Connect the ends of the wire to the galvanometer. Rotate the coil between the poles of a U-magnet, as in Part **a** of Experiment 45. Observe the galvanometer needle. Now place another U-magnet across from the first one but separated by a small space, as shown in Figure 114. Be sure that unlike poles of the two magnets are facing each other. Now rotate the coil at about the same speed as before in the space between the magnets and observe the galvanometer needle. What happens? How do the results compare with those obtained when only one pair of field poles were used? (If you wish, you may repeat the experiment with like poles facing each other. Also try using four bar magnets with their poles alternated. To do this, set the magnets on supports and rotate the coil vertically.)

Experiment 48: **Commutation**

THINGS NEEDED: Two reversing switches (double-pole, double-throw). Galvanometer. 3000-ohm resistor. No. 6 dry cell. No. 18 insulated copper wire.

WHAT TO DO: Connect the apparatus as shown in Figure 116. (If the galvanometer cannot be used on 1.5 volts, you must use the resistor.) Close the circuit by throwing both switches to the right. What happens to the galvanometer needle? Now throw the switch connected to the cell to the left. Observe the galvanometer needle. Now throw the other reversing switch to the left. What happens to the galvanometer needle now? Try throwing the two switches back and forth in the same direction at the same time, using both hands. Carefully observe the galvanometer needle. What kind of current is flowing through the part of the circuit containing the galvanometer? Is it steady or does it fluctuate? Does it alternate? Explain your results.



10. Motors

FINDING OUT WHAT YOU KNOW

1. What energy change takes place in a generator? In a motor?

2. Name the main parts of a simple electric motor and tell what each part does.

3. Explain briefly how a motor works.

4. List as many uses of electric motors as you can.

5. How does the speed of a motor affect the amount of current used?

6. Why do you think electric motors are so widely used?

7. Can a generator be used as a motor? Explain.

8. Why does an electric clock keep good time?

THE MAIN REASON WHY electric current is so useful is that it provides such a convenient way to transmit energy from where the energy is available to where the energy is needed. As you know, energy is the ability to do work. Many different devices make use of the energy of electric current. But when we think of electrical energy doing work, we are likely to think first of electric motors, because the energy change in motors is more obvious than in many other electrical devices. Motors change electrical energy to mechanical (kinetic) energy by means of magnetism. Thus, the energy change which takes place in motors is exactly opposite to that in generators.

Electric motors are used a great deal for all sorts of purposes. In our homes, motors furnish the force to sweep floors, run refrigerators, wash clothes, whip cream, mix cake, operate sewing machines and fans, move the hands of clocks, and even run model locomotives. On farms, motors are used to run machines for grinding grain, sharpening tools, chopping feed, milking cows, and pumping water. Motors run all sorts of machines in shops and factories. Automobile and airplane engines are started with electric motors. Streetcars, electric trains, streamlined trains, and some trucks are run by electric motors. Ocean liners and modern warships are often operated by electric motors. If all the electric motors were destroyed, the world would be in serious trouble for a long time.

No one kind of electric motor can do all the jobs we have mentioned. For some jobs direct-current motors are most satisfactory; for other jobs alternating-current motors are just as good or even

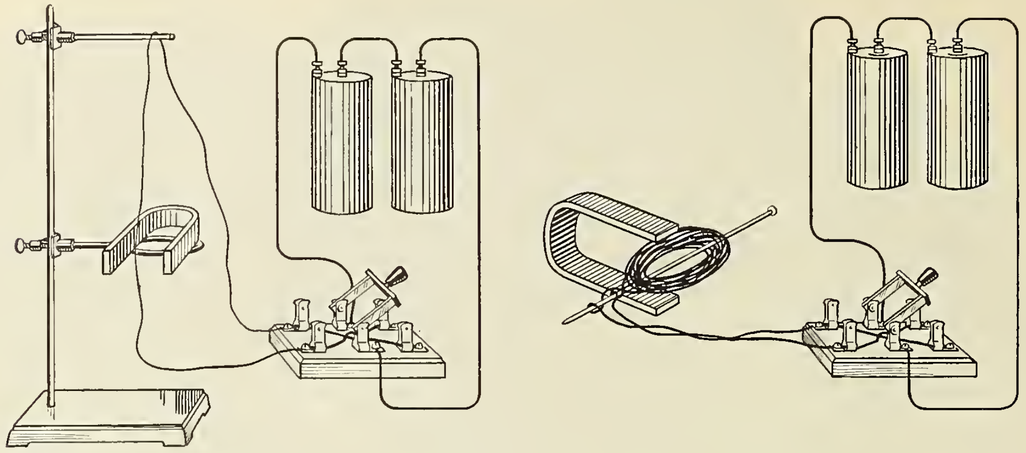


Figure 121 *shows that the direction of the current determines which way a current-carrying conductor will move in a magnetic field. The wire at the left moves forward when the switch lever is thrown to one side, and the opposite way when the lever is thrown to the other side, reversing the current. A coil of many turns, as shown at the right, can be made to turn one way and then the other by throwing the switch lever from side to side.*

better. Tiny motors that will fit into a thimble have been made for special purposes. To drive battleships and ocean liners, huge motors designed to handle thousands of kilowatts of power are used. In an electric clock the motor must run at a certain speed, while in a streetcar the motor must work effectively at a variety of speeds. For some purposes a motor must provide a strong twisting or turning action, or high starting *torque*, at the instant the shaft begins to turn; for other purposes the motor has no load until the shaft is turning at full speed. Obviously, different kinds of motors are required for different uses. In this chapter you will learn how various kinds of motors work.

Current-Carrying Conductor in a Magnetic Field

In Chapter 6 you learned about several devices that change electrical energy into mechanical energy by means of magnetism. For example, the magnetic effects of an electric current produce motion in an electric bell. Actually, the bell is operated by a very simple back-and-forth motor. Some of the first electric motors worked much as a bell does. However, to produce steady, rotary motion, a different plan must be used. You know that a current is induced in the wire of a circuit when the wire is moved across lines of force in a magnetic field. In other words, mechanical (kinetic) energy used in moving the wire or the magnetic field is changed into electrical energy. With a single wire and a magnetic field you can also show that electrical energy can be changed into mechanical (kinetic) energy, or motion. Experiment 49 (page 250) tells you how to do this.

In the experiment a length of small insulated wire is suspended between the poles of a strong U-magnet, as shown in the picture at the left in Figure 121. The ends of the wire are connected

---

Torque: Twisting or turning. Torque is not the same as force, since it is the result of force acting at a distance to produce rotation. At a distance of one foot from the center of rotation a force of one pound produces a torque of one pound-foot (**not** foot-pound).

Left-hand rule for motor: Extend the thumb, forefinger, and center finger of the left hand so that they are at right angles to one another, as shown in Figure 122. If the forefinger points in the direction of the magnetic flux, and the center finger points in the directon of current flow (from positive to negative), the thumb will point in the direction of motion of the conductor.

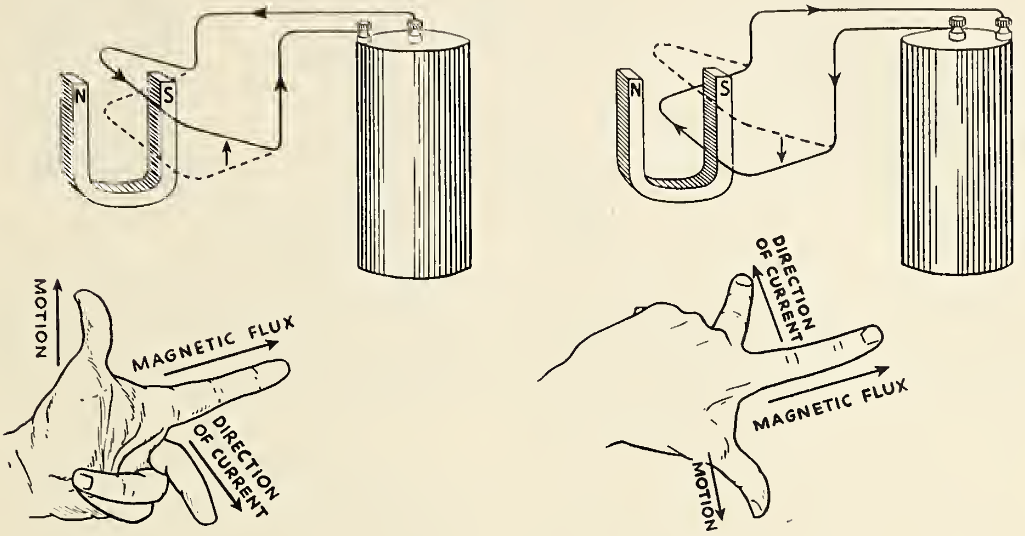


Figure 122. *These diagrams will help you learn to use the left-hand rule for motor. Notice that the forefinger always points in the direction of the magnetic flux— that is, from N to S; the center finger always points in the direction of the current—that is, from positive to negative; and the thumb always points in the direction in which the conductor moves. When any two of these elements are known, the third can be quickly found.*

through a reversing switch to a battery of two dry cells in series. The purpose of the switch, as you know, is to provide an easy way to reverse the current through the wire. When you close the circuit by throwing the switch to one side, the wire is pushed out of the magnetic field in one direction. Now if you reverse the current through the wire by throwing the switch to the other side, the wire is pushed out of the magnetic field in the opposite direction.

You can make the wire move faster, that is, with more force, if you send more current through the wire by adding cells in series or strengthen the magnetic field by adding another U-magnet.

If the experiment is repeated with the wire in a horizontal position and the magnet in a vertical position, the wire will be pushed upward when the current flows in one direction and downward when the current flows in the opposite direction. You will get the same results if the wire is placed between the poles of an electromagnet. Of course, the motion of the wire will be faster, if the electromagnet has a stronger field than the U-magnet. Another thing you might try is using the coil from Experiment 45. If the coil is connected to the reversing switch and battery and then supported between the poles of a U-magnet, as shown in the picture at the right in Figure 121, the coil will turn first in one direction and then in the opposite direction as you reverse the current through the coil. If you reverse the poles of the magnet in any part of this experiment without reversing the current, the wire (or coil) will move in the opposite direction. Obvi-

Motion of a current-carrying conductor in a magnetic field: Whenever a current-carrying conductor is in a magnetic field, it tends to move in a direction at right angles to both the direction of current flow and the direction of magnetic flux.

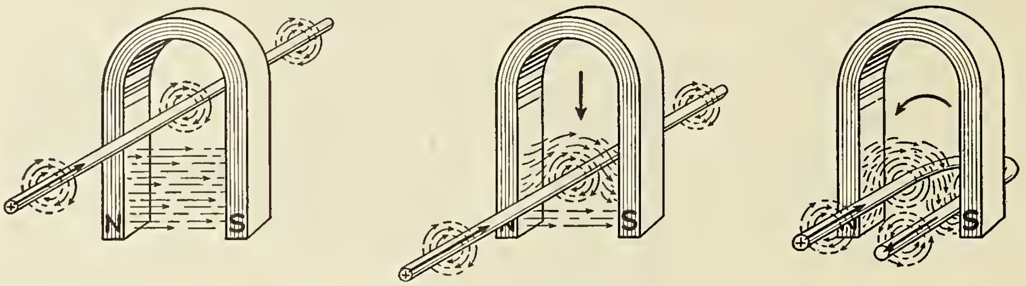


Figure 123. *At the left are shown the lines of force around a current-carrying conductor about to enter the field of a magnet. The center diagram shows how the lines of force pile up one side of the wire, pushing it downward. At the right a current-carrying loop is caused to turn as the lines of force push down on one side and push up on the other side.*

ously, there is some relation between the direction of magnetic flux, the direction of current flow, and the direction of movement of the wire (or coil). Figure 122 illustrates a rule, called the **left-hand rule for motor**, which shows what this relation is. Except for the use of the left hand, it is exactly the same as the right-hand rule for generator shown in Figure 83 (page 154).

You can understand the results of Experiment 49 better if you refer to Figure 123. The diagram at the left shows the magnetic field between the poles of a U-magnet, while above it is shown the magnetic field around a wire carrying a current. The middle diagram shows what happens when the wire is placed between the poles of the U-magnet. You can see that the lines of force of the magnet and of the wire flow in the same direction *above* the wire. The result is an increase in the lines, or a strengthening of the flux, above the wire. However, the lines of force of the magnet and of the wire flow in opposite directions *below* the wire. The result is a decrease in the lines, or a weakening of the flux, below the wire. Since the flux is stronger above the wire than below the wire, the wire is forced downward. You remember that lines of force act somewhat like stretched rubber bands; the greater number of lines of force above the wire appears to push downward on the wire as the wire "stretches" them.

If the direction of current flow through the wire is reversed, the direction of the magnetic flux around the wire reverses. As a result, the wire is pushed upward instead of downward. The same thing will happen if the poles of the magnet and thus the direction of its flux with relation to the wire are reversed. The diagram at the right in Figure 123 shows a loop of wire between the poles of the U-magnet. The two arrows represent current flow in the opposite sides of the loop. Since the current flows in one direction through one side and in the opposite direction through the other side, the magnetic flux around the wire on one side is clockwise and counterclockwise on the other side. The flux of the magnet is strengthened above one wire and weakened above the other. As a result, one side is pushed down as the other side is pushed up. If you did all of Experiment 49, you saw the coil turn part way around as a current was sent through its wire.

At about the same time, the British scientist, Michael Faraday, and the American scientist, Joseph Henry, observed the motion of a current-carrying conductor in a magnetic field. They saw that the direction of motion depends on the direction of current flow and the direction of magnetic flux. Their observations may be stated as a scientific law: *Whenever a current-carrying conductor is in a magnetic field, it tends to move in a direction at right angles to both the direction of current flow and the direction of magnetic flux.* Motors operate on the principle stated in this law. Electrical energy in the wire is changed to mechanical energy, or motion, by means of magnetism.

CHECKING WHAT YOU LEARNED

1. What does a wire in a strong magnetic field do when a current is sent through the wire? When the current is sent in the opposite direction?
2. If the poles of a magnet are reversed without the current being reversed in the wire between the poles, what happens?
3. **a.** Tell what determines the direction of motion of a wire carrying a current in a magnetic field. **b.** State the direction in which such a wire will move.
4. If a coil is supported in a strong magnetic field, what happens when a current is sent through the coil? When the current is sent in the opposite direction?
5. State the left-hand rule for motor.
6. Explain why a wire carrying a current will move in a magnetic field.

USING WHAT YOU LEARNED

1. Refer to the center diagram in Figure 123. Draw a similar diagram of a wire carrying a current in a magnetic field but reverse the poles of the U-magnet. Use arrows to indicate the directions of magnetic flux, current flow, and motion.
2. Current flows from north to south in a wire placed in a magnetic field whose flux is from east to west. Which way will the wire move?
3. A wire moves upward when placed in a magnetic field whose flux is from front to back. What is the direction of current flow in the wire?
4. How could you use a wire carrying a current to determine the polarity of a U-magnet?

The Direct-Current Motor

A generator changes mechanical energy to electrical energy by means of magnetism, while a motor does just the opposite: It changes electrical energy to mechanical energy by means of magnetism. Perhaps you are wondering whether a generator could be used as a motor, or a motor as a generator. If the motor or generator is designed for use with direct current, one can be used in place of the other. In fact, the D.C. generator in an automobile may run as a motor if the belt or shaft connecting it to the gasoline engine breaks or if the automatic "cut-off" fails to work properly. Current from the storage battery will flow through the generator, making it turn like a motor.

The fact that direct-current motors and generators are interchangeable has been put to good use in some streetcars and electric locomotives. Several electric motors geared to the wheels drive the car or locomotive. By throwing a switch, the motors become generators turned by the wheels, and current is sent back into the transmission line (overhead wire and track). Of course, when the wheels turn the generators, mechanical energy is used. This energy comes from the moving car or train. As a result, the car or train slows down. Using a motor as a generator in this way is called *regenerative braking*. It avoids the undue wear on the wheels caused by friction brakes in stopping quickly or slowing down on steep hills.

A direct-current motor, or D.C. motor, has exactly the same parts as a direct-current generator: field magnets, armature, and commutator and brushes. The field magnets may be either permanent magnets or electromagnets. As you might guess, electromagnets provide the field in all powerful motors. The field magnets may be bipolar or multipolar, depending on the use for which the motor is intended. Multipolar field magnets are used in motors that must pull with great force at slow speeds. The armature of a D.C. motor may also be bipolar or multipolar, that is, it may have two or more coils wound on its core. Usually, there is an odd number of armature poles. This arrangement prevents the motor from stopping on *dead center,* that is, in a position in which it will not turn when a current is sent through the armature coils. A bipolar arma-

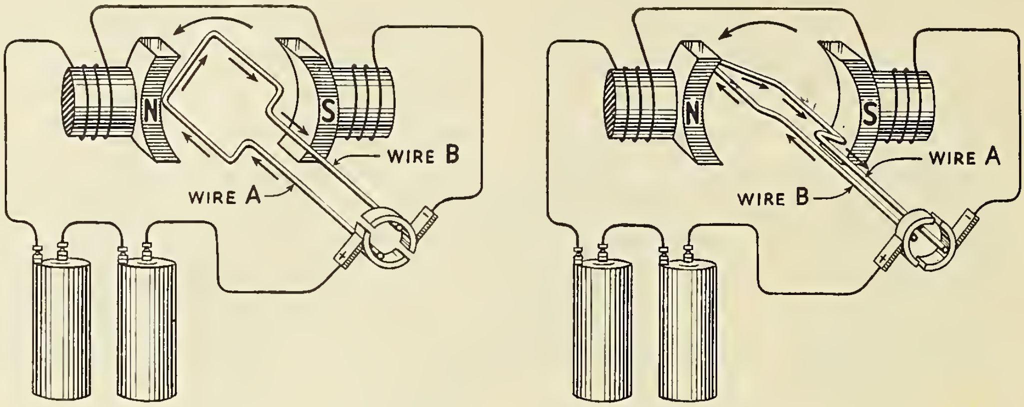


Figure 124 *shows the operation of a commutator in a simple direct-current motor. At the left the positive brush is connected to wire A, and the negative brush to wire B. At the right the loop has turned so that the commutator now connects the positive brush to wire B, and the negative one to wire A. As a result, the left side of the loop is always being pushed down, while the right side is being pushed up—thus causing the loop to turn.*

ture is on dead center when its poles are directly in line with the field poles. The armature coils are connected to the external circuit by a commutator and brushes, which are just like those in a D.C. generator. There is at least one commutator segment for each armature coil.

Operation. In the second part of Experiment 49, a current was sent through a coil in a magnetic field. The coil turned as one side was pushed up while the other side was pushed down. When the coil reached a point where its poles were in line with the magnetic field, it stopped turning. In order to keep the coil turning, the current flowing through it must be reversed. Just as in a D.C. generator, the commutator of a D.C. motor acts as a reversing switch. However, in the motor the commutator reverses the direct current supplied by a source of electrical energy. Let us see how the commutator of a D.C. motor reverses the current at just the right times to keep the armature turning.

Figure 124 shows one rotation of a simple D.C. motor with two field poles and a single turn of wire for an armature coil. Actually, there are many turns in an armature coil, and the armature has an iron core. The first diagram shows side A of the coil being pushed down as side B is pushed up. Arrows show the direction of current flow and the direction of rotation. Each commutator segment is in contact with a brush. The second diagram shows what happens as the armature continues to turn. Side A is now pushed up as side B is pushed down. Each commutator segment is now in contact with the other brush. As a result, the current flows in through side B of the armature coil and then out through side A. But since the armature coil has turned, the current still flows in on the side that is pushed down, and out on the side that is pushed up. In other words, current always flows in one direction on the left side of the armature coil and in the other direction on the right side. The force exerted on each side of the armature is thus always in the same direction, and the armature rotates in one direction.

If you wish to see how a simple D.C. motor operates, you can make one in Experiment 50. Figure 125 shows such a motor made from two U-magnets and an armature coil wound on a cork. The commutator segments are nails, and the brushes are the bare ends of wires connected to

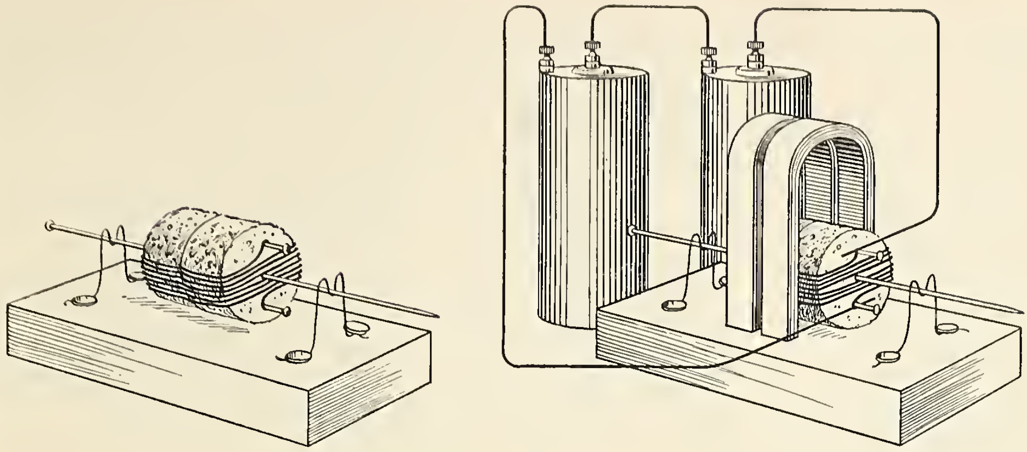


Figure 125. *At the left is shown the armature of a simple direct-current motor that you can make. The coil is wound on a large cork, each end of the wire being fastened to a small nail that takes the place of a commutator segment. At the right is shown the motor with the field magnets in position. It is necessary to hold the battery wires so that the bare ends make contact with the small nails twice during each rotation of the armature.*

two dry cells in series. The shaft is a long needle supported on bearings made of bent wires. When the wires from the dry cells are touched to the nails, the armature turns. The current going in one direction in all the wires on one side of the armature coil causes that side to be pushed up through the magnetic field, while the same current going in the other direction in all the wires on the other side of the coil causes that side to be pushed down. When one side is pushed up as the other side is pushed down, the armature turns.

When the armature turns, the nails (commutator segments) turn away from the bare ends of the wires (brushes). Inertia keeps the armature turning until the nails touch the wires again. Now the nails are reversed, and current flows through the coil in the opposite direction. But the position of the turns of wire has also been reversed, so that the side of the coil that was pushed down on one side is now pushed up on the other side.

One trouble with the simple D.C. motor in the experiment is that it turns in "fits and starts;" in other words, its rotation is not steady. Its operation could be improved by adding another coil at right angles to the first one or by adding several coils. Then with the proper changes in the commutator and brushes at least one set of armature coils would be pushed up or down at all times. Commercial electric motors have several armature coils wound with many turns of wire about an iron core. A large current is sent through the coils in order to change large amounts of electrical energy into mechanical energy. A strong magnetic field is supplied by electromagnets, whose magnetism is controllable. Thus the mechanical energy supplied by a motor depends on three things:

1. The number of turns in the armature coils.
2. The amount of current flowing through the armature coils.
3. The strength of the field magnets.

Obviously, using an iron core in the armature will strengthen the field set up by the armature coil. As you know, the poles of a coil are at either end. By means of the right-hand rule for coil, you can determine the polarity of the armature coil when current is sent through it. If you do Experiment 51, you can observe the effect of the field poles on the armature poles. Figure 126 shows a coil suspended at right angles over a U-magnet whose poles point upward. The coil is connected

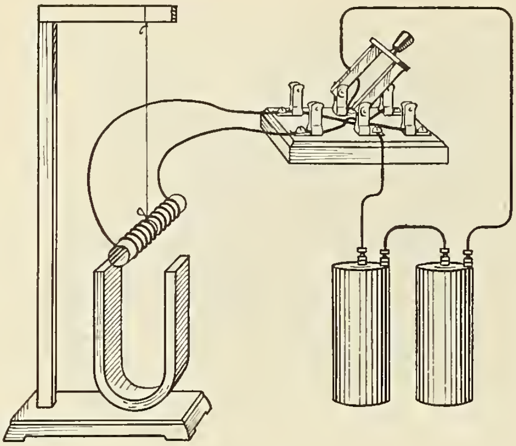


Figure 126. *A coil suspended over the poles of an upright U-magnet, at right angles to the magnetic flux, will turn to the left when a current is sent through the coil in one direction, and to the right when the current is sent through the coil in the other direction. Thus the coil acts like the armature of a motor. When a large iron nail is put into the coil, the coil turns with more force, indicating that an armature coil with an iron core can exert more force than one with an air core.*

to a battery of two dry cells in series through a reversing switch. When the circuit through the coil is closed by throwing the switch to one side, the coil turns in one direction. If the current through the coil is reversed, the coil turns in the other direction.

When an iron nail is placed in the coil and a current is sent through the coil as before, the coil turns faster, indicating that it moves with more force. Another way to make the coil turn with more force is to add another U-magnet with its poles touching the like poles of the first magnet. Of course, you could also increase the number of turns in the coil or send more current through the coil. If the U-magnet is held so that its poles are in line with the poles of the coil, the coil will not turn in either direction. The coil is on dead center, because its turns are not pushed sidewise by the magnetic field between the field poles. When a bipolar armature is in this position, the motor will not start. However, once the motor is started, inertia keeps the armature moving past dead center.

Back E.M.F. If you do Experiment 52, you can observe a curious fact about motors. When a motor is operated with no load, that is, when it is doing no useful work, it runs at full speed. An ammeter connected in the circuit, as shown in Figure 127, shows that the motor is using very little current when it is running at top speed. However, when the motor is used to run some device, it slows down. You can easily tell this by listening to its hum. As the speed of the motor decreases, more and more current is drawn. This is probably not what you would expect to happen, because a decrease in speed usually means that less energy is used. Let us see why the current drawn by a motor increases with a decrease in speed and also decreases with an increase in speed.

In Chapter 7 you learned that an E.M.F. is produced in a conductor, especially a coil, as a result of self-induction. When the self-induced E.M.F. opposed the **impressed E.M.F.**, that is, the E.M.F. supplied to the circuit or any part of it, we called the self-induced E.M.F. a **back E.M.F.**, or **counter E.M.F.** A back E.M.F. acts against the impressed E.M.F. and reduces the current. In accordance with Lenz's Law, the back E.M.F. in a conductor has such a direction that it opposes the E.M.F. which induced it. Now how does this explain what happens in a motor?

Whenever a conductor cuts lines of force, an E.M.F. is induced in the conductor. The armature coils of a motor contain many turns of wire. As the armature rotates, the lines of force in the magnetic field provided by the field magnets are cut by the turns of the coils. An E.M.F. is induced in the generator. In this respect, the motor acts as a generator. The direction of the induced E.M.F. is the same as it would be if the motor were used as a generator. In other words, the induced E.M.F. is a back E.M.F. that opposes the

Impressed E.M.F.: The electromotive force supplied to a circuit or any part of it.
Back E.M.F.: An induced electromotive force that opposes the impressed electromotive force and thus reduces the current. Also called **counter E.M.F.**

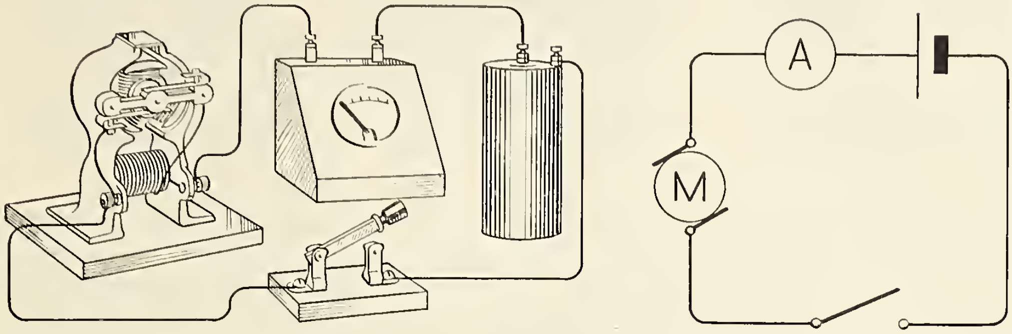


Figure 127. *The ammeter in series with the small motor at the left shows that less current is used by the motor at high speeds than at low speeds. The explanation for this is that at high speeds the motor produces a greater back E.M.F., allowing less current to flow through the motor windings. At the right is a diagram of the circuit at the left. Notice the symbol often used for a motor in electrical diagrams.*

impressed E.M.F. supplied to the armature coils. As you know, the direction of the back E.M.F. is determined by Lenz's Law. Now let us see how this back E.M.F. affects the current flowing through a motor at different speeds.

When the motor is started with no load, it picks up speed and induces a back E.M.F. in the armature. The faster the motor turns, the greater is the back E.M.F. You know that this is true because the strength of an induced E.M.F. depends on the number of lines of force cut per second. When the motor is turning at top speed, the back E.M.F. is almost equal to the impressed E.M.F. Only enough force is used to overcome the friction in the motor. For example, suppose that the impressed E.M.F. is 100 volts and the back E.M.F. is 98 volts. The *effective voltage* driving the current through the motor is equal to the difference between the impressed E.M.F. and the back E.M.F., or 2 volts. With this small voltage only a small current can be forced through the coils of the motor. Thus, a motor operating with no load uses very little current. When the motor is used to turn some device, such as a fan, saw, or lathe, it slows down. As it slows down, the rate of cutting lines of force decreases, and thus the back E.M.F. is reduced. Since the impressed E.M.F. remains the same, the effective voltage increases because it is the difference between the impressed E.M.F. and the counter or back E.M.F.

If you have ever operated a machine driven by a motor, you may have had the experience of jamming the machine so that it stuck. When this happens, the motor stops, too. It gets very hot at once; and if the current is not shut off, the heat developed may be great enough to melt the wires in the motor or to set the insulation on fire. You can easily see why this happens. The resistance of the coils in a motor is very small. If the armature is kept from moving, a large current immediately flows through the coils because no back E.M.F. is induced to oppose the impressed E.M.F. For example, a motor operating on 100 volts may have a resistance as low as .5 ohm. If there is no back E.M.F. opposing the impressed E.M.F., the pressure of 100 volts will force a current of 200 amperes through the motor coils (by Ohm's Law, $I = \frac{E}{R} = \frac{100}{.5}$ or **200 amperes**). Such a large

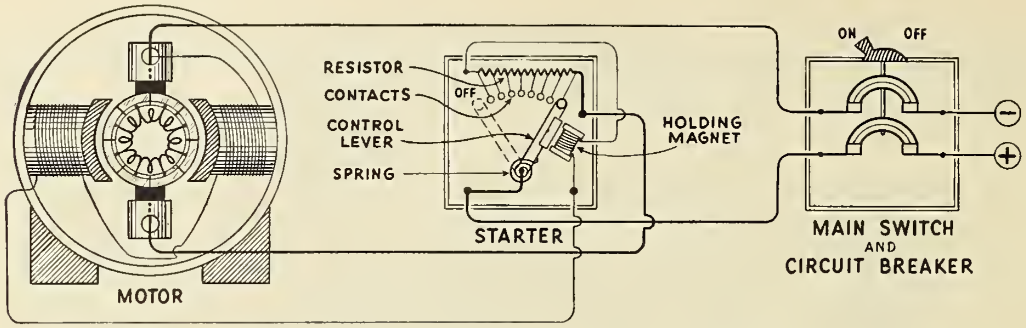


Figure 128. *Large D.C. motors are protected with both starter and circuit breaker. The starter limits the current while the motor is being brought up to full speed. Interrupting the current in any way causes the holding magnet to release the control lever, which is moved back to* OFF *by a spring. Overloading the motor in any way trips the circuit breaker.*

current will of course produce a great deal of heat and may "burn out" the motor. If for any reason a motor or a machine driven by a motor jams, shut off the current as quickly as possible.

Now that you know why a motor uses more current at slow speeds than at fast ones, you also know why a motor heats up more when it is used to turn a heavy load. The load slows down the motor, thus reducing the back E.M.F. and increasing the current through the coils. You know that the heat (in calories) produced by a current is represented by the formula $\mathbf{H = .24\ I^2Rt}$. Since the resistance of the motor remains the same, the heat produced increases as the square of the current. The slower the motor turns, the smaller is the back E.M.F. and the larger is the current. Since the power loss is given by the formula $\mathbf{P = I^2R}$, you can also see that there is a greater loss in power when a motor is turning slowly than when it is running at top speed.

Starting resistor. If you have ever seen a large motor started in a factory or machine shop, you probably noticed that a *starting resistor,* or *starter,* was used. First a switch is thrown, closing the circuit, and then the control lever, shown in Figure 128, is moved so that it touches the first contact point. The motor then starts to turn. As it picks up speed, the lever is quickly moved to the next contact point, where it is held for a few seconds. Then as the motor continues to turn more rapidly, the lever is moved to the third contact point, and so on. Now let us see why this method of starting a large motor is necessary.

Since the armature is heavy, it has a great deal of inertia. A large force is needed to start it turning. But if the full voltage of the power line is impressed on the motor, a large current will flow and probably burn out the motor. The reason for this, of course, is the fact that no back E.M.F. is induced when the motor is not turning. To prevent a large current from flowing when a motor is started, some kind of starting resistor is used.

A starting resistor is a rheostat. It usually has a coil of many turns of iron wire (or wire made from an iron alloy), which offers high resistance. The coil may be tapped at various places, and the taps connected to contact points. When the control lever is on the first contact point, all of the resistance of the coil is in the circuit. The result is a voltage drop through the resistance of the coil, and less voltage is available at the terminals of the motor. With less voltage a smaller current flows than would flow if the full line voltage were impressed on the motor. As the speed of the motor increases, the control lever is moved to the next contact point, thus cutting out some of the resistance of the coil. It is safe to do this because the back E.M.F. of the motor is now sufficient to reduce the current somewhat. This process is continued until all the resistance of the coil is cut out,

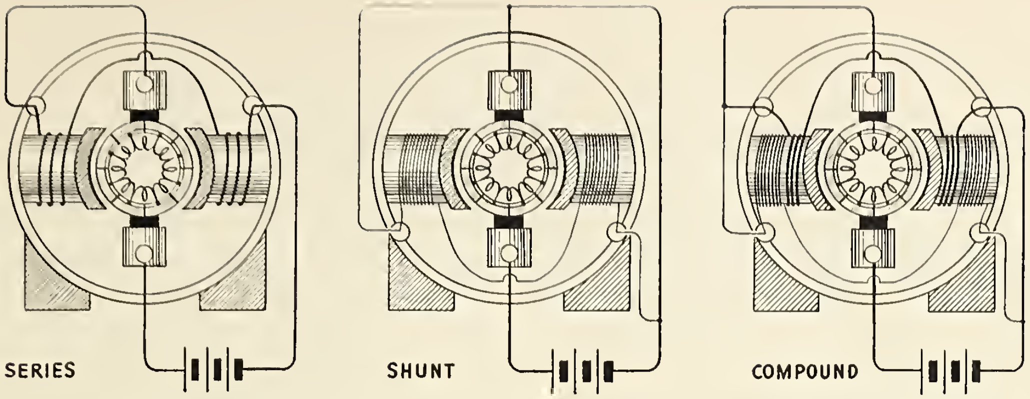
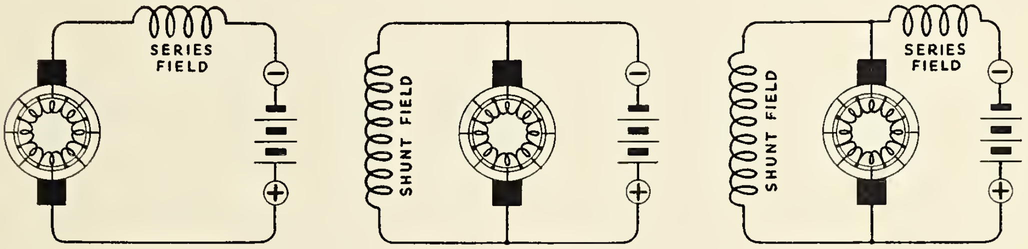


Figure 129 *shows three types of D.C. motors. In the* SERIES *motor at the left the field coils are in series with the armature coils. In the* SHUNT *motor the field coils are in parallel with the armature coils. The* COMPOUND *motor at the right has two sets of field coils—one set in series with the armature coils and one set in parallel with them. The diagrams below show how the field coils are connected to the commutator brushes in each type.*



and the full line voltage is impressed on the motor. About 30 seconds should be used to move the lever arm from START to FULL SPEED.

A starting resistor is usually equipped with two safety devices to prevent injury to the motor. Occasionally, the current may be shut off for a time because of some failure in the transmission system. If this happens in a motor circuit, the full line voltage will be impressed on the stopped motor when the current comes on again. To prevent this, a small electromagnet is placed on the far side of the last contact point. When current is flowing through the motor circuit, this electromagnet is energized. It holds the control lever on the last contact point. If the current is shut off for any reason, no current flows through the electromagnet, and it is no longer energized. A spring attached to the control lever pulls the lever back to the OFF position. When the current comes on again, it is therefore necessary to use the starting resistor to start the motor again.

The other safety device used with a starting resistor is either a fuse or a magnetic circuit breaker. Either of these will prevent too much current from flowing, as you know. If the control lever is moved too fast, too much current will flow through the motor circuit. The fuse will melt or the magnetic circuit breaker will trip, thus opening the circuit and stopping the motor. To start the motor again, the fuse must be replaced or the circuit breaker reset.

Another type of safety device used in smaller motors is a thermostatic (or heat-operated) circuit breaker. One kind is made of two different metals fastened together to form a bar. When the bar is heated, one metal expands faster than the other, thus bending the bar and opening the circuit. Another kind has a small, notched wheel fastened to a shaft with solder or some other easily melted alloy. When the shaft is heated, the solder melts enough for the wheel to turn slightly and release a spring catch, thus opening the circuit. Thermostatic circuit breakers will pass brief overloads, such as occur in starting, but will trip before other overloads can cause damage to the motor windings.

Types of D.C. motors. Just as with D.C. generators, there are three main types of D.C. motors: (1) series-wound, (2) shunt-wound, and (3) compound-wound. Each has special characteristics that make it suitable for certain jobs.

In a *series-wound,* or *series,* motor the armature coils and field coils are connected in series, as shown in Figure 129. A series motor has a much greater starting torque than other types. But if it is turning a heavy load, it slows down. On the other hand, if the load is light, the motor speeds up. Thus the speed of a series motor varies directly with its load. For this reason, it is not suitable for use where a constant speed is needed. For example, it would not be satisfactory to use where many machines are turned by belts attached to pulleys on a rotating shaft. If a few machines were used, the motor would turn very fast. If many machines were used, it would turn very slowly.

However, the high starting torque of a series motor makes the motor very suitable for use in streetcars, electric locomotives, elevators, derricks, cranes, and hoists. Practically all streetcars and electric locomotives use series motors, whose speed is regulated by a device called a *controller.* This contains a starting resistor connected in series with the coils of the motor. It is used just like any other starting resistor connected to a motor. However, it is usually equipped with a switch for connecting the motors in series and in parallel. When the streetcar or locomotive starts up, the motors are connected in series to get the maximum starting torque. When the controller handle is turned so that the motors reach full speed, a switch connects the motors in parallel. In climbing a hill, the motors are connected in series by moving the controller handle back.

A *shunt-wound,* or *shunt,* motor is used more than other kinds of D.C. motors. Like the shunt-wound generator, its field coils and armature coils are connected in parallel, as shown in Figure 129. If the current supplied to the motor has a constant voltage, the motor will run at a constant speed under different loads. Even if the load varies a great deal, a shunt motor will maintain an almost constant speed. Because a shunt motor has such a constant speed whether it is pulling a load or not, it is used in factories and machine shops where machinery must be run at constant speeds.

The speed of a shunt motor can be controlled in two ways: (1) field control and (2) armature control. Field control is accomplished by means of a rheostat in series with the field coils. The rheostat regulates the current through the field, thus strengthening or weakening the magnetic field of the motor. When the magnetic field is weakened, the motor turns faster. And when the magnetic field is strengthened, the motor turns slower. Does this seem strange? Let us see what happens.

If the field strength of a motor is decreased, the first result is a decrease in the back E.M.F. induced in the armature. This decrease in back E.M.F. increases the effective voltage, and a larger current flows through the armature coils. The larger current produces a greater magnetic flux around the armature coils. As a result, the armature is pushed down harder on one side and pushed up harder on the other. The speed of the motor increases. Just the opposite takes place when the field strength is increased. The back E.M.F. is increased, and the effective voltage is decreased. Less current flows through the armature coils, and a smaller flux is produced. The sides of the armature coils are not pushed up or down so hard, and the speed of the motor decreases.

Armature control of shunt motors is accomplished by means of a rheostat in series with the armature. By adding more resistance to the armature circuit, the speed of the motor is decreased. However, field control is ordinarily used, because it gives better regulation with less power loss than armature control does. Like a series motor, a shunt motor requires resistance in the circuit when starting. The resistance is in series with the armature to prevent too much current from flowing as the motor starts. As the motor speeds up, the resistance is decreased as in starting any D.C. motor.

As you might suppose, *compound-wound,* or *compound,* motors can be designed to have the desirable characteristics of both series and shunt motors. A compound motor can be designed to have an almost constant speed as well as a high starting torque. Its main advantage lies in the fact that it can be adapted to meet special requirements. For example, the so-called *cumulative-compound* motor is used to run heavy machinery that works under large loads but does not need careful speed regulation. The rollers and shears in steel mills are often operated by this type of compound motor.

Reversing D.C. motors. Look back at Figure 122, which illustrates the left-hand rule for motor. You can see that the direction of motion is determined by the direction of the flux and the direction of the current. If you stop and think a moment, you can probably guess how direct-current motors are reversed. The direction of rotation of a D.C. motor is reversed by reversing the armature connections or the field connections. Reversing the armature connections changes the direction of the current, while reversing the field connections changes the direction of the flux. However, if both the field connections and the armature connections are reversed, the direction of rotation will not change. You can easily check this by using the left-hand rule. Motors that are reversible usually have a switch that reverses either the field or armature connections.

CHECKING WHAT YOU LEARNED

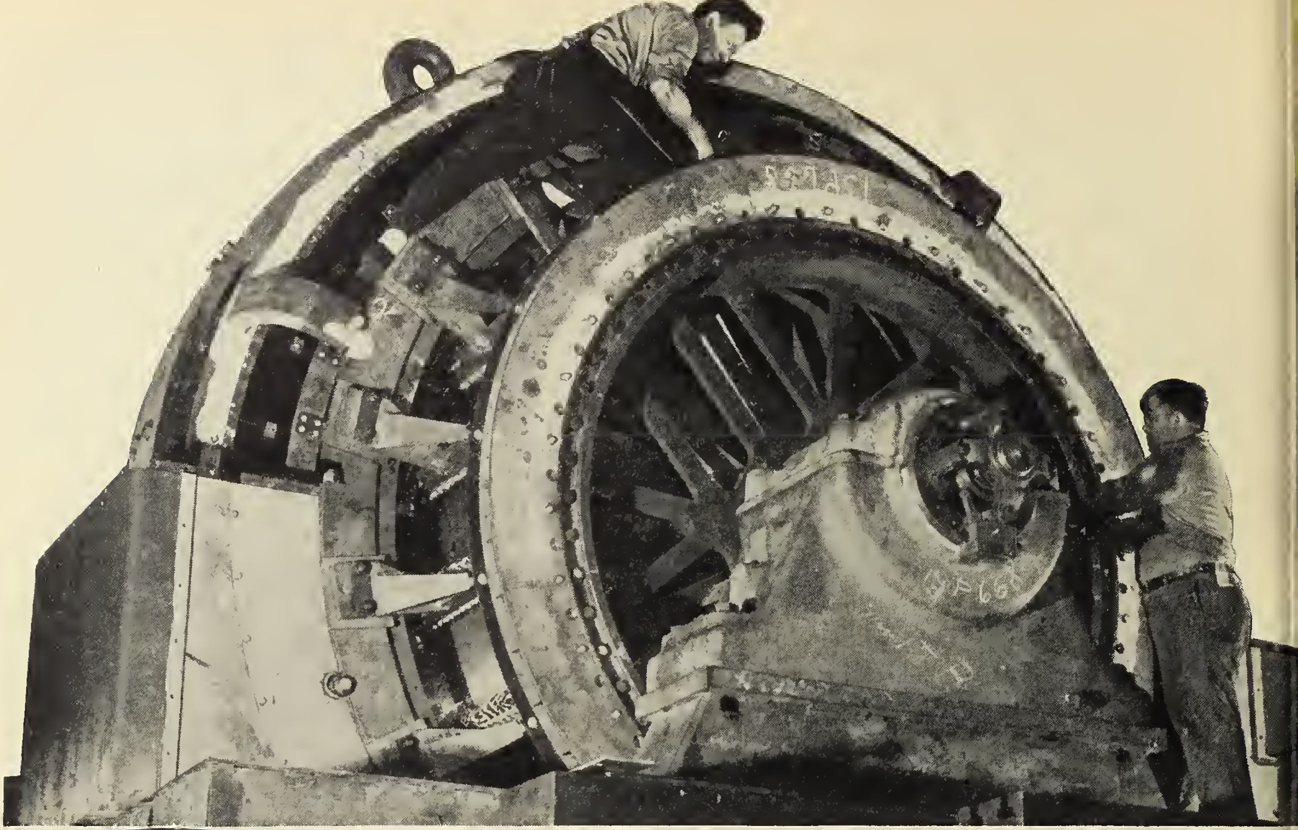
1. **a.** How does the energy change in a motor compare with that in a generator? **b.** Explain why some motors and generators are interchangeable.
2. Why are brushes and a commutator necessary in a direct-current motor?
3. **a.** Explain why a motor needs field magnets in order to run. **b.** What kind of field magnet is ordinarily used? Why?
4. Tell what happens when a current is sent through the armature of a direct-current motor.
5. **a.** Why do the armatures of most electric motors have several coils of wire on them? **b.** What is the reason for using many turns in each coil?
6. On what three things does the mechanical energy supplied by a motor depend? Why?
7. Why does a decrease in speed cause an increase in current drawn by a direct-current motor?
8. **a.** Explain why a starting resistor is used in bringing a motor up to speed. **b.** What safety devices are used with a starting resistor to prevent injury to the motor? Explain what each one does.
9. Name three main types of direct-current motors and tell what each name means.
10. How is a direct-current motor reversed? Explain.

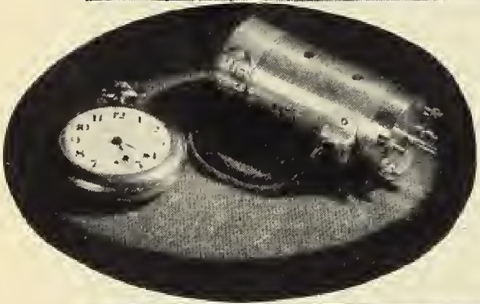
USING WHAT YOU LEARNED

1. Make a diagram of a simple motor like the one in Figure 124, but show the armature turning in the opposite direction. Use arrows to indicate the direction of the current and the direction of the flux.
2. Explain why a starting resistor is not used with small motors.
3. Why is every motor also a generator when it is running?
4. A motor armature has a resistance of .6 ohm. If the impressed E.M.F. is 110 volts and the back E.M.F. is 107 volts, how much current flows through the armature?
5. Explain how the speed of a motor is controlled.
6. The resistance of a motor armature is .5 ohm. **a.** If the motor is operated on 110 volts, how much resistance must be included in the starting resistor to keep the starting current down to 22 amperes? **b.** What is the voltage drop through the starting resistor?

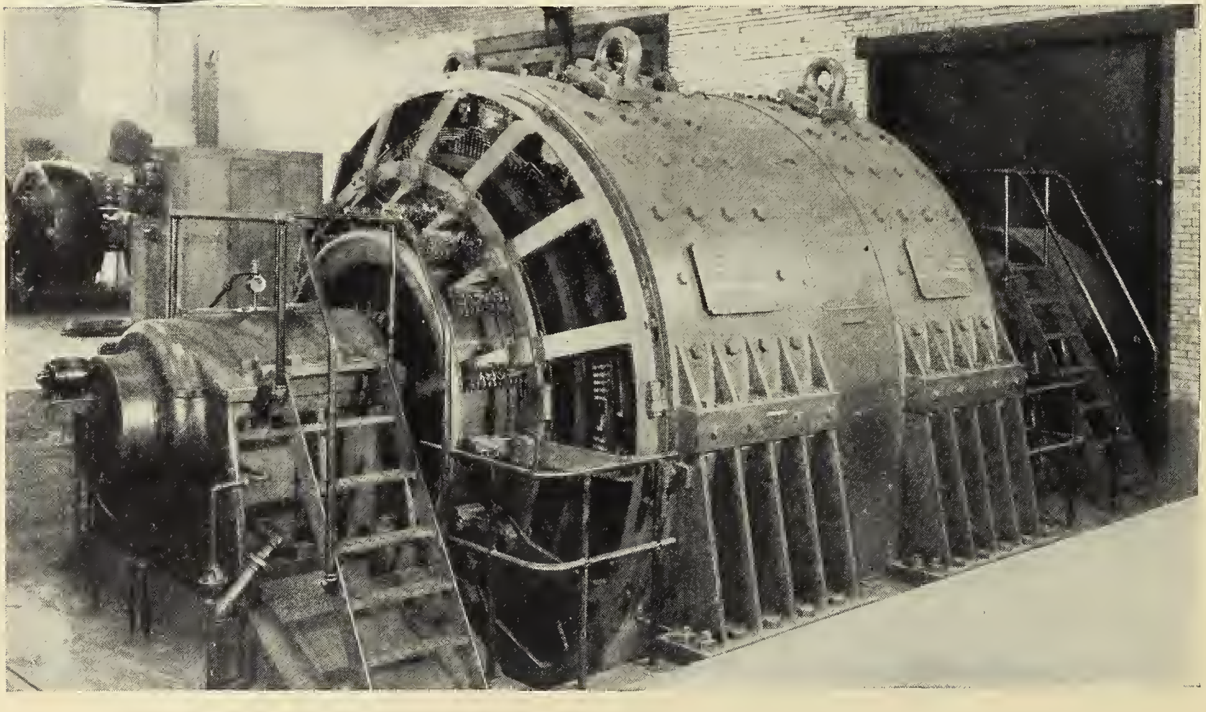
The Alternating-Current Motor

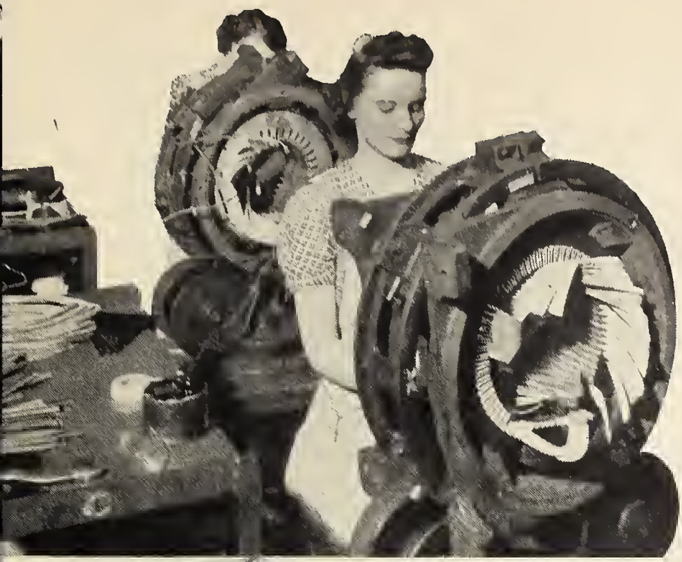
One reason for using direct current is the fact that direct-current motors are more easily controlled than alternating-current motors. However, the economy of transmission obtained by using alternating current has resulted in the replacement of many direct-current transmission lines. Today most homes are supplied with alternating current. Therefore, motor-driven appliances, such as fans, washing machines, electric refrigerators, vacuum cleaners, and food mixers, are usually designed to operate on alternating current. The motors used



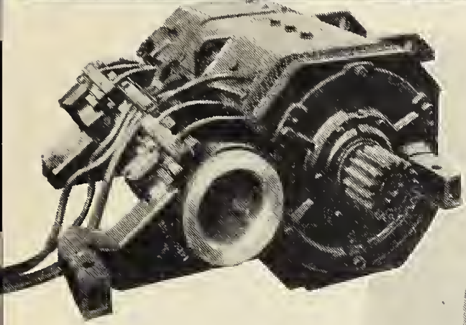


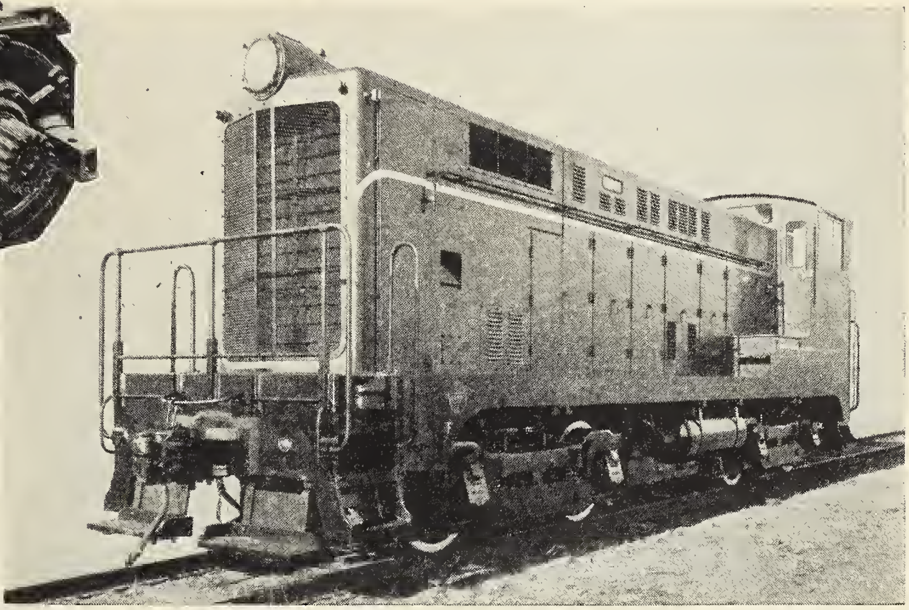
The big 5400-kilowatt rotary converter shown above is now being used to supply direct current needed in the production of aviation gasoline. At the left is a small, reversible 24-volt D.C. motor used in aircraft for remote control. It has a rated output of 2 watts, while the huge 750-volt D.C. motor shown below, used in the manufacture of steel, is rated at 7000 horsepower.





The two girls at the left are inserting stator windings into the slotted cores of alternating-current motors of the type used in factories. More than a third of a mile of copper wire is needed for a motor of average size, such as the ones shown. At the left center is shown one of the four compact direct-current motors used on the Diesel-electric switching locomotive below. Supplied with current from the powerful Diesel-driven generator illustrated on page 220, the four motors combine to give the locomotive a rating of 660 horsepower.





The workman at the right is fitting windings into the stator slots of what is probably the largest induction motor in the world. For this is the stator of the huge 40,000-horsepower motor that forces as much as six tons of air per second through the Army's big wind tunnel at Wright Field, Dayton. Driving two 40-foot fans that weigh 197 tons each, this giant motor can send a 400-mile-an-hour wind screaming past airplane models with a 16-foot wingspread.

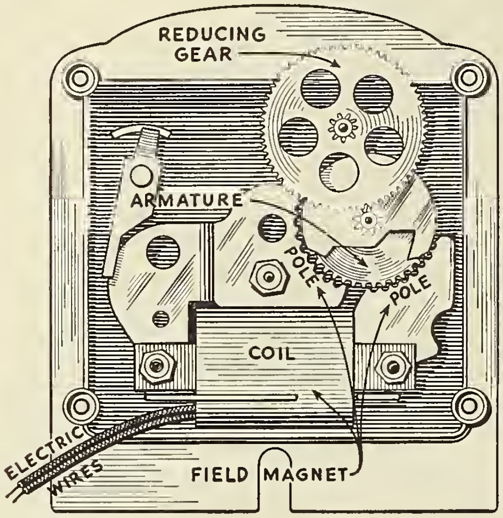


Figure 130. *Most of the electric clocks we now have in our homes use synchronous motors to turn the hands. Because the force required to do this is small, the motors are usually simple, as shown by the picture of one at the left, but they are designed to keep in step with the carefully regulated generators at the power station. Since the coil of the field magnet is wound with many turns of fine wire, the motor uses very little current. In order to secure a relatively slow speed for the armature, or rotor, the poles are set so that the teeth on the armature can line up with the teeth on only one pole piece at a time.*

in the last two appliances are ordinarily of the *universal* type. A universal motor will run on either alternating or direct current. For this reason, it is also called an *A.C.-D.C. motor.* Actually, this type of motor is nothing more than a series D.C. motor with a few changes to make it suitable for use on alternating current. Although satisfactory for running small household appliances, a universal motor is rather inefficient when run on alternating current. Sparking at the commutators of such motors is a common source of radio interference.

Synchronous motor. Aside from the universal motor, which is not—strictly speaking—an alternating-current motor, there are two main types of alternating-current motors. One of these you have probably seen in operation many times, for it is used to run electric clocks. This type of motor is called a *synchronous motor.* (*Synchronous* means "timed with.") A synchronous motor rotates at a fixed speed, which depends on the frequency of the alternating current and the number of poles. At 60 cycles, for example, a 2-pole motor will revolve 3600 times a minute, while one with 4 poles will revolve half that fast. Large synchronous motors are made very much like A.C. generators, with a rotating field in a stationary armature. In fact, almost any A.C. generator can be used as a synchronous motor if some way of starting it is provided. Once the rotating field coils are in step with the alternations of the current supply, a synchronous motor will continue to run at a constant speed as long as the frequency of the current supply does not change. Large synchronous motors are used in electric substations to drive D.C. generators. They are also used where constant speed with a varying load is required.

As already mentioned, the commonest use of the synchronous motor is in electric clocks. The motors used are small and simple, as shown in Figure 130. By studying the diagram, you can see how a synchronous motor works. Current flowing through the coil energizes the electromagnet. Since the current alternates, the polarity of the electromagnet alternates, too. In Chapter 7 you saw how an alternating current in one circuit induces an E.M.F. and thus a current in another circuit by means of a varying flux. In a synchronous motor, such as used in an electric clock, the current is induced in the armature, and it flows in the projecting teeth of the armature. The induced current sets up a magnetic field around the teeth of the armature. As a result, the projecting teeth of the armature are pushed out of the field of the electromagnet, just as the wire carrying a current was pushed out of the magnetic field in Experiment 49. Notice that the armature is not connected to the electromagnet circuit.

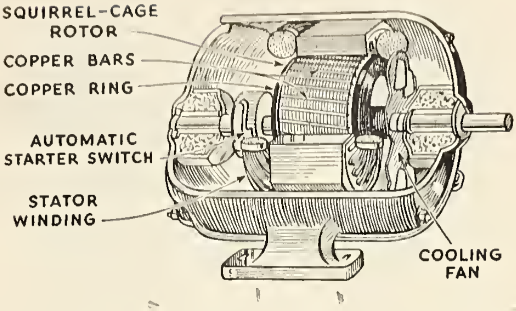


Figure 131 *shows a cut-away view of an induction motor designed for household use. Notice that the "squirrel-cage" rotor is made up of copper bars connected at each end by a copper ring. The starter switch operates by centrifugal force, disconnecting the special starting coils when the motor reaches operating speed.*

Once the armature of such a motor is turning at the correct speed, the alternations of current in the electromagnet keep it turning in step with the A.C. generator in the power station. Since the A.C. generator is very carefully regulated to furnish 60-cycle current, the motor can be used to turn the hands of a clock at a constant speed. You may have noticed that many electric clocks must be started by hand to get them up to speed. However, some kinds are provided with a device to get them started at the correct speed.

Induction motor. The other type of alternating-current motor is the *induction motor*. In its simplest form an induction motor has two parts: the stationary coil, or *stator*, and the rotating part, or *rotor*. Alternating current flows through the stator and produces a rotating magnetic field even though the stator itself does not move. This happens because an alternating current increases from zero to a maximum, then dies down to zero again, reverses its direction, increases to a maximum in the opposite direction, and then dies down to zero once more. These changes in the direction and strength of the magnetic flux result in a rotating field.

The coils and pole pieces of the stator are arranged in such a way that each pole piece becomes a N pole, then loses its magnetism, becomes a S pole, then loses its magnetism again, becomes a N pole once more, and so on. For example, a certain pole piece A becomes a N pole. An instant later A is losing its magnetism, while pole piece B next to it has become a N pole. In another instant A has become a S pole, while B is losing its magnetism. Pole C next to B has now become a N pole, and so on. In this way the N and S poles move around the stator as the current in the coils alternates. How the coils are wound to produce this effect is too complicated to explain in this book.

The rotor of an induction motor is usually of the *squirrel-cage* type, as shown in Figure 131. It consists of an iron core with slots to hold copper bars. The ends of the copper bars are connected to copper rings. Although the rings are not connected to any external circuit, they form a closed path with the copper bars. The rotating magnetic field induces a large current in the circuit of copper bars and rings. The current in this circuit magnetizes the iron core, which together with the copper bars and rings forms an electromagnet. The rotating field acts on the electromagnet and drags it around. Thus you can see that an induction motor turns somewhat like the magnetic speedometer operated by eddy currents, which was described in Chapter 8.

In an induction motor, the rotor does not move so fast as the magnetic field. It moves just enough slower than the rotating field of the stator to allow the copper bars to cut lines of force. The difference between the speed of the rotating field in the stator and the speed of the rotor is known as the *slip*. As the load on the motor increases, the slip increases. The slip of an induction motor is also a measure of the losses. If the slip is 3½ per cent, that much of the energy is lost as heat. Induction motors are likely to get very hot. Therefore, fan blades are usually mounted on the rotor shaft to drive air through the rotor as the motor rotates.

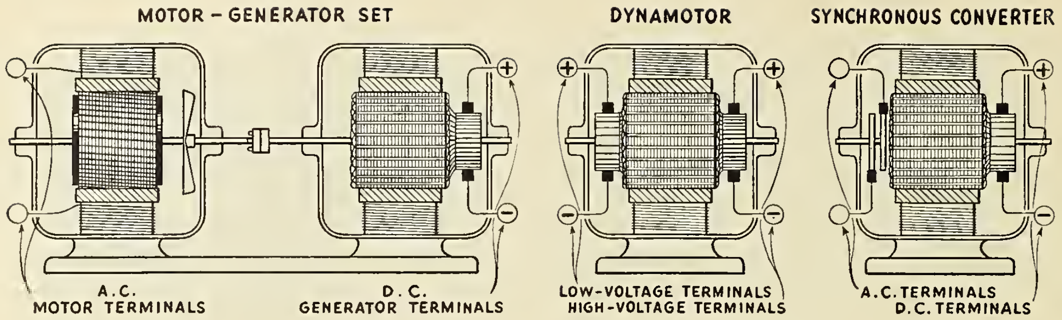


Figure 132 *shows three types of converters. The motor-generator set at the left is simply an A.C. induction motor driving a D.C. generator. The dynamotor in the center has two windings on one armature—one for turning the armature with low-voltage D.C. and one for producing high-voltage D.C. The synchronous converter at the right has one armature winding connected both to slip rings for A.C. and to a commutator for D.C.*

A properly designed induction motor will run on the alternating current supplied to homes. To start these motors, special stator coils or a commutator and brushes connected to separate rotor coils are used. Current flows through the windings and magnetizes the iron core. The rotor gradually reaches its proper speed. At this point a switch operated by centrifugal force disconnects the starting coils or brushes. The current induced in the squirrel cage then keeps the rotor turning.

Converters. A machine used to change current of one kind to current of another kind is called a *converter*. There are three types in common use. The easiest to understand is the *motor-generator*. As its name suggests, it is a motor connected to a generator. If the motor is run by alternating current, the generator connected to it can produce direct current. Sometimes two or three generators are connected to the same motor. A motor-generator is thus a mechanical rectifier, for it can be used to change alternating current into direct current. It is especially useful for rectifying large amounts of current. Motor-generators are also used to change direct current to alternating current, or to change the frequency of an alternating current.

Another type of converter is called the *dynamotor*. Because it is very compact, it is frequently used in airplanes. A dynamotor is used mainly to change low-voltage direct current to higher-voltage direct current, but it can also be used to change direct current into alternating current. A dynamotor usually has two armature windings and two commutators. One commutator and winding are part of a motor, while the other commutator and winding form part of a generator. Dynamotors are sometimes called *rotary transformers*.

A *synchronous converter* is still another type. It is ordinarily used to change alternating current to direct current. Like a dynamotor, it is both a motor and a generator. However, it has only one armature winding. Connected to this armature winding are a commutator and slip rings. If run by an engine, the synchronous converter becomes a double generator, furnishing alternating current at the slip rings and direct current at the commu-

---

Slip of an induction motor is usually expressed as a percentage of the synchronous speed. For example, a motor rated at 1800 r.p.m. may operate at 1738 r.p.m. when loaded. The difference is 62 r.p.m. If this is divided by 1800 and then multiplied by 100 to change to per cent, the slip is 3½ per cent.

tator. Electric railways and power substations use this type of converter, because it supplies large amounts of direct current from alternating current with very little loss.

Care of motors. Like all machines, motors must be properly cared for to give efficient operation and long life. First of all, the bearings must be correctly lubricated. Probably more motors have been ruined by too much oil rather than too little. In filling the oil cups, see that they do not overflow. If too much oil is put in, it leaks along the shaft and finally reaches the coils. Oil will penetrate windings, damaging the insulation and ruining the coils. Never put oil on the commutator or slip rings, since a film of oil prevents a good contact with the brushes. Wipe off any excess oil spilled on the commutator, slip rings, or shaft.

Motors must be kept clean on both the inside and the outside. Do not let dust, dirt, oil, water, or lint accumulate on the motor. Dust and dirt clog the ventilating spaces of the motor and keep air from circulating freely. As a result, the motor is not adequately cooled. Dust is also a poor conductor of heat; it prevents heat from being carried away from the motor. To clean windings that have become covered with oil, use clean rags, preferably cheesecloth, moistened with carbon tetrachloride. A hand bellows, bicycle pump, or vacuum cleaner can be used to force air through the windings to remove dirt and dust. Never use gasoline to clean a running motor, because sparks may ignite the gasoline and cause a serious explosion.

As with any kind of machinery, an unusually high temperature indicates that something is wrong with a motor. If the motor heats up, turn it off, and find out what is wrong. A common cause of overheating is overloading. If the heat is caused by overloading, reduce the load or turn the motor off at frequent intervals and let it cool. When the bearings become hot, lubrication is needed.

CHECKING WHAT YOU LEARNED

1. **a.** What is a universal motor? **b.** For what purpose is it commonly used?
2. Explain briefly how a synchronous motor works.
3. **a.** What produces the rotating field in an induction motor? **b.** How is its rotor constructed?
4. **a.** Tell what is meant by a converter. **b.** Name three types of converters and give a use for each one.

USING WHAT YOU LEARNED

1. **a.** If a motor heats up, what are some possible causes of overheating? **b.** Tell what you would do to remedy each cause.
2. Why is a universal motor sometimes not considered as one of the main types of alternating-current motors?
3. The rotating part of a synchronous motor is not connected to the stationary part, yet an alternating current of the same frequency flows through each part. Explain.
4. When large amounts of direct current are needed, why is it usually better to transmit the current as alternating current and then convert the current to direct current?

THINKING OVER WHAT YOU LEARNED

1. After each topic in the chapter write down in complete sentences the big ideas or principles you learned.
2. Show that you understand the meaning of the following terms. You may use either a sentence or a definition. **a.** starting resistor, **b.** back E.M.F., **c.** stator, **d.** converter, **e.** dead center, **f.** torque, **g.** rotor, **h.** motor-generator, **i.** induction motor, **j.** impressed E.M.F., **k.** dynamotor, **l.** synchronous motor, **m.** counter E.M.F., **n.** universal motor, **o.** slip, **p.** squirrel-cage, **q.** synchronous converter.

Experiment 49: **Current-Carrying Conductor in a Magnetic Field**

THINGS NEEDED: No. 30 insulated copper wire. Strong U-magnet. Support for U-magnet, such as a ringstand and clamp. Two No. 6 dry cells. Reversing switch (double-pole, double-throw). Coil and knitting needle from Experiment 45. Support for the coil.

WHAT TO DO: **a.** Hang a length of No. 30 insulated copper wire (or other small wire) between the poles of a strong U-magnet, as shown in Figure 121. Be sure that the wire is loose and free to move. Attach the ends of the wire to the reversing switch and connect two dry cells in series through the reversing switch to the length of wire. Now throw the switch to one side and observe what happens. Reverse the current through the wire by throwing the switch to the other side. What happens now? Compare your results with what is shown in Figure 122. (Open the switch to shut off the current.)

b. Connect the ends of the wire in the coil to the reversing switch and dry cells. Then support the coil in the magnetic field between the poles of the U-magnet, as shown in Figure 121. Be sure that its turns are vertical. Throw the switch to one side and observe what happens. Then throw the switch to the other side. What happens this time?

c. (*Optional*) Repeat Part **a**, but use a stronger current or field. To get a stronger current, add one or more dry cells in series. To make a stronger field, place another U-magnet alongside the first so that like poles are next to each other. Also repeat Part **a**, placing the U-magnet with poles pointing upward and arranging the wire horizontally between two supports. Next try reversing the poles of the magnet and thus the direction of magnetic flux in relation to the wire. If an electromagnet with two facing poles is available, repeat Parts **a** and **b**. Also try the wire placed horizontally between the poles of the electromagnet. (You will need to use a separate battery to energize the electromagnet.)

Experiment 50: **Simple Direct-Current Motor**

THINGS NEEDED: No. 26 cotton-covered or enamel-coated copper wire. Cylinder of cork or soft wood about 2 inches long and 1 inch in diameter. Knife. Thread. Two small nails. Steel knitting needle. No. 18 insulated copper wire. Two U-magnets. Two No. 6 dry cells.

WHAT TO DO: **a.** (See Fig. 125.) For field magnets use the two U-magnets with like poles together. Make the armature by cutting two shallow lengthwise notches in the cylinder of cork or soft wood. In these notches wind about 20 turns of No. 26 wire and tie a thread around the middle of the cylinder over the wire to hold it in place. Push two small nails into the cylinder, as shown in Figure 125. Fasten one free end of the wire to each nail. Use a knitting needle for the shaft of the armature and support it on bearings of bent wires. The armature will work better if it is balanced so that it will stand in any position.

b. Place the field magnets over the armature, as shown in Figure 125. Set the armature coil horizontal. Connect wires to the battery of two dry cells in series. Hold the bare ends of the wires against the nails on the cylinder. What happens? Does the armature turn steadily? (Sometimes it may be necessary to give the armature a little push to start it turning. You may need some practice before you can hold the wire brushes to get the best results. With a little thought you can probably work out a way to fasten the wires on nails or screws so that you will not need to hold them.)

c. (*Optional*) Add another armature coil and two more commutator segments. To do this, cut two more shallow notches at right angles to the first notches. Wind about 20 turns of No. 26 wire in the notches and tie the wire with thread as before. Connect the ends of the wire to two nails halfway between the first two. Then repeat Part **b**.

Experiment 51: **Effect of Field Poles on Armature Poles**

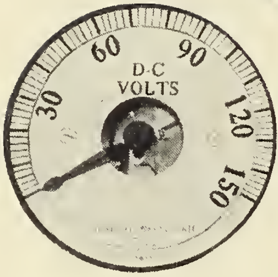
THINGS NEEDED: Coil from Experiment 25. Two No. 6 dry cells. Reversing switch (double-pole, double-throw). String. Overhead support. Iron nail. Two U-magnets.

WHAT TO DO: Connect the coil to a battery of two dry cells in series, using a reversing switch as shown in Figure 126. Suspend the coil from an overhead support by means of a string. Be sure the coil is free to turn easily. Hold a U-magnet under the coil with its poles pointing upward. The poles of the U-magnet should be at right angles to those of the coil. Throw the reversing switch to one side and notice what happens. Then throw the switch to the other side and watch the coil. Place an iron nail as a core inside the coil and repeat the experiment. Also try using two U-magnets with like poles placed together. Then hold the U-magnet (or magnets) with its poles in line with those of the coil. What happens when the current from the dry cells is sent through the coil in either direction? Explain the effect of field poles on armature poles.

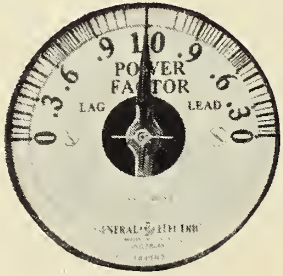
Experiment 52: **Back E.M.F.**

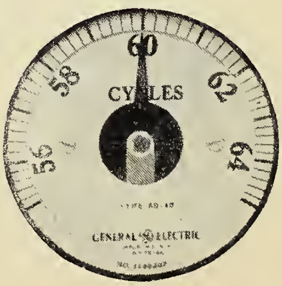
THINGS NEEDED: Small toy motor. No. 6 dry cell. Knife switch. Ammeter reading to 30 amperes (or 1.5-volt flashlight bulb and socket). No. 18 insulated copper wire. Stick.

WHAT TO DO: Connect the motor in series with a dry cell, ammeter, and knife switch, as shown in Figure 127. (If an ammeter is not available, use a flashlight bulb and socket. The brightness of the bulb will indicate the current drawn.) Close the circuit by throwing the switch. How much current is used? Slow the motor down by pressing a stick against the pulley on its shaft. What happens to the current when the speed of the motor decreases as the load increases? Explain.



11. Meters and Measurements





FINDING OUT WHAT YOU KNOW

1. What three things does a galvanometer indicate about current?
2. Name the two types of direct-current meters in common use. Tell how each type works.
3. State the main difference between an ammeter and a voltmeter. How is each one connected in a circuit?
4. Explain why the usual types of direct-current meters will not work on alternating current.
5. In what ways can we measure resistance? Electric power? Electrical energy?
6. How are the heating effects of current used to operate meters?
7. What is an electrometer?
8. How are measurements made with a Wheatstone bridge?

In the experiments and explanations of this book, meters are often used to indicate something we wish to know about current in a circuit. If you did the experiments, you have connected and taken readings with ammeters, voltmeters, and galvanometers many times. Without knowing just how these meters operate, you can take readings and get satisfactory results. But if you are going to work with electrical equipment, you should understand what happens when you take measurements with meters.

Obviously, the meters you have used are operated by current flowing through them, for they do not show a reading unless they are connected with a source of electrical energy. In most meters, the magnetic effects of a current are used to move the needle. But the heating effects of a current can also be used to move meter needles, as you will see. Still another way to operate a meter is by means of electrical charges. However, this way is seldom used except in laboratories.

To give accurate readings, a meter must be carefully compared with a standard meter of the same kind and its scale marked off into divisions of the correct length. For example, if an ammeter is to measure amperes correctly, the needle must stand at the 1-ampere mark when 1 ampere is flowing through the meter, the needle must stand at the 2-ampere mark when 2 amperes are flowing, and so on. Marking the scale of a meter or checking it for correction is called *calibration*. In practical work, meters need not be exactly calibrated; but in very precise work, each meter must be carefully calibrated.

Galvanometer: An instrument for indicating the presence, strength, and direction of an electric current. There are two main types: the **fixed-coil** galvanometer and the **moving-coil** (or **D'Arsonval**) galvanometer.

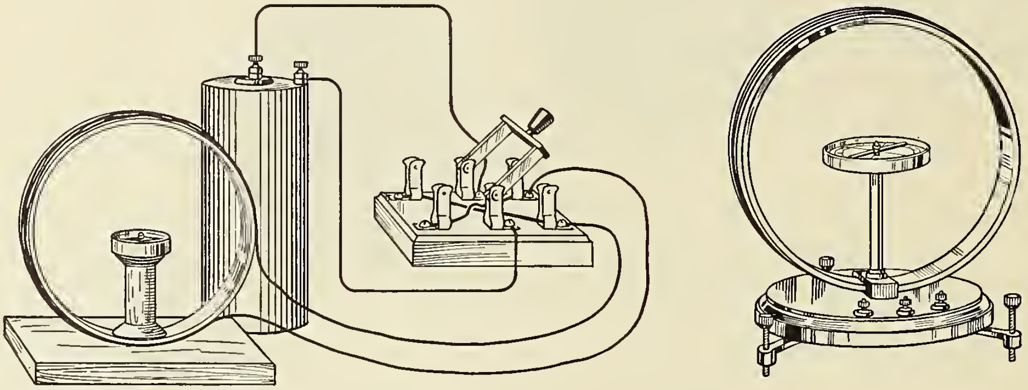


Figure 133. *At the left is shown a simple fixed-coil galvanometer. When set up for use, the turns of the coil must be parallel with the compass needle, which is held in a north-south direction by the earth's magnetic field. At the right is shown a fixed-coil galvanometer of the type used in the laboratory to measure small currents.*

Galvanometers

The simplest kind of meter used in experiments with electric current is the **galvanometer**, an instrument that indicates the presence, strength, and direction of a current. If you did Experiment 16, in Chapter 4, you made and used one type of galvanometer to test a simple cell. This type is known as the **fixed-coil** galvanometer. It consists of a magnetic compass inside a coil of wire. As shown in Figure 133, the turns pass over the compass in one direction only and then under the compass in the opposite direction. Before this type of galvanometer can be used, the coil must be turned or the whole instrument moved until the turns of the coil are parallel to the needle. If you do Experiment 53 (page 274), you can see how this type of galvanometer works.

Fixed-coil type. When a fixed-coil galvanometer is connected to a source of direct current, such as a dry cell, current flows through the coil, and the compass needle swings to one side. If the current is reversed, the needle swings in the opposite direction. In either case, the amount of swing, or deflection, is the same because the same amount of current flows through the coil. The galvanometer thus indicates not only the presence of a current but also its direction. By using the right-hand rule for coil (page 137), you can determine the direction of the current. If more current is sent through the coil by adding more cells in series, the needle swings farther to the side than before. When the current is reversed, the needle swings just as far in the opposite direction. Thus the galvanometer indicates the strength as well as the direction of the current.

From what you know about magnetism and electromagnetism, you can easily explain the action of a fixed-coil galvanometer. The compass needle is held in a north-south direction by the earth's magnetic field. When the galvanometer is set up for use, the turns of the coil must be parallel to the needle. As current flows through the coil of wire, it produces a magnetic field around the wire at right angles to the earth's magnetic field. The magnetic field of the coil exerts a sidewise push on the needle. The north-seeking end of the needle swings toward the east or the

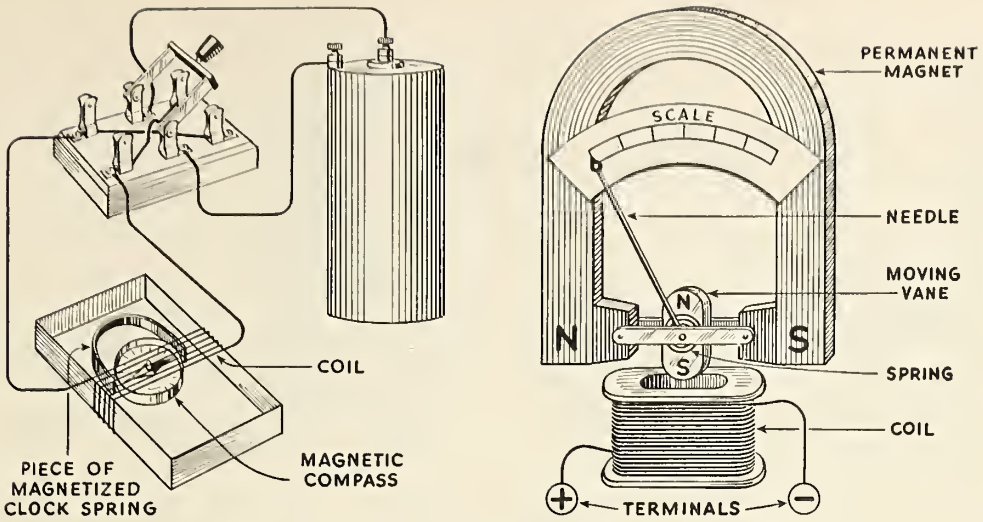


Figure 134. *At the left is the fixed-coil galvanometer from Experiment 16. A piece of magnetized clock spring has been added to keep the compass needle parallel to the turns of the coil regardless of which direction the box is turned. At the right is a fixed-coil meter that uses a small magnetized vane in place of a compass needle.*

west, depending on the direction of the current. The larger the current, the stronger the field of the coil, and the greater the swing of the needle.

The fixed-coil galvanometer is rather unhandy to use, because the coil and compass needle must be properly aligned. Also, it cannot be used in any place where the compass needle might be deflected by masses of iron or steel. Then, too, the needle must swing horizontally, although we usually prefer to have the needle swing vertically or on a slant. One improvement that can be made is to substitute a permanent horseshoe magnet for the earth. Instead of a compass needle, a magnetized bar called a *moving vane* is used, as shown in Figure 134. Meters of this kind have fixed coils, but they are known as *moving-vane* meters. The moving vane is attached to a needle that swings over a scale. In Experiment 53 you can make a moving-vane meter.

Moving-coil type. Another way to avoid the inconveniences of the fixed-coil galvanometer is to use a fixed permanent magnet and a moving coil. The type of galvanometer in which this is done is called the **moving-coil** galvanometer. It is also known as the **D'Arsonval** galvanometer. If you do Experiment 53, you can see how this type of galvanometer works. Figure 135, on page 256, shows a coil of very fine wire suspended so that it can be easily turned between the poles of a U-magnet. When the switch is closed, the coil becomes an electromagnet. Its poles are attracted by the unlike poles and repelled by the like poles of the permanent magnet. As a result, the coil turns like the armature of a motor. If the current is reversed, the coil turns in the opposite direction. An increase in current causes a greater turning of the coil. In other words, the results are the same as for the fixed-coil type.

In a commercial galvanometer, the moving coil has an iron core to increase the strength of the magnetic field. A pointer attached to the coil moves over a scale as the coil turns in either direction. The middle point on the scale is zero, indicating no current in either direction. From the middle point scale divisions are marked off on either side. The part of the scale to the right of zero indicates a flow of current from the right-hand terminal to the left-hand terminal, while the part of the scale to the left of zero indicates an opposite flow of current.

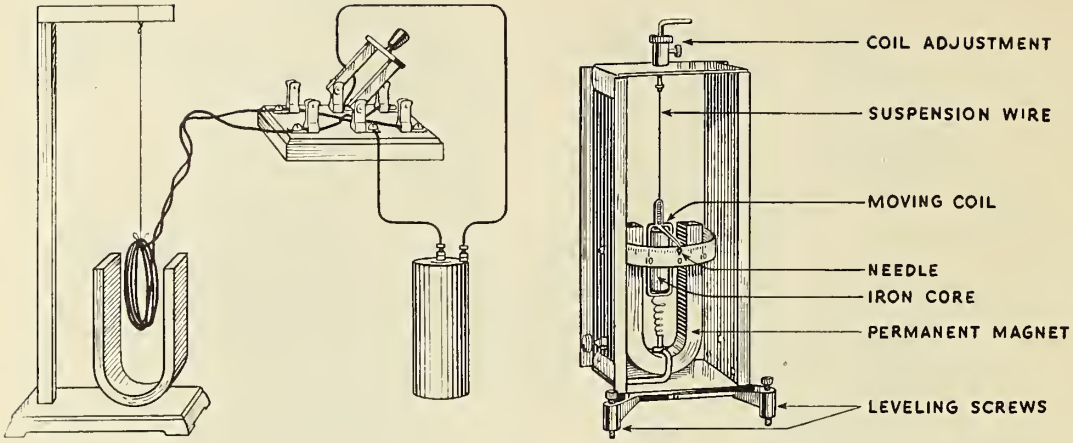


Figure 135. *The coil at the left turns in one direction when the switch lever is thrown to the right, and in the other direction when the lever is thrown to the opposite side. This experiment demonstrates the principle of the moving-coil galvanometer shown at the right. The iron core does not turn with the coil; it merely strengthens the magnetic field.*

Moving-coil galvanometers that are very sensitive have their coils wound on light frames of copper or aluminum. As the coil turns, it cuts lines of force in the magnetic field of the permanent magnet. Cutting lines of force induces eddy currents in the copper or aluminum frame. These currents have such a direction that their magnetic fields oppose the magnetic field which induced the current, in accordance with Lenz's Law. As a result, the eddy currents act as a brake on the rotating coil. They keep the coil from vibrating back and forth, and thus make it easier to take the reading. Meters whose coils are checked by eddy currents are called *dead-beat* meters.

A common use of the galvanometer is one that you must have noticed many times on the instrument panel of automobiles. The *charge-discharge meter* is a galvanometer that shows when current is flowing into the storage battery from the generator (CHARGE) or flowing out from the storage battery (DISCHARGE). The zero mark is in the middle of the scale, while CHARGE is to the right and DISCHARGE to the left, as shown in Figure 136. In some automobiles, the scale of the charge-discharge meter is marked in amperes. For this reason, the meter is often called an ammeter. In many automobiles, however, the marks are merely lines that indicate whether the charge or discharge rate is large or small. If the engine speeds up, the generator turns faster, and the meter may show a greater charge. If the lights are turned on, the extra flow out of the battery may cause the needle of the meter to move to the left.

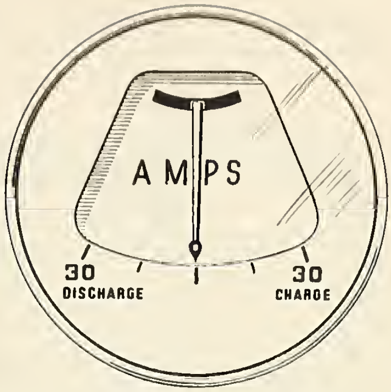
CHECKING WHAT YOU LEARNED

1. For what purposes do we use a galvanometer?
2. Name the two types of galvanometers and explain briefly how each type works.
3. How does a moving-vane meter differ from the simple type using a coil and compass needle?
4. Tell how eddy currents may be put to good use in meters.
5. What is the purpose of the galvanometer used in an automobile?

USING WHAT YOU LEARNED

1. A galvanometer needle swings rapidly from side to side. What kind of current is flowing through its coil? Explain.
2. When a fixed-coil galvanometer is set up properly and connected, the colored end of the

Figure 136. *The charge-discharge meter used on most automobiles is a galvanometer. When the needle moves to the right of the center zero mark, the meter indicates approximately how much current from the generator is flowing into the storage battery. When the needle moves to the left, the meter indicates the current flowing from the storage battery to the various electrical devices. Since all that is needed is an approximate indication of the current flow, moving-vane galvanometers are generally used. The scale sometimes is marked* AMPS *or* AMPERES *to show what is being measured.*



compass needle swings to the left. Which end of the coil is the N pole?

3. Why is a moving-coil galvanometer ordinarily used in preference to a simple fixed-coil meter?

Direct-Current Meters

Galvanometers of both the fixed-coil and the moving-coil types are ordinarily used with direct current, though they can be used to show the reversal of alternating current of very low frequency. If you did the experiments with induced currents, you used a galvanometer for this purpose. However, if a higher-frequency alternating current flows through the meter coil, the needle will not swing far to one side and then to the other. It will merely "flutter," or vibrate back and forth near the zero mark. The reason for this, of course, is that the current reverses its direction so often that the needle never gets a chance to swing very far to either side.

The scale on the usual galvanometer indicates no special units. For example, if a galvanometer needle stands at the 2-mark to the right of zero, it indicates a current of twice the strength as would be shown by the needle at the 1-mark. Often, however, we want to know more than the comparative strength of currents. You have already learned that the charge-discharge meter in automobiles is sometimes calibrated in amperes. In other words, it indicates a certain number of amperes flowing into or out of the storage battery. We can thus use a galvanometer as an ammeter.

Direct-current ammeter. Many times in the experiments we have used an ammeter to measure the size of a direct current. An **ammeter,** as you know, is an instrument that measures the rate of current flow in amperes. The more expensive type of direct-current ammeter is simply a moving-coil galvanometer with its scale calibrated in amperes, while the cheaper type is a moving-vane meter with the same kind of scale. Both types have a permanent magnet to provide the magnetic field. A spring attached to the moving coil pulls the needle back to zero when no current is flowing through the meter. Some ammeters have a zero adjustment so that the needle can be set exactly at zero before taking a reading. Since the zero mark is usually at the left side of the scale, the needle can move only to the right to show an increase in current. Therefore, the terminals of the ammeter must be connected correctly in the circuit. The positive (+) terminal, which is often the only one marked, must be connected to the positive side of a cell, battery, or generator. Of course, connecting wires and devices may be in between.

To respond to small changes in current, the moving part of an ammeter must be very light. If a moving coil is used, its wire is wound on a light, well-balanced frame. Very fine wire is used for the coil, but such wire can carry only a small current without overheating. The usual coil will carry about .05 ampere at the most. In order to measure a larger current, the meter must be constructed so that only a part of the total current

Ammeter: An instrument for measuring the rate of current flow in amperes. It is always connected in series with the circuit.

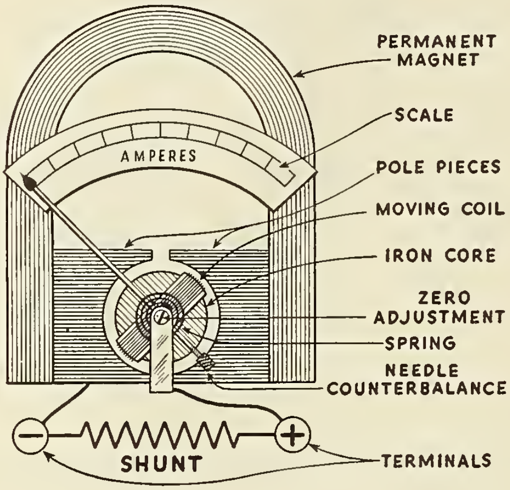


Figure 137. *At the left is shown a direct-current ammeter of the moving-coil type. The light, well-balanced coil turns easily in the gap between the fixed iron core and the poles of the magnet. A spring at each end returns the coil to the zero position when current stops flowing, an adjustment being provided to set the needle exactly at the zero mark. Because an ammeter is always connected in series, a shunt is provided to carry currents larger than can be carried by the fine wire on the coil. The lower the resistance of the shunt, the larger the current that can be measured by the ammeter.*

flows through the coil, while most of the current flows through a wire or strip of low resistance connected across (in parallel with) the coil. The wire or strip connected in this way is called a *shunt.* Figure 137 shows how the shunt is connected.

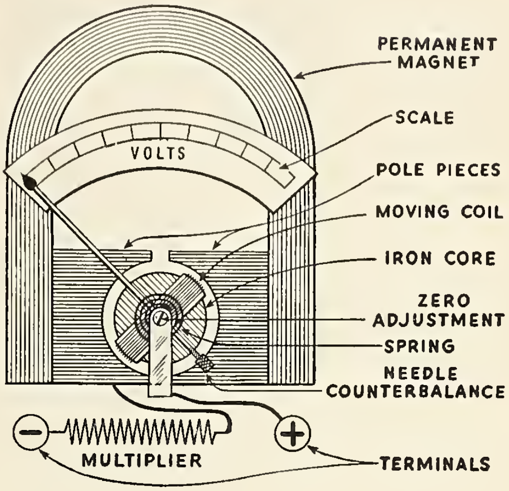
The amount of current that flows through the coil is determined by the relative resistance of the shunt and coil. For example, if the resistance of the coil is equal to the resistance of the shunt, half the current flows through the coil and the other half through the shunt. However, if the resistance of the coil is four times as high as that of the shunt, only 1/5 of the current flows through the coil. The remaining 4/5 of the current flows through the shunt. In many ammeters, the coil has a resistance from 100 to 1000 times that of the shunt. This means that from 1/100 to 1/1000 of the current flows through the coil, while from 99/100 to 999/1000 flows through the shunt. However, the needle moving across the scale of the ammeter indicates the total current flowing through both the coil and the shunt. Ordinarily, the shunt in an ammeter has a very low resistance. Furthermore, to keep the resistance from varying, the shunt must carry its share of the current without becoming hot. For this reason, shunts are often made of copper or silver bars that have less resistance than the conductors in the rest of the circuit.

In order to extend their range, ammeters are often constructed so that one or more external shunts can be added. For example, suppose that an ammeter will measure up to 5 amperes when the needle swings across the whole scale. We say that the full-scale deflection of this meter is 5 amperes. If an external shunt of the proper resistance is connected across the terminals of the meter, the range of the meter may be extended, let us say, to 25 amperes for full-scale deflection. Of course, the numbers on the scale are not changed by adding a shunt. Therefore, to get the correct reading at any point on the scale, you must multiply the reading by 5. If the reading on the scale is 2, the correct reading is 10 amperes (2 x 5). External shunts supplied for meters are labeled to show the full-scale deflection when each shunt is used.

In measuring current with an ammeter, you must be sure to connect the meter in *series* with the rest of the circuit. If an ammeter is connected across (in parallel with) the rest of the circuit, such a large current will flow through the meter that the coil and shunt will probably be melted. (If the meter is designed for short-circuit use, as a pocket meter for testing dry cells is, it may be used

Voltmeter: An instrument for measuring the electrical pressure in volts. It is always connected in parallel with part of the circuit.

Figure 138. *At the right is shown a direct-current voltmeter of the moving-coil type. Notice that it is exactly like the ammeter in Figure 137, except that a multiplier is used in place of a shunt, and the scale is marked for volts instead of amperes. Because a voltmeter is always connected in parallel with one or more parts of a circuit, a multiplier is provided to limit the current through the fine wire on the coil. Like the ammeter shunt, the voltmeter multiplier is a resistor. The higher the resistance of the multiplier, the higher the voltage that can be measured by the voltmeter.*



to take brief short-circuit readings.) As already mentioned, the ammeter terminals must be properly connected to the source of direct current. Of course, the range of the ammeter must be great enough to measure the current in the circuit. Obviously, an ammeter whose full-scale deflection is 5 amperes cannot be used to measure a current of more than 5 amperes unless the meter is provided with the proper external shunt.

Direct-current voltmeter. Besides the rate of current flow, we often want to know the electrical pressure in a circuit. To measure the pressure, we use a voltmeter. As you know, a **voltmeter** is an instrument that measures electromotive force or potential difference in volts. The ordinary voltmeter is a galvanometer calibrated in volts. It has either a moving coil or a moving vane, and its magnetic field is supplied by a permanent magnet. A voltmeter has a spring to return the needle to zero and may have a zero adjustment. It must be connected properly; that is, its positive terminal must be connected directly or indirectly to the positive side of a cell, battery, or generator. A voltmeter thus appears to be very much like an ammeter. How then does a voltmeter measure electrical pressure while an ammeter measures current?

In the first place, a voltmeter has a high resistance connected in series with its coil. The resistance cuts down the current so that only a very small current flows through the voltmeter. The current that does flow through the meter is proportional to the voltage, in accordance with Ohm's Law. Thus, a voltmeter differs from an ammeter in having a high resistance. An ammeter, as you recall, has a low resistance. Another difference between the instruments is that a voltmeter is

Ohm's Law applied to shunts: By using Ohm's Law, you can calculate the resistance of a shunt to increase the range of an ammeter. The joint resistance of the coil and the shunt determines the current that will flow through the meter. In the following formula developed from the formulas based on Ohm's Law, **R** is the joint resistance of the coil and shunt, while $\mathbf{R_c}$ is the resistance of the coil and $\mathbf{R_s}$ the resistance of the shunt. Since the joint resistance and the resistance of the coil are known, the resistance of the shunt can be found from the formula:

$$R_s = \frac{R_c \times R}{R_c - R}$$

always connected across (in parallel with) part of the circuit. To measure open-circuit voltage, it is connected directly across the terminals of a cell, battery, or generator. When the closed-circuit voltage is measured, the meter is connected in the same way; but a current flows through an external circuit connected to the source of energy. To measure the voltage drop through any part of the circuit except the source, the voltmeter is connected across that part of the circuit. A voltmeter is thus always in parallel with part of the circuit, while an ammeter is in series with the circuit.

The amount of current that flows through a voltmeter is determined by the resistance of the meter. To prevent a large loss of power through the meter itself, the current flowing through it is kept very low. Some voltmeters are made so that they can be used for different ranges. Instead of a shunt, however, extra resistances are provided. A portable voltmeter with several terminals can be used to measure different ranges of voltages. On such a meter, one terminal is the positive connection. Each of the other terminals is connected to a tap on a tapped resistance in series with the meter coil Other voltmeters are made so that their ranges may be increased by adding external resistances, called *multipliers*. A multiplier is simply a fixed resistor whose resistance increases the range of a certain meter. Like the shunts used with ammeters, the multipliers are labeled to show the range of voltages that can be measured. The scale reading must be multiplied by a certain number to get the correct voltage reading.

In measuring with a voltmeter, be sure to connect the instrument in *parallel* with part of the circuit. If a voltmeter is connected in series with the circuit, its resistance reduces the flow of current. Of course, the positive terminal of the meter must be connected directly or indirectly to the positive terminal of the source of energy. The range of the voltmeter must be sufficient for measuring the voltage in the part of the circuit across which the meter is connected.

CHECKING WHAT YOU LEARNED

1. How is a galvanometer made into an ammeter? Into a voltmeter?
2. Explain why the terminals of a direct-current ammeter or voltmeter must be properly connected.
3. **a.** In what way is an ammeter connected in a circuit? A voltmeter? **b.** Explain why each meter is connected in this way.
4. **a.** How can the range of an ammeter be increased? **b.** The range of a voltmeter?

USING WHAT YOU LEARNED

1. Explain why the fixed coil of a moving-vane voltmeter usually contains many turns of fine wire, while the coil of a moving-vane ammeter usually contains a few turns of larger wire.
2. Why does connecting a direct-current meter to alternating current weaken the permanent magnet?
3. Tell how the range of an ammeter and a voltmeter can be doubled.
4. The range of a galvanometer may be increased in either of two ways. Tell what each way is and how it increases the range.

Alternating-Current Meters

Direct-current meters of the moving-coil or moving-vane type will not work on alternating current if the magnetic field is supplied by a permanent magnet. Every reversal of the current reverses the polarity of the coil in such meters. As a result, the needle will merely flutter. Even if the meters would work on alternating current, the reversal of polarity in the coil would weaken the permanent magnet. Also, eddy currents in the core would soon overheat the coil, thus burning out the meter.

Ohm's Law applied to multipliers: By using Ohm's Law, you can calculate the resistance of a multiplier to increase the range of a voltmeter. The total resistance of the coil and multiplier determines the current that will flow through the meter. In the following formula developed from the formulas based on Ohm's Law, **R** is the total resistance of the coil and multiplier, while $\mathbf{R}_c$ is the resistance of the coil and $\mathbf{R}_m$ the resistance of the multiplier. Since the total resistance and the resistance of the coil are known, the resistance of the multiplier can be found from the formula: $R_m = R - R_c$

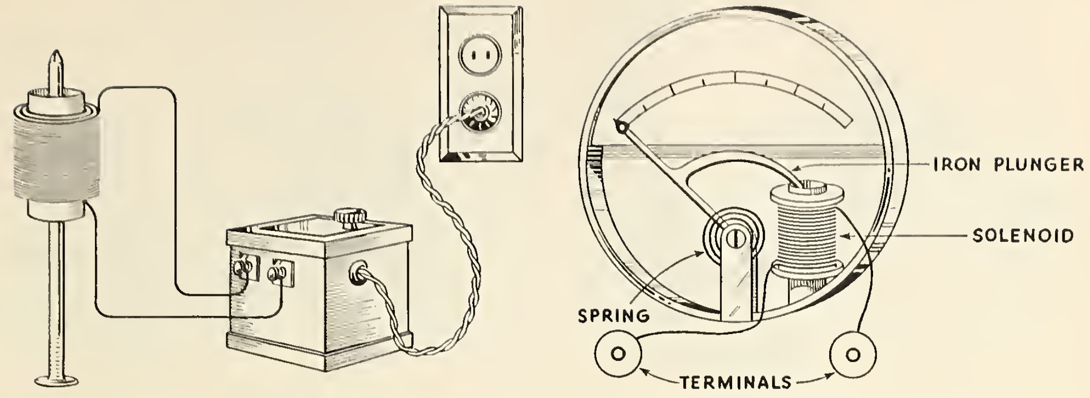


Figure 139 *shows how a plunger-vane meter works. When current flows through the coil at the left, the nail is drawn into the coil. In a similar way the plunger fastened to the needle of the meter at the right is drawn into the solenoid when current flows. The stronger the current, the farther the needle is pulled to the right.*

Alternating-current meters use either moving coils or moving vanes, but they contain no permanent magnets. Curiously enough, most alternating-current meters will work on direct current. Some of them are labeled "A.C.-D.C." to indicate this fact. However, since D.C. meters with coils and permanent magnets are much more sensitive than the usual A.C. meters, there is little reason besides that of convenience for using A.C. meters on direct current, too.

Like D.C. meters, the ammeters used on alternating current can be equipped with shunts to increase their range, and the voltmeters can be equipped with multipliers. The shunts and multipliers are calculated in the same ways as for D.C. meters. Also, an A.C. ammeter is connected in series with the circuit, while an A.C. voltmeter is connected in parallel with part of the circuit. However, it makes no difference how the meter terminals are connected, because the alternating current reverses its direction many times each second. If the A.C. meter is used on direct current, its terminals can be connected without regard to positive or negative. The only new thing for you to learn about A.C. meters is how they are made.

Plunger-vane meters. In the plunger-vane type of meter the current energizes a solenoid, thus setting up a magnetic field. An iron plunger is drawn into the coil, as shown in Figure 139. The distance which the plunger moves depends on the current. In other words, the larger the current, the farther the plunger moves. If the meter is to be used as an ammeter, the solenoid is wound with large wire. If, however, the meter is intended for use as a voltmeter, the solenoid is wound with many turns of fine wire.

Since the solenoid is energized no matter which way the current flows, it makes no difference how the terminals are connected to the source of electrical energy. Either direct current or alternating current will energize the solenoid. As already mentioned, a meter of this type can be used with either alternating or direct current. However, the solenoid draws more current than a moving-coil meter. As a result of the greater voltage drop, the meters of the plunger-vane type are not so sensitive as the better D.C. meters although the plunger-vane type is cheaper to make. If you wish to see how a plunger-vane meter works, do the first part of Experiment 54.

Repulsion-vane meters. Instead of working by attraction, the repulsion-vane type of meter works in just the opposite way, as shown in Figure 140. When current flowing through the coil energizes the coil, both the fixed core and the moving vane

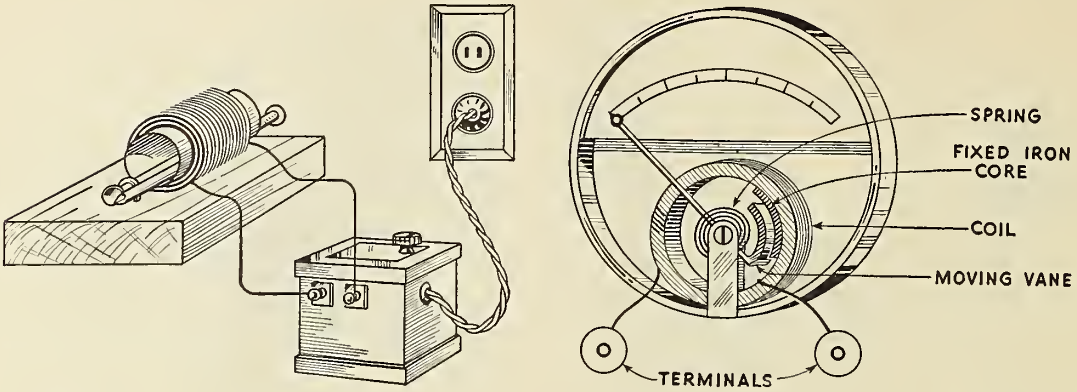


Figure 140 *shows how a repulsion-vane meter works. When current flows through the coil at the left, the movable nail is repelled by the fixed one. In a similar way, in the meter at the right, the iron vane fastened to the needle is repelled by the fixed iron core fastened to the inside of the coil. The stronger the current, the farther the needle is pushed to the right.*

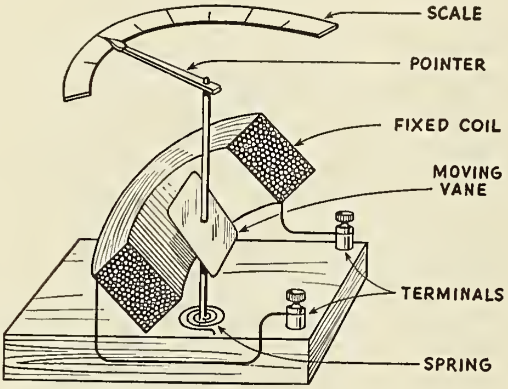


Figure 141 *shows a cross section of an inclined-coil meter, which is suitable for use with alternating current. Springs hold the moving vane at right angles to the fixed coil until current flows. Then the moving vane turns the pointer as it tries to align itself with the magnetic lines of force. The angular mounting of the vane and the coil makes possible a rotation of nearly 180 degrees from minimum to maximum.*

are magnetized, since they are in the same magnetic field. The like poles of the core and vane repel each other. The result is a partial rotation of the vane; the distance that the vane moves depends on the current flowing through the coil.

Obviously, the coil can be energized by either alternating or direct current. The meter can be used as an ammeter or voltmeter, depending on the scale and the resistance of the coil. However, this meter suffers from the common fault of most alternating-current meters: When an alternating current is used to energize the coil, the vane will vibrate somewhat as the current reverses its direction. The needle will move across the scale, but it will flutter with the reversal of current. As a result, it may be difficult to take an exact reading with such meters. If you want to understand how repulsion-vane meters work, do the second part of Experiment 54.

Inclined-coil meters. Figure 141 shows another type of meter. Notice that the coil and vane are set at an angle. Springs keep the vane at right angles to the coil when no current flows through the meter. When current flows through the coil, the coil is energized. As a result, the vane is magnetized; it tends to align itself with the coil. Acting against the springs, the shaft turns, and the pointer indicates the reading. A large current turns

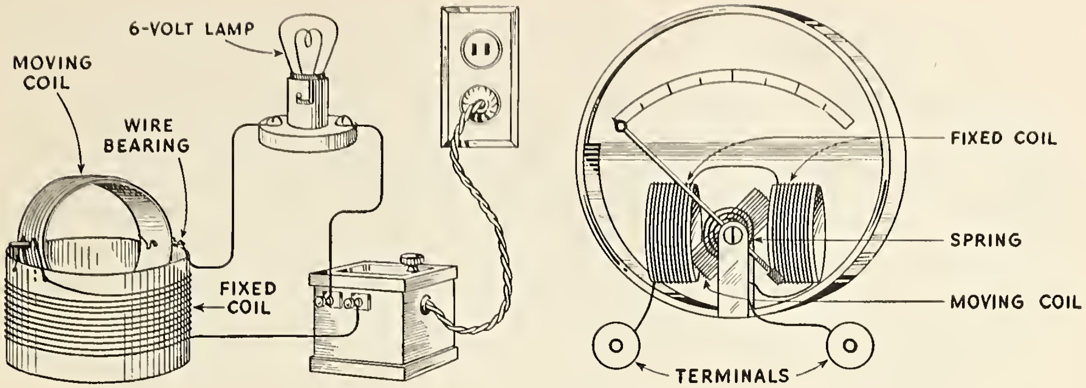


Figure 142 *shows how a dynamometer works. When current flows through the coils at the left, the smaller coil turns. In a similar way the movable coil in the meter at the right turns between the two parts of the fixed coil. The stronger the current, the more the moving coil turns, and the farther the needle is moved to the right.*

the shaft farther than a small current. The main advantage of using this type of meter is the expanded scale. Instead of a scale of only 90 degrees, it is possible to spread the scale to cover almost 180 degrees with an inclined coil. Spreading out the scale makes possible more accurate measurements; but the inclined-coil meters are inefficient, so that much of the advantage is lost.

Dynamometer. Still another type of meter is the so-called *dynamometer,* as shown in Figure 142. It consists of two coils connected in series; one coil is fixed, and the other is movable. (In Figure 142 the fixed coil in the meter is split into two parts.) As the current alternates, the polarity of both coils changes at the same time. Except for a slight flutter of the needle, the meters of this type are very accurate. However, the most serious fault of this type of meter, in common with other A.C. meters, is that the scale markings are crowded at one end, since the movement is not uniform. If you do Experiment 55, you can see how a dynamometer works.

Direct-current meter with rectifier. Most of the difficulties encountered with A.C. meters can be avoided by changing the alternating current to direct current and measuring it with a D.C. meter. In Chapter 4 we mentioned rectifiers in connection with charging storage batteries. When you study the next chapter, you will learn how rectifiers work. To make very accurate measurements of the pressure of alternating current, a vacuum-tube voltmeter is often used. This meter uses a vacuum tube like the tubes in a radio set to change alternating current to direct current, which is then measured by a sensitive direct-current meter. The advantage of using a vacuum-tube meter is that it draws only a tiny current.

CHECKING WHAT YOU LEARNED

1. **a.** Can direct-current meters be used on alternating current? Explain. **b.** Is it possible to use alternating-current meters on direct current? Give your reasons.
2. Name four types of alternating-current meters and tell briefly how each type works.
3. Why are alternating-current meters used on direct current?
4. How are very exact measurements of alternating-current voltage made?

USING WHAT YOU LEARNED

1. Why do alternating-current meters contain no permanent magnets?
2. The needles of most alternating-current meters flutter somewhat. Explain why this happens.
3. Explain why an increase in current through the

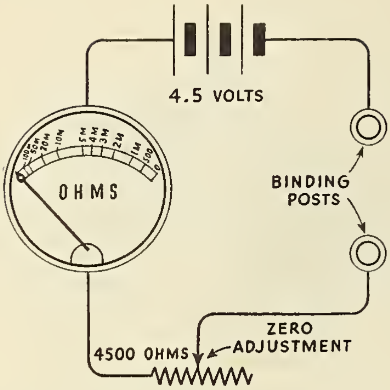


Figure 143 *shows an ohmmeter connected to three dry cells and a variable resistor, which is used to limit the current through the meter. Before use, a metal bar or heavy wire is put between the binding posts, and the resistor is adjusted so that the needle points to zero. Since maximum current will flow through the circuit when there is minimum resistance between the terminals, zero is at the right-hand end of the scale. The drawing shows that an ohmmeter of this kind does not have an even scale—the right half of the scale reads to about 5000 ohms (or 5 M), while the left half reads to more than 100,000 ohms (or 100 M).*

coil of an alternating-current meter causes the needle to show a greater deflection.

4. Could you use an alternating-current meter to find the direction of current flow in a circuit connected to a source of direct current? Why?

Other Kinds of Meters

The meters described so far in this chapter are the ones used in the experiments. Besides these, however, there are other meters specially made for taking certain electrical measurements. In a beginning book like this we can cover only the more important meters among the other kinds. If you continue your work with electrical equipment, you may meet with meters not explained here. But when you examine these meters, you are likely to find that many of them are merely galvanometers with scales calibrated to read in a particular unit. The moving part of such meters is almost always a coil or a vane that works just like the moving part in meters already described.

Ohmmeter. As its name suggests, an ohmmeter is an instrument for measuring resistance in ohms. It consists of a very sensitive galvanometer calibrated in ohms, a battery, and a variable resistor (rheostat). The parts of the meter are connected in series in a circuit containing two binding posts, as shown in Figure 143. The resistance to be measured is connected in series with the rest of the circuit. Before a resistance can be measured, a metal bar of very low resistance is placed between the binding posts. The circuit is now closed, and a current flows through it. The variable resistor is adjusted until the meter needle stands at zero. The purpose of this adjustment is to take care of the slight decrease in the battery voltage as the cells grow older.

The metal bar is then removed, and an unknown resistance is connected to the binding posts. Current now flows through the circuit including this added resistance. Since the meter needle was adjusted to take care of all the circuit except the unknown resistor, the current now flowing causes a different meter reading. The position of the needle shows the value of the unknown resistance in ohms. There are other ways to measure resistance besides using an ohmmeter, as you will see later on in this chapter; but an ohmmeter is such a simple device that it is now commonly used except where extremely accurate measurements are needed.

Wattmeter. A meter for measuring electrical power is appropriately called a wattmeter. It consists of a dynamometer such as previously described. However, there are two differences between a wattmeter and the dynamometer used to measure voltage or amperage. First of all, the scale is calibrated in watts (or kilowatts). The other difference is in the connections of the two coils. Instead of being connected in series, the coils are separately connected. The fixed coil is in series with the circuit, while the moving coil is in parallel with part of the circuit. Figure 144 shows how a wattmeter is connected in a circuit. Notice that the meter has three terminals.

Figure 144. *A wattmeter is made like the dynamometer shown in Figure 142, except that the fixed and moving coils are not connected in series. The diagram at the right shows that the fixed coils, of heavy wire, are connected in series with the circuit, while the moving coil, of fine wire, is connected in parallel. Since the needle is moved by the combined field strength of the fixed and moving coils, the meter indicates power.*

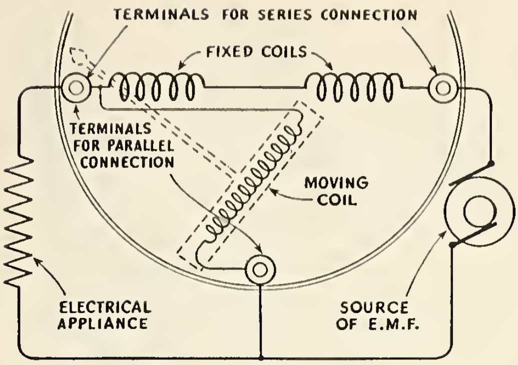
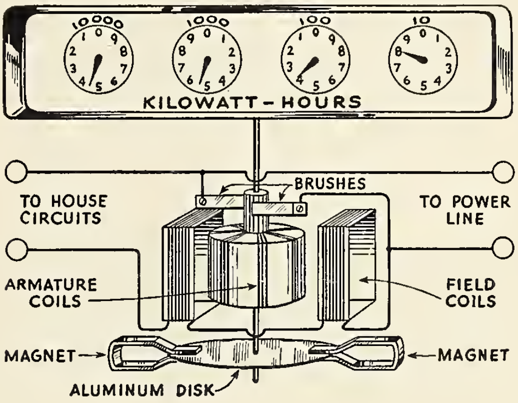


Figure 145. *The direct-current watt-hour meter shown at the right is actually a small motor connected by reducing gears to the meter dials, which are marked in kilowatt-hours. Notice that the field coils are connected in series with the circuit, while the armature is connected in parallel with the circuit. The speed of rotation depends on the combined field strength of the two sets of coils and is thus proportional to the amount of electrical energy used.*



You can see that the moving coil is connected as in a voltmeter, while the fixed coil is connected as in an ammeter. The magnetic field provided by the moving coil is proportional to the voltage, and the magnetic field set up around the fixed coil is proportional to the current. The action of these magnetic fields on each other turns the moving coil and the needle attached to it. The movement of the coil and needle is proportional to the power. The reason for this, of course, is that the strength of one magnetic field is proportional to the voltage, while the strength of the other is proportional to the current. The combined strength is equal to the strength of one multiplied by that of the other. In other words, power equals volts times amperes, or $P = EI$. A wattmeter operates on either direct or alternating current.

Watt-hour meter. The wattmeter is sometimes confused with the watt-hour meter, although the two meters are used for completely different purposes. A wattmeter measures power, that is, the rate of doing work or expending energy. On the other hand, a watt-hour meter measures the work done by electrical energy or the electrical energy expended. A wattmeter is a dynamometer-type of meter, while a watt-hour meter is actually a small motor. You can see a watt-hour meter connected near the place where electrical current is brought into your home.

Figure 145 shows a direct-current watt-hour meter. The armature of the small motor rotates at a speed proportional to the amount of electrical energy used. The shaft of the armature is connected by gears to the pointers on the dials. The pointer at the right makes one complete rotation for each 10 kilowatt-hours of energy used. The second pointer from the right rotates once for each 100 kilowatt-hours; and the third, once for each

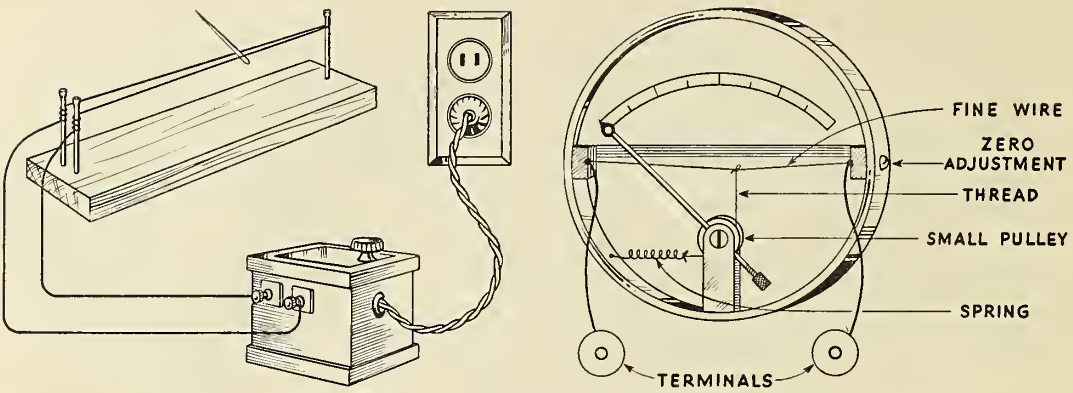


Figure 146 *shows how a hot-wire meter works. When current flows through the wire at the left, expansion of the wire allows the toothpick to turn downward. In a similar way the fine wire in the meter at the right expands when a current flows, allowing the spring to pull the thread around the pulley and turn the needle toward the right.*

1000 kilowatt-hours. The fourth pointer makes one rotation for each 10,000 kilowatt-hours. You can read the meter by taking the last figure passed by each pointer. The meter reading in Figure 145 is 4538 kilowatt-hours.

The field coils of the motor are connected in series with the circuit, and their field strength is proportional to the current flowing through the circuit. The armature coils are connected across the circuit; therefore, the current flowing through them is proportional to the voltage. The speed at which the motor turns is thus proportional to the power in watts (or kilowatts). Since the motor turns for a certain time whenever current is used, the movement of the pointers geared to the armature shaft records the electrical energy used. From Chapter 8 you recall that energy is equal to power multiplied by time, or watt-hours equal watts multiplied by hours. This is shown by the formulas $Wh = Pt$ and $Kwh = Kw \times t$, in which t is the time in hours.

An alternating-current watt-hour meter has a coil of a few turns of large wire below an aluminum disk and another coil of many turns of fine wire above the disk. The coil of few turns is in series with the circuit, while the coil of many turns is in parallel with the circuit. The disk is thus the rotor of an induction motor. Both kinds of watt-hour meters make good use of eddy currents to control the movements of their shafts. A small aluminum disk attached to the shaft rotates between the poles of two permanent magnets. As the disk rotates, lines of force in the magnetic fields of the magnets are cut, thus inducing a current that flows around the disk. In accordance with Lenz's Law, the induced current has such a direction that its magnetic field opposes the motion which induced the current. The eddy currents thus act as a brake on the shaft. They keep the shaft from turning too fast or from "coasting" after current through the meter is turned off.

Hot-wire meters. The heating effects of an electric current can be used to operate meters. When a current, or part of it, flows through a fine wire or metal strip inside a hot-wire meter, the wire or strip is heated because of its resistance. The heat makes the wire or strip expand, and the expansion can be used to move a needle. Since the amount of expansion is proportional to the current flowing through the meter, the needle indicates a reading proportional to the current. Figure 146 shows a hot-wire meter. If you do Experiment 56, you can see how the heating effects of an electric current can be used to make a pointer move.

Figure 147 *shows one kind of thermocouple meter. When alternating current flows, the two wires become heated at the point of contact, and the thermocouple produces a direct current at low voltage that is measured by the sensitive meter. In another kind of thermocouple meter, the alternating current is sent through a small heater coil surrounding the thermocouple.*

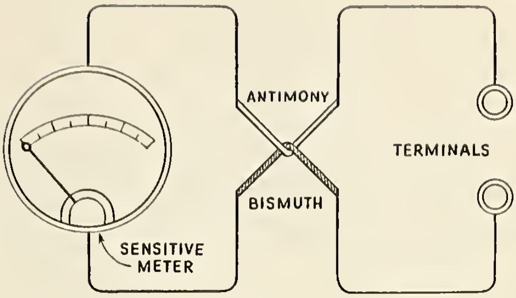
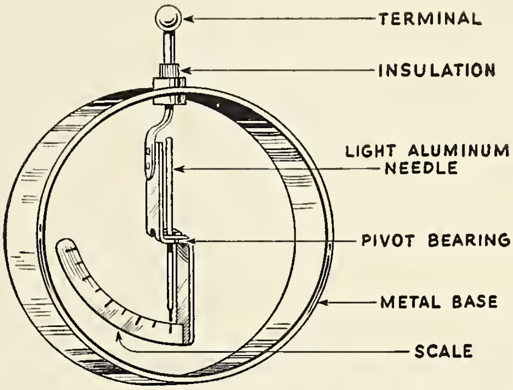


Figure 148 *shows one kind of electrometer, used to measure true potential difference or electromotive force when a current is not flowing. The well-insulated terminal leads the charge to an extremely light aluminum vane which acts like a leaf of an electroscope, being repelled by the like charge on the fixed vane. The greater the charge, the farther the lightweight, counterbalanced vane is repelled at top and bottom, and the higher the voltage indicated on the scale.*



Hot-wire meters are used both as ammeters and voltmeters. The ammeters can be equipped with shunts, while the voltmeters can be used with multipliers. Hot-wire meters will work on either direct current or alternating current. However, since better types of direct-current meters are available, hot-wire meters are generally used on alternating current.

Thermocouple meters. Another kind of meter operated by heat is the thermocouple meter shown in Figure 147. As explained in Chapter 8, a thermocouple is made of two wires of different metals joined together. If the other ends of the wires are connected to a sensitive galvanometer and the joint is heated, a current at very low voltage will flow through the circuit. The current is said to be produced by *thermoelectric* action.

This current is a direct current, and its strength depends on the amount of heat applied to the joint and the kinds of metals used. In thermocouple meters, the joint is heated by the resistance of a wire connected in the main circuit. Ordinarily, the wires used for the thermocouple are made of alloys of bismuth and antimony, since these two metals have been found to produce the greatest voltage when heated in this way.

Since thermoelectric action takes place when the joint is heated, it does not matter whether the heating is done by direct or alternating current. Thus, thermocouple meters may be used with either kind of current. They can also be used as either ammeters or voltmeters, depending on how their scales are calibrated. The direct current produced by heating flows through a sensitive meter, usually of the moving-coil type. Thermocouple meters are especially useful in radio, where alternating currents of very high frequency are used.

Electrometer. As you know, all the kinds of meters described so far are operated by either the magnetic or heating effects of an electric current. Whether the meter is an ammeter, voltmeter, or ohmmeter, its needle deflection is proportional to the current. However, since Ohm's Law relates the current to the voltage and resistance, a current-operated meter can be calibrated to indicate volts or ohms. Strictly speaking, the usual kinds of voltmeters measure current instead of voltage.

In order to measure the true potential difference or electromotive force, scientists use an instrument called an electrometer, or *electrostatic voltmeter,* shown in Figure 148. If you compare this picture with Figure 20 (page 38), you will see that an electrometer is an electroscope with a scale marked in volts. One vane of the electrometer is fixed, while the other is movable. Like charges on the two vanes repel each other. The movable vane is forced to swing up. Its position shows the voltage on the scale, because the amount of swing is proportional to the force of repulsion between the charges on the vanes. The main use of electrometers is in laboratories where very accurate measurements of voltage are sometimes needed.

CHECKING WHAT YOU LEARNED

1. **a.** What is an ohmmeter? **b.** Tell how it is used.
2. How do a wattmeter and a watt-hour meter differ from each other?
3. Name two kinds of meters that use the heating effects of current and explain briefly how each kind works.
4. Do the ordinary types of voltmeters actually measure electrical pressure? Explain.

USING WHAT YOU LEARNED

1. Does more current flow through an ohmmeter when the needle is set at zero or when an unknown resistance is being measured? Why?
2. Does the rotating disk in a direct-current watt-hour meter turn the dial pointers? Explain.
3. Could you use a wattmeter to measure electrical energy? Give your reasons.
4. One end of a tungsten wire is connected to a terminal of a sensitive galvanometer, and one end of an aluminum wire is connected to the other terminal. The other ends of the two wires are twisted together and then heated. **a.** Will the galvanometer needle indicate a current? If so, what kind of current? **b.** If the connections are reversed and the heating is repeated, what will happen? Why?

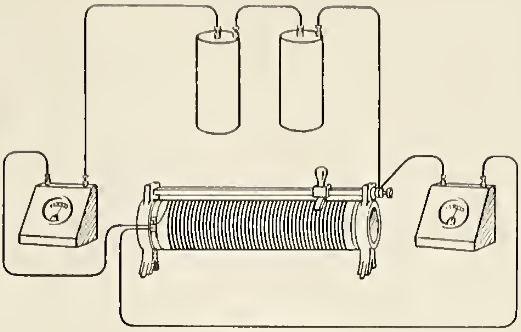
Measurements

Of course, we do not connect meters just for fun. Meters tell us something we wish to know about electric circuits or parts of circuits. If you turn back to page 252, you can see a variety of meters used in electrical work. Some of these meters have been explained in this chapter, while others have not been explained because an explanation of their operation is beyond this beginning book. Each of these meters tells something about the current, voltage, resistance, power, and so forth, in an electric circuit. In electrical work, meters are used mainly in controlling or testing circuits and devices. By watching the movement of meter needles, an operator of electrical equipment can tell what is going on in a circuit. If he knows this, he can make whatever changes are necessary by throwing switches, turning rheostat knobs, and so on. Meters are absolutely invaluable in all kinds of electrical work, because measurements made with meters furnish practically all of the usable information we have about electrical devices and electric circuits.

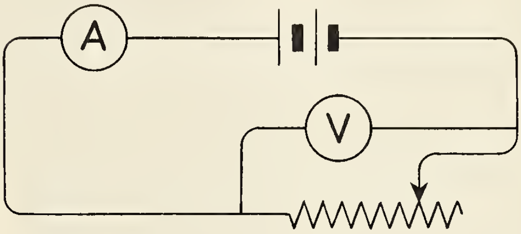
Measuring with ammeter and voltmeter. You already know how to connect an ammeter or a voltmeter in a circuit. Figure 37 (page 67) shows that an ammeter may be connected in any part of a series circuit in order to measure the current. An ammeter, as you know, is always a series instrument. Figure 51 (page 94) shows how to connect a voltmeter to measure both the open-circuit voltage and the closed-circuit voltage. To measure the voltage drop through part of a circuit, you connect a voltmeter across that part of a circuit, as shown in Figure 29 (page 53). When a voltmeter is connected to measure closed-circuit voltage, it also indicates the voltage drop through all parts of the circuit except the source of E.M.F. As you remember from Chapter 4, you must subtract the closed-circuit voltage from the open-circuit voltage to find the voltage drop through the source of E.M.F. If you do Experiment 57, you can connect an ammeter and a voltmeter to take various measurements.

Ammeters measure rate of current flow, while voltmeters measure electrical pressure. You know that the amperage and voltage of a circuit are related to its resistance, and that Ohm's Law states the relationship. You are familiar enough with

Figure 149 *shows how resistance is measured with an ammeter and a voltmeter. The rheostat represents the unknown resistor whose value is to be measured. The ammeter measures the current flowing in the circuit, while the voltmeter measures the voltage drop through the unknown resistor. Dividing the voltage drop in volts by the current in amperes gives the resistance in ohms.*



The diagram at the right shows how two meters are used to measure resistance in this way. Positive (+) and negative (—) terminals must be properly connected. The unknown resistor is connected to the voltmeter terminals in place of the rheostat.

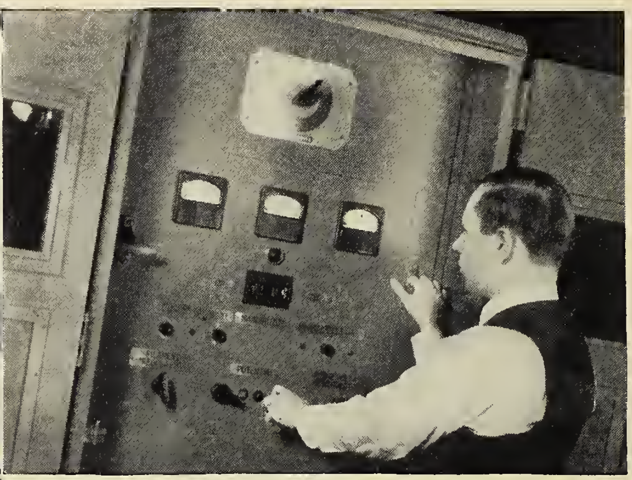


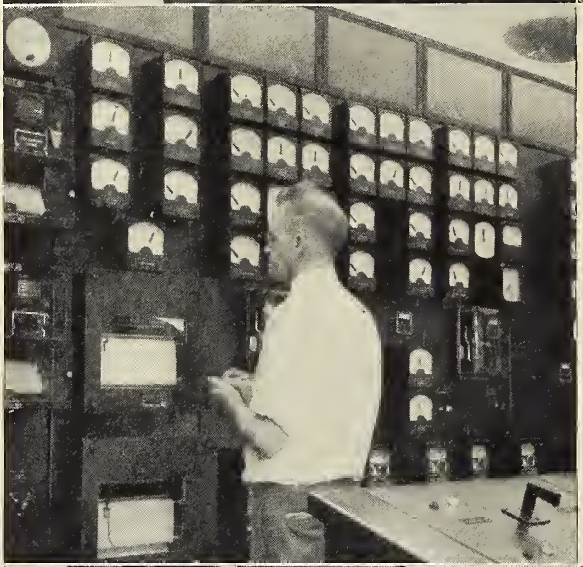
Ohm's Law by now to know that if the amperage and voltage are indicated, the resistance can be calculated. Thus, by measuring the voltage drop and the current with meters, you should be able to find the resistance of any part of an electric circuit. In other words, resistance can be measured by the voltmeter-ammeter method as well as by the ohmmeter method. Figure 149 shows how the resistance of a rheostat or any part of it can be measured with a voltmeter and an ammeter.

The ammeter is connected in series with the rheostat and thus shows the current flowing through the rheostat. The voltmeter is connected across the rheostat, and thus its reading shows the voltage drop through the rheostat wire connected in the circuit. In other words, the voltmeter indicates the difference in potential between the points connected to its terminals. If you know the current and voltage, the resistance can be easily calculated from the formula $R=\frac{E}{I}$ in which R is the resistance, E is the voltage drop, and I is the rate of current flow. For example, if the voltage drop is 1 volt and the current is .5 ampere, the resistance is equal to 1 ÷ .5, or 2 ohms. In Experiment 57 you can measure resistance in this way.

Obviously, if the voltage and amperage are known, the wattage can be easily calculated from the formula $P=EI$. Also, the power loss can be calculated from the amperage and resistance by using the formula $P=I^2R$. If the current is direct current, the power in watts is exactly equal to the product of volts times amperes. If the current is alternating current, you may determine the power, provided that the circuit contains only resistance without appreciable amounts of inductance or capacity. If the circuit contains inductance or capacity, you must allow for the power factor, as mentioned on page 198. In Experiment 57, you can measure power with an ammeter and a voltmeter.

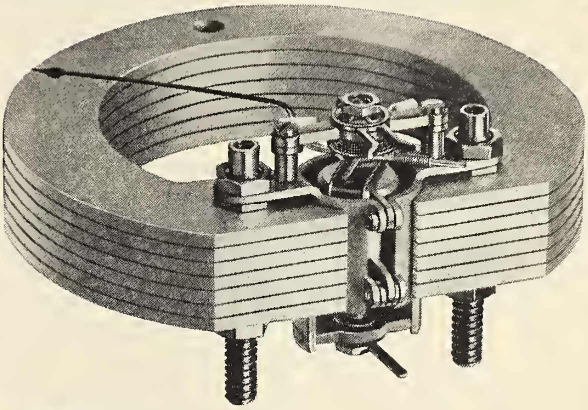
Measuring with Wheatstone bridge. A third way to measure resistance is by means of the Wheatstone bridge, a circuit that provides a convenient and very accurate method for measuring resistance. Figure 150 (page 272) shows a bridge circuit that can be used to measure resistance. It has four arms marked A, B, C, and D. A galvanometer is connected as shown in the diagram. Arms A and B are fixed resistors whose values are known. Arm C is a variable resistor with a scale that may be read directly in ohms. Arm D is the unknown resistor whose resistance is to be measured.

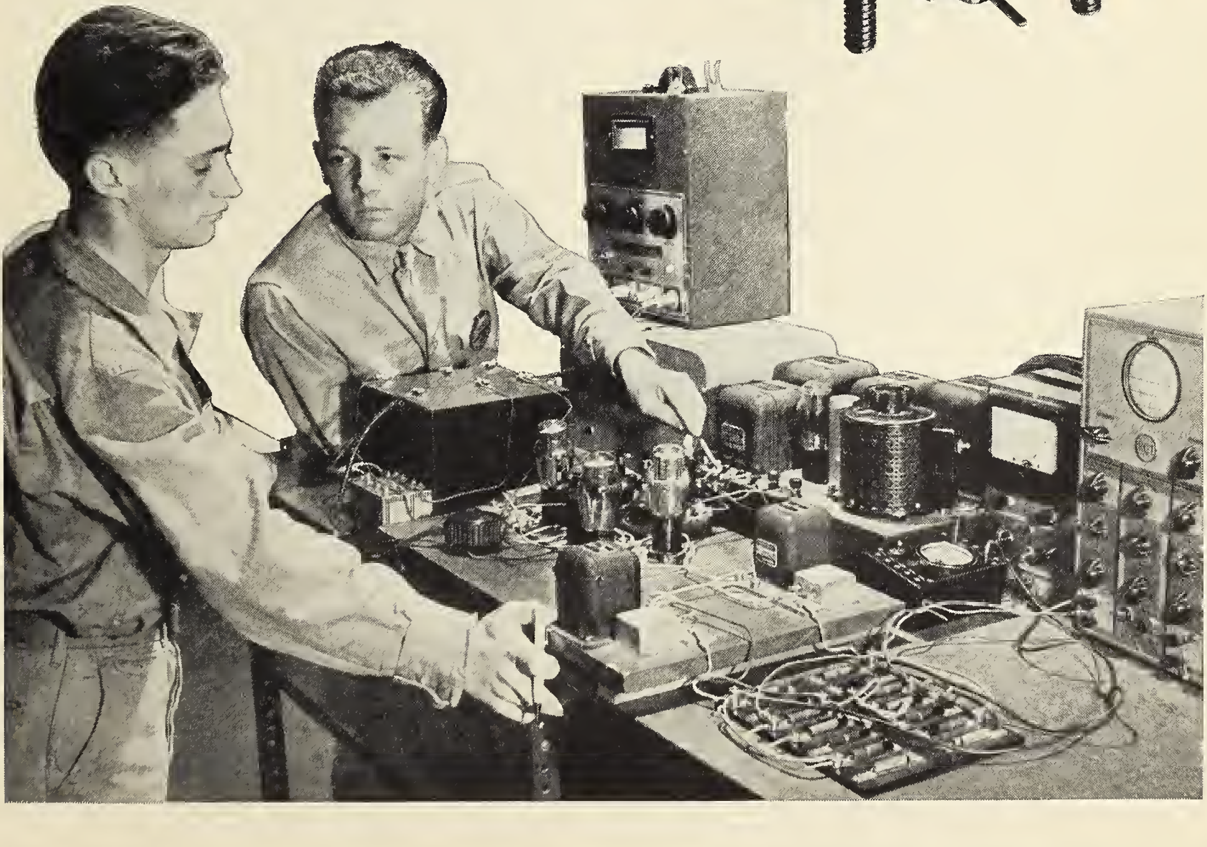




The three meters at the upper right are for adjusting the operation of a 220,000-volt X-ray machine used to locate hidden defects in steel welds and castings. The single watt-hour meter at the upper left is adequate for measuring the electrical energy used by one household, but dozens of meters of many kinds are needed in the control room of a large power station, such as shown at the left center. And as shown below, the commercial transport plane also requires meters for measuring and controlling its complex electrical and radio circuits.

Shown above is a Wheatstone bridge, used to measure resistance accurately. At the right are shown the "insides" of a modern moving-coil meter. Notice the magnets, coil, core, and springs. Signal Corps instruction in the elements of radio requires a thorough knowledge of electricity, as indicated by the condensers, resistors, batteries, transformers, and meters in the picture below.





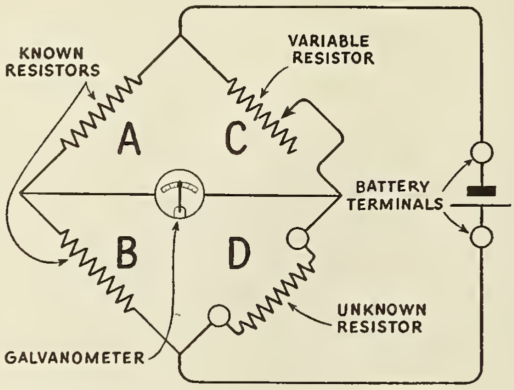


Figure 150. *The diagram at the left will help you remember how to use the Wheatstone bridge, one of the most accurate methods of measuring resistance. When the bridge is balanced, the galvanometer shows no current flowing. The ratio between A and B is then the same as between the variable resistor C and the unknown resistor D, whose value can be calculated by using the equation* $\frac{A}{B}=\frac{C}{D}$

The terminals of the Wheatstone bridge are connected to a source of electrical energy. The galvanometer shows that a current is flowing between the arms. Next the variable resistor is adjusted until the galvanometer needle stands at zero, showing that no current is flowing through the galvanometer. Then the scale of the variable resistor is read. The value of the unknown resistor can be calculated from the equation

$$\frac{A}{B}=\frac{C}{D}$$

For example, suppose that the known values of A and B are 30 ohms and 50 ohms, respectively. The scale reading of the variable resistor shows 90 ohms. Substituting these values, we get

$$\frac{30}{50}=\frac{90}{D} \quad 30\ D=4500 \text{ ohms} \quad D=150 \text{ ohms}$$

The Wheatstone bridge uses the principle of Ohm's Law. The rate of current flow depends on the voltage and resistance of the circuit. In the Wheatstone bridge, the voltage at the source remains the same; therefore, only the resistance must be considered. In the example already given, let us see what happens before arm C is adjusted. Arm A has a resistance of 30 ohms, arm B of 50 ohms, arm C of 100 ohms before it is adjusted, and arm D of 150 ohms. Obviously, a larger current will flow through arms A and B than through arms C and D, because A and B have a resistance of 80 ohms, while C and D have a resistance of 250 ohms. Because there is a potential difference between the two points where the galvanometer is connected, part of the current flows through the meter.

When the variable resistor in arm C is adjusted to 90 ohms, current no longer flows through the galvanometer. The bridge is now said to be "balanced." The voltage drop through A is the same as that through C, and the voltage drop through B is the same as that through D. No current flows through the galvanometer because there is no potential difference between its terminals.

The same method may be used with alternating current, except that the galvanometer is not used. In its place, a pair of headphones can be connected. The variable resistor in arm C is adjusted until the hum heard in the headphones disappears or is at a minimum. The reading of the variable-resistor scale at this point then gives the

---

Measuring reactance: By using alternating current, you can measure the reactance due to capacity or inductance with a Wheatstone bridge. The connections are the same as in Figure 150 except that a variable capacity or inductance is substituted for arm C. Alternating current and headphones are used. When the variable capacity or inductance is adjusted so that the hum disappears or is reduced to a minimum, the reactance due to the unknown capacity or inductance can be calculated as before.

value of arm C. When that is known, the value of the unknown resistor can easily be calculated. You must remember that arm C is a variable resistor and also that the fixed resistors in arms A and B usually have different values. In fact, in one form of Wheatstone bridge, arms A and B are a single wire with a sliding contact connected to the galvanometer. The position of this contact determines the ratio between A and B. If you do Experiment 58, you can measure unknown resistances with a Wheatstone bridge.

Units of electrical measurement. To help you in reviewing the various units of electrical measurement, they are listed here with their definitions. Some definitions are given that have not previously been presented. The list here is mainly for reference and review rather than for study.

Ampere: The unit for measuring the rate of current flow. One ampere is a flow of one coulomb per second. It is also the amount of current that an E.M.F. of one volt will drive through a resistance of one ohm.

Coulomb: The unit for measuring the quantity of electrical charge. One coulomb is believed to contain 6,280,000,000,000,000,000 electrons. This figure is usually expressed as 6.28×10^{18}. Passing through a standard solution of silver nitrate, a coulomb deposits .001118 gram of silver on the negative electrode, thus increasing the weight of the electrode by that amount.

Farad: The unit for measuring capacity. When one coulomb is stored at a pressure of one volt, the capacity is one farad. Since the farad is too large a unit for practical work, the **microfarad** (one millionth of a farad) is more commonly used.

Henry: The unit for measuring inductance. When the current changes at a rate of one ampere per second, an inductance of one henry will cause an E.M.F. of one volt to be induced. Since the henry is too large for practical work, the **millihenry** (one thousandth of a henry) is more commonly used.

Ohm: The unit for measuring resistance. At the freezing temperature of water a column of mercury 106.3 centimeters long and 1 square millimeter in cross section has a resistance of one ohm.

Volt: The unit for measuring electrical pressure, that is, E.M.F. or potential difference. When 100,000,000 lines of force are cut in one second, an E.M.F. of one volt is induced.

Watt: A unit for measuring electrical power. A current of one ampere at a pressure of one volt has a power of one watt. The **kilowatt** (one thousand watts) is very commonly used.

Watt-hour: A unit for measuring electrical energy or the work done by electrical energy. A current with the power of one watt acting for one hour uses one watt-hour of energy or does one watt-hour of work. The **kilowatt-hour** (one thousand watt-hours) is very commonly used.

CHECKING WHAT YOU LEARNED

1. Where in a series circuit should an ammeter be connected to measure the rate of current flow? Why?
2. **a.** When a voltmeter is connected across the source of E.M.F. in a closed circuit, what two things does it indicate? **b.** How can you use a voltmeter to measure the voltage drop through any part of a circuit except the source of E.M.F.?
3. **a.** How can you measure resistance with an ammeter and a voltmeter? **b.** In what other ways can resistance be measured?
4. Tell how you can use an ammeter and a voltmeter to measure the power in a circuit.

THINKING OVER WHAT YOU LEARNED

1. After each topic in this chapter state the big ideas or principles you learned, using complete sentences.
2. Show that you understand the meaning of the following terms by using a sentence or a definition: **a.** ohmmeter, **b.** dynamometer, **c.** shunt, **d.** Wheatstone bridge, **e.** plunger-vane, **f.** multiplier, **g.** ammeter, **h.** thermocouple, **i.** hot-wire meter, **j.** repulsion-vane, **k.** moving-coil meter, **l.** voltmeter, **m.** galvanometer, **n.** moving-vane meter, **o.** electrometer, **p.** wattmeter, **q.** watt-hour meter.

Experiment 53: **Galvanometers**

THINGS NEEDED: No. 26 insulated copper wire. Oats box or embroidery hoop. Magnetic compass. Spool. Two No. 6 dry cells. Reversing switch. Galvanometer from Experiment 16. Clock spring. Bar magnet. Coil from Experiment 45. U-magnet and support. String.

WHAT TO DO: **a.** (See Fig. 133.) Wind a coil of No. 26 wire around an embroidery hoop or oats box. Set the compass and spool in the coil. Connect a dry cell to the coil through a reversing switch. **Keep the switch open except when you are watching the movement of the compass needle.** Turn the coil so that its turns are parallel with the compass needle. Throw the switch to one side and watch the needle. Then throw the switch to the other side and notice what happens. Using the right-hand rule for coil, determine the polarity of the coil in both instances. Also try adding another dry cell in series.

b. (See Fig. 134.) Magnetize a curved section of clock spring with a bar magnet and place its ends against opposite sides of the compass used in the galvanometer from Experiment 16, as shown in Figure 134. Using a reversing switch, send the current through the coil first in one direction and then in the other. Watch the compass needle. Also try adding another dry cell in series.

c. (See Fig. 135.) Suspend the coil from a string between the poles of a U-magnet. Send the current through the coil first in one direction and then in the other by reversing the connections. Watch the movement of the coil. Also try adding another dry cell in series.

d. (*Optional*) Using the 1.5- or 2-volt terminals of a toy transformer, repeat Parts **a**, **b**, and **c**. (In Parts **a** and **b**, turn the current on and then off quickly to avoid weakening the magnetism of the compass needles.)

Experiment 54: **Vane Meters**

THINGS NEEDED: No. 18 insulated copper wire. Cardboard cylinder ½ inch in diameter. Two large iron or steel nails. Toy transformer. No. 6 dry cell. Two staples. Hammer. Board.

WHAT TO DO: **a.** (See Fig. 139.) Wind about 100 turns of wire on the cylinder and set up the nail, as shown in the diagram. Connect the coil to the 1.5- or 2-volt terminals of the transformer. Notice what happens when an alternating current is sent through the coil. Then substitute a dry cell for the transformer.

b. (See Fig. 140.) Using staples, fasten each end of a nail to a board so that the nail and coil are held firmly. Lay another nail alongside the first one and send an alternating current at 1.5 or 2 volts through the coil, as in Part **a.** What happens? Why? Repeat, using a dry cell in place of the transformer.

Experiment 55: **Dynamometer**

THINGS NEEDED: Two cardboard cylinders, one slightly larger than the other. No. 18 insulated copper wire. No. 26 insulated copper wire. Toy transformer. 6-volt automobile headlight bulb and socket.

WHAT TO DO: **a.** (See Fig. 142.) Wind 10 turns of No. 18 wire around the larger cardboard cylinder and 20 turns of No. 26 wire on the smaller cylinder. Arrange the coils as shown in Figure 142. Support the smaller coil on bearings made of wire. Connect the two coils in series and then connect them in series with a 6-volt bulb and socket and the 6-volt terminals of a toy transformer. Notice what happens to the coil. (If you wish, you may repeat this part of the experiment, using four dry cells in series.)

b. (*Optional*) Connect the coils as a wattmeter, as shown in Figure 144. The stationary coil should be in series with the 6-volt bulb and transformer, while the movable coil should be in parallel with the terminals of the transformer. Turn on the current and notice what happens. (If you care to do so, you may try using four dry cells in series in place of the transformer.)

Experiment 56: **Hot-Wire Meter**

THINGS NEEDED: No. 30 bare iron wire. Three nails. Hammer. Board. Toothpick. Toy transformer.

WHAT TO DO: (See Fig. 146.) Drive three nails in the board and stretch a piece of No. 30 bare iron wire around the nails, as shown in the diagram. Place a toothpick between the wires. Connect the ends of the wire to the 1.5- or 2-volt terminals of a toy transformer. What happens when a current is sent through the wire? Explain. (If you wish, you may repeat the experiment, using a dry cell in place of the transformer.)

Experiment 57: **Measuring with Meters**

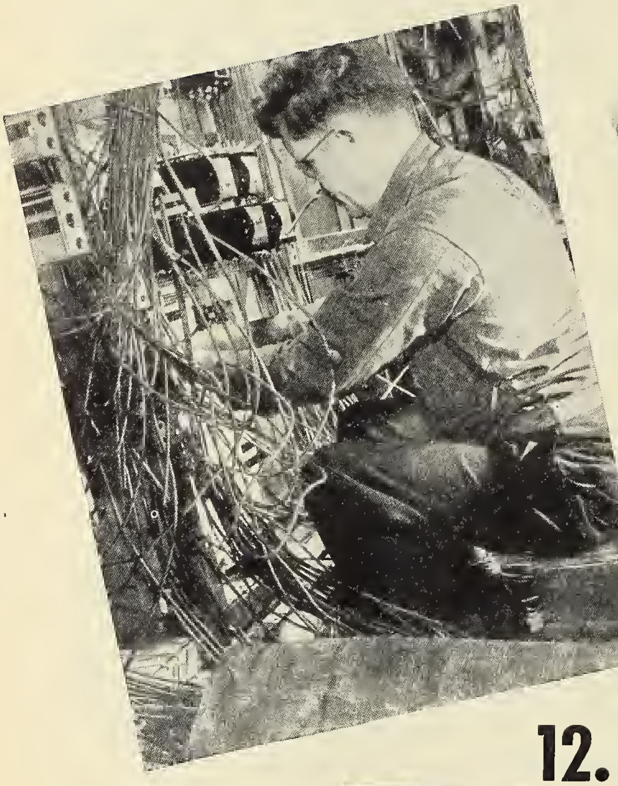
THINGS NEEDED: D.C. ammeter. D.C. voltmeter. Two No. 6 dry cells. 10-ohm rheostat. No. 18 insulated copper wire. 3-volt bulb and socket.

WHAT TO DO: (See Fig. 149.) Connect the apparatus as shown in the diagram. (Set the rheostat in the OFF position except when taking meter readings.) Vary the resistance of the rheostat by moving the sliding contact. What happens to the voltmeter reading as the resistance is increased? What happens to the ammeter reading? Why? Set the sliding contact so that .5 ampere flows through the circuit. Take the voltmeter reading and then open the circuit by moving the sliding contact back to OFF. Calculate the resistance of that part of the rheostat used to cut the current down to .5 ampere. Also calculate the power used in watts. Then substitute a 3-volt bulb and socket for the rheostat and determine the resistance and the power.

Experiment 58: **Measuring with the Wheatstone Bridge**

THINGS NEEDED: Wheatstone bridge. Unknown resistances. Galvanometer. No. 6 dry cell. Toy transformer. Headphones.

WHAT TO DO: (See Fig. 150.) Connect the apparatus as shown in the circuit diagram. Place an unknown resistance in the arm marked D. Move the sliding contact until the galvanometer shows no current flowing. Take the reading of the sliding contact in ohms. Then calculate the unknown resistance from the three known resistances. Repeat, using headphones in place of the galvanometer and the 1.5- or 2-volt terminals of the transformer in place of the dry cell. Adjust the sliding contact until the hum in the headphones is reduced to a minimum. Then take the reading and make the calculations as before.



12. Types of Electric Circuits

FINDING OUT WHAT YOU KNOW

1. Is the current the same in all parts of a series circuit?
   Of a parallel circuit? Explain your answers.

2. How do the voltages at the branches of a parallel circuit compare with one another? Why?

3. How can you calculate the resistance of a series circuit? Of a parallel circuit?

4. Explain what is meant by a divided circuit.

5. Give some ways in which alternating current can be changed to direct current.

6. How does full-wave rectification differ from half-wave rectification?

7. Why are filters used with rectifiers?

8. Name the important parts of a radio power supply.
   State the purpose of each part.

THE FIRST CHAPTER OF this book was about the electric circuit, and now we are back on the same subject again. This time, however, we can study the circuit in the light of what we have learned about the construction and operation of electrical devices and the way the electric current behaves.

Electric circuits must be designed so that the correct amount of current flows through the various devices connected in the circuits. In order to understand how this is accomplished, you must understand the different methods of arranging circuits so as to control the flow of current.

Series Circuits

You already know that a direct current will flow only when there is a complete conducting path between the positive and negative terminals of the source of E.M.F. This is true for both battery circuits and circuits connected with generators. And for our purpose here, we can consider that a complete conducting path is also necessary for alternating-current circuits.

The flow of current in a circuit, under pressure of a given E.M.F., is limited by the amount of resistance in the circuit. This follows from the formula of Ohm's Law, $I = \frac{E}{R}$

Figure 151 shows a series circuit which includes a resistance of 10 ohms, a 6-volt battery, and an ammeter. From the formula above

$$I = \frac{6}{10} \text{ or } .6 \text{ ampere}$$

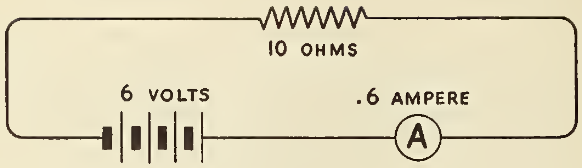


Figure 151 *shows that there is only one path for the current in a series circuit. Consequently, wherever the ammeter is connected in this circuit, the needle will indicate the total current of .6 ampere.*

If you trace the current from the positive terminal of the battery through the connecting wires, ammeter, and resistance, and then back to the negative terminal of the battery, you see that in a series circuit the total current flows through every part of the circuit. In other words, there is only one path for the current to follow. This path is from one terminal of the source, through all the devices in succession, and back to the other terminal of the source.

You can see that the same current flows in all parts of the circuit if you connect an ammeter at different points in the circuit. No matter where you connect it, it will always read the same. Remember, therefore, that *the current in a series circuit is the same in all parts of the circuit.*

Now suppose we connect another resistance in this series circuit in such a way that it becomes part of the single path the current must follow. Figure 152 (page 279) shows the same circuit as above, with a resistance of 20 ohms added. The total resistance of the circuit is now 30 ohms. From the Ohm's Law formula

$$I = \frac{6}{30} \text{ or } .2 \text{ ampere}$$

Adding resistance to a series circuit reduces the current. As far as the result is concerned, it makes no difference where the resistance is added in the circuit. The total resistance of the circuit determines the flow of the current, and the current is the same in all parts of the series circuit.

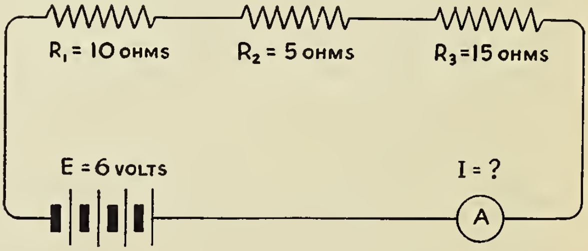
To find the current flowing in a series circuit, it is necessary to know two things: (1) the voltage across the circuit, and (2) the total resistance of the circuit. *The total resistance of a series circuit is equal to the sum of the various resistances in the circuit.* This is expressed in the formula

$$R_{total} = R_1 + R_2 + R_3, \text{ etc.}$$

In solving problems concerning circuits, it is helpful to draw a wiring diagram showing the circuit. In the first place, if you can draw the diagram, you may be certain that you understand the problem. In the second place, it is easier to see what information is given and what information must be found if you can refer to a diagram. And finally, drawing a diagram is of practical value in tracing or designing a circuit. It is a good idea to place on the diagram the information given. A good method of solving such circuit problems follows.

Suppose the problem asks you to find what current will flow through a series circuit in which there are resistances of 10 ohms, 5 ohms, and 15 ohms, when the E.M.F. is supplied by a 6-volt battery. Take the following steps:

1. Draw a wiring diagram and place the information at the proper points, as shown below.

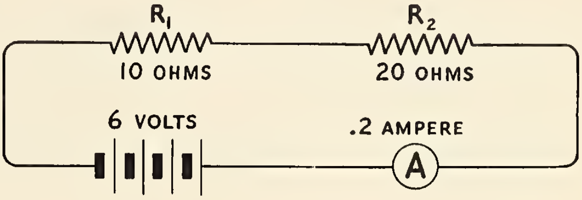


Alternating-current circuits: Alternating current will flow in circuits containing capacitance (a part that acts as a condenser), even though there is not a complete conducting path. This fact is discussed later in this chapter.

Current in series circuits: The current in a series circuit is the same in all parts of the circuit. For a given voltage, the current is determined by the total resistance of the circuit.

Resistance in series circuits: The total resistance of a series circuit is equal to the sum of the various resistances in the circuit.

Figure 152 *shows that with a fixed voltage the current in a series circuit is determined by the total resistance of the circuit. Adding another resistor to the circuit of Figure 151 reduces the current as shown here.*



2. To solve a problem with the formulas of Ohm's Law, you must know two of the three values, so write down the symbols:

$E=$ $I=$ $R=$

Then read the problem over again to see which values are given. Write them down, putting a question mark after the unknown value. In the problem above, you have an E.M.F. of 6 volts. Write this after **E**. You have three resistances—R_1, R_2, R_3. You know the total resistance is the sum of these three. Write the formula down and substitute numbers for the three resistances. Put a question mark after **I**. Now you have:

$E = 6$ volts $I = ?$ amperes

$R = 30$ ohms $(R_1+R_2+R_3 = 10+5+15)$

3. Now select the formula you must use. You learned in Chapter 3 (see Fig. 26, page 49) that Ohm's Law can be stated in three ways:

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

The formula to use is the one that can be solved most easily for the value you want; in this case it is $I=\frac{E}{R}$. Write down the formula and substitute the values, thus:

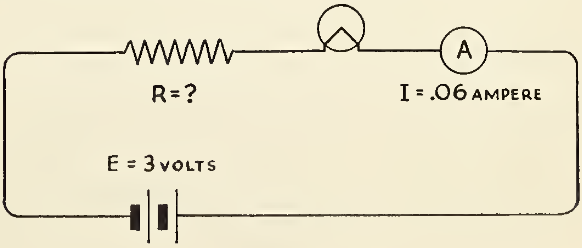
$$I=\frac{E}{R} \quad \text{or} \quad I=\frac{6}{30}=.2 \text{ ampere}$$

Let us take a practical example of designing a circuit in order to see how the engineer thinks through his problem. One of the common vacuum tubes used in portable radio sets is designed to draw .06 ampere at 2 volts. That is to say, a pressure of 2 volts is required to force enough current through the filament so that it will operate at the correct temperature. It is clear that one dry cell with a voltage of 1.5 is not sufficient to operate the tube, for it cannot force enough current through the filament. Two cells, connected in series, will supply 3 volts. At this voltage more current will be forced through the filament than is needed, and the life of the tube will be reduced. Now, how can we design a circuit that will supply a current of .06 ampere to the tube?

To solve this problem, we first need to know how much resistance must be in the circuit to limit the current from two dry cells to .06 ampere. To make it clear, we draw the diagram as shown below. (Note that the symbol used for the filament of the vacuum tube is somewhat like the lamp symbol used earlier in this book.) From the Ohm's Law formula $R=\frac{E}{I}$, we get

$$R=\frac{3}{.06}=50 \text{ ohms}$$

The total resistance in the circuit must be 50 ohms. With the same formula we can also find



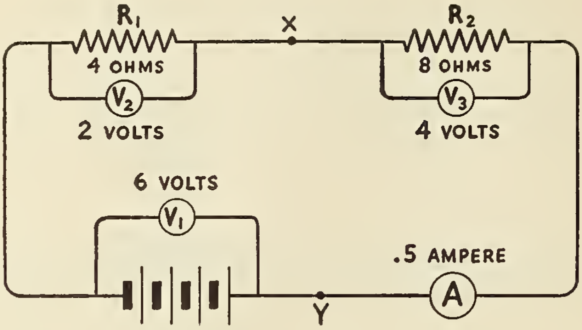


Figure 153 *shows that the total voltage drop in a series circuit is equal to the sum of the voltage drops through the various resistances. Hence, 6 volts, the total voltage drop at .5 ampere in this circuit, is equal to the sum of 2 volts drop through the first resistor and 4 volts drop through the second resistor.*

the resistance of the filament. We know that it is designed to take .06 ampere at 2 volts; therefore $R = \frac{E}{I} = R = \frac{2}{.06} = 33\frac{1}{3}$ ohms. Now if the total resistance needed to reduce the current to .06 ampere is 50 ohms, and the resistance of the filament is 33⅓ ohms, then a resistance of 16⅔ ohms must be connected in series with the tube.

Let us take another practical example from radio. Suppose that we have three vacuum tubes of the type described and we wish to operate them with a 6-volt storage battery. How can this be done? We can use the same diagram as before, simply by substituting different values and adding symbols for the extra tubes.

First of all, we must see how much resistance is required in a 6-volt circuit to supply .06 ampere of current. $R = \frac{6}{.06} = 100$ ohms. We know (from the previous problem) that the filament of each tube has a resistance of 33⅓ ohms. The filaments of the three tubes connected in series will give us a total resistance of 100 ohms. This is just what we need to limit the current to .06 ampere, so no additional resistance is needed in the circuit. In some radio sets the tubes are connected in this manner. This example also shows how strings of lamps for Christmas trees are connected. The lamps used are for use on 15 volts. When eight of them are connected in series, they can be used in a 110-volt circuit. If nine are used, less current flows through each lamp because the total resistance of the circuit is increased, and the lamps are not so likely to burn out.

Now let us consider a series circuit from a somewhat different angle. Figure 153 shows a series circuit with two resistances. We know that the total resistance is 12 ohms, for R_1 has a resistance of 4 ohms and R_2 has a resistance of 8 ohms. If we connect a voltmeter at the various places shown in the circuit diagram by the voltmeter symbol, we will get the voltage drops through various parts of the circuit. If we connect it just long enough to get a reading across the terminals of the battery, we see there is a total voltage of 6 volts there. (The negative side is considered to be at zero potential.) We know that 6 volts are available to drive the current through the circuit.

You have learned that the amount of current flowing in a series circuit is the same in every part of the circuit. Now let us see how the voltage drops through parts of the circuit vary, and discover the relation between these voltage drops and the total voltage.

When the voltmeter is connected across R_1, it shows 2 volts. Thus 2 volts are used to drive the current through that resistance. If 2 of the 6 volts are used, then 4 volts should be left. You can check this by measuring across from X to Y. The voltmeter will show a difference of 4 volts between these two points in the circuit. Only 4 volts are available between these points.

If you connect the voltmeter across R_2, it will read 4 volts. This means that 4 volts are needed to drive the current through the resistance of 8 ohms. The voltage drop through R_2 is therefore 4 volts.

The total voltage drop in the circuit is 2 volts through R_1 and 4 volts through R_2, a total of 6

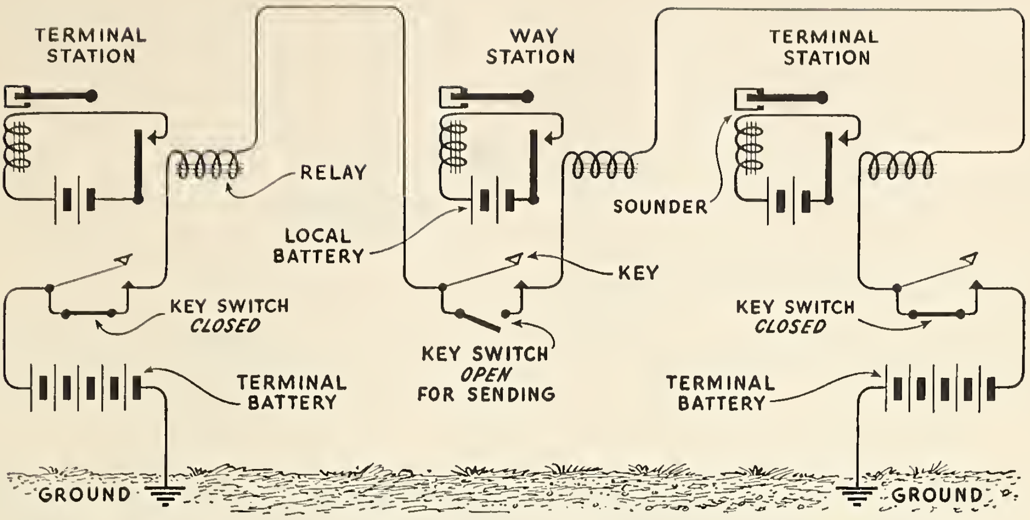


Figure 154. *A good example of a series circuit is the simplified telegraph circuit shown here. If you trace the main line from one terminal station to the other, you will see that batteries, keys, and relays are all in series. Each sounder is in series with a local battery and the relay contacts. The key switch at the way station is open, indicating that this operator is sending. All key switches are closed when the line is not in use.*

volts. We can state this as follows: *The total voltage drop in a series circuit is equal to the sum of the voltage drops through the various resistances.*

If we know the current and the values of different resistances in a circuit, we can use the formula $E = IR$ to determine the voltage drop through each resistance. For example, $R_1 = 4$ ohms,

$I = .5$ ampere. $E = IR = .5 \times 4 = 2$ volts.

The voltage drop through each resistance is equal to the current times the resistance ($E = IR$).

To be absolutely accurate, the voltage drops through the wires used in connecting different resistances (lamps, motors, tubes, etc.) should also be considered. The copper wires used in connecting devices in a circuit offer some resistance to the flow of currents. For our immediate purposes, this resistance need not be taken into consideration. In the problems which follow, it will be assumed that these wire connections do not offer noticeable resistance. In Experiment 59 (page 303) you can measure the voltage drops in a series circuit.

There are several kinds of problems relating to series circuits. These types and the methods of solving them are:

1. *To find the current in a series circuit.* First find the total resistance. Use the formula $R = R_1 + R_2 + R_3$, etc. Then use the formula

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

2. *To find the voltage required in a series circuit when the various resistance values and the current are known.* First find the total resistance. Then use the formula $E = IR$.

Inductance and capacitance in series circuits: When coils are connected in series, the total inductance can be determined from the formula: $L = L_1 + L_2 + L_3$, etc.

When condensers are connected in series, the joint capacitance can be determined from the formula: $\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}$, etc.

3. *To find the voltage drop through a resistance when the current and the resistance are known.* This is the reading of the voltmeter when its terminals are attached to the terminals of the resistance. The reading shows the voltage used in driving the current through the resistance. The voltage drop is calculated from the current and the resistance by using the formula $E = IR$.

4. *To find the total voltage when the voltage drops through the circuit are known.* The total voltage in a circuit is always equal to the sum of the individual voltage drops. This is expressed in the formula:

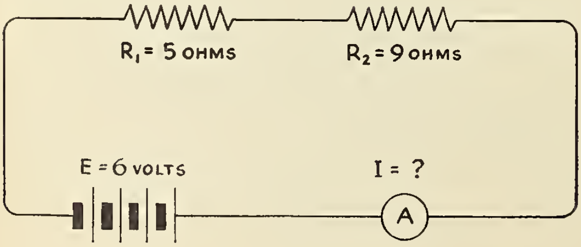
$$E = E_1 + E_2 + E_3, \text{ etc.}$$

CHECKING WHAT YOU LEARNED

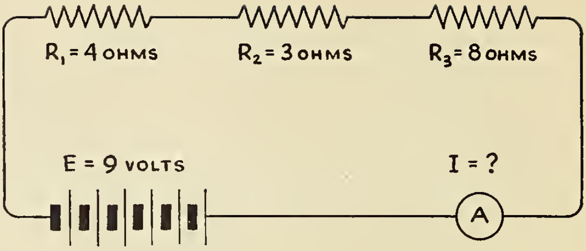
1. Why is the current the same in all parts of a series circuit?
2. Does it make any difference where an ammeter is connected in a series circuit? State a reason.
3. If resistances are added to a series circuit, will the total resistance be more or less? Will the current be more or less? Explain.
4. If four resistances of 3 ohms, 4 ohms, 5 ohms, and 8 ohms are connected in series, what is the total resistance? If 6 dry cells connected in series furnish the E.M.F. for this circuit, what will the current be?
5. Why is there a voltage drop through a resistance?
6. If a current of 3 amperes flows through a resistance of 4 ohms, what will be the voltage drop through the resistance? If a voltmeter is connected across the resistance, will it show this voltage drop?
7. If you know the voltage drops through the different resistances in a series circuit, how can you determine the total voltage needed for the circuit?

USING WHAT YOU LEARNED

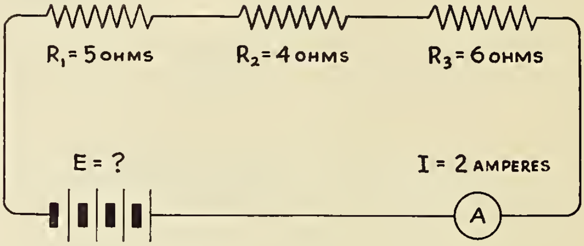
1. Find I.



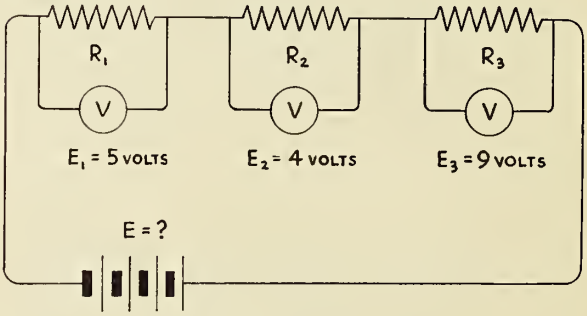
2. Find I.



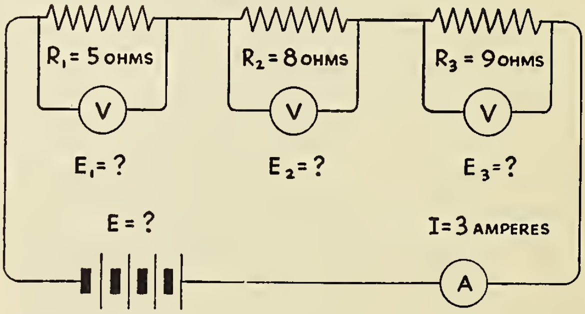
3. Find E.



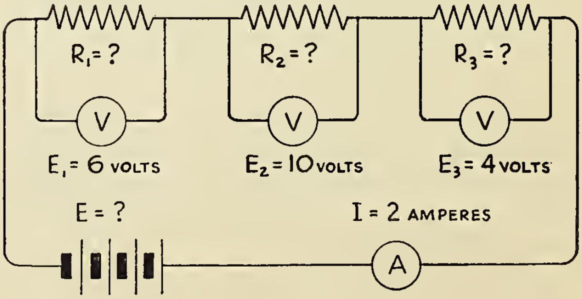
4. Find E.



5. Find E, E_1, E_2, and E_3.



6. Find E, R_1, R_2, and R_3.



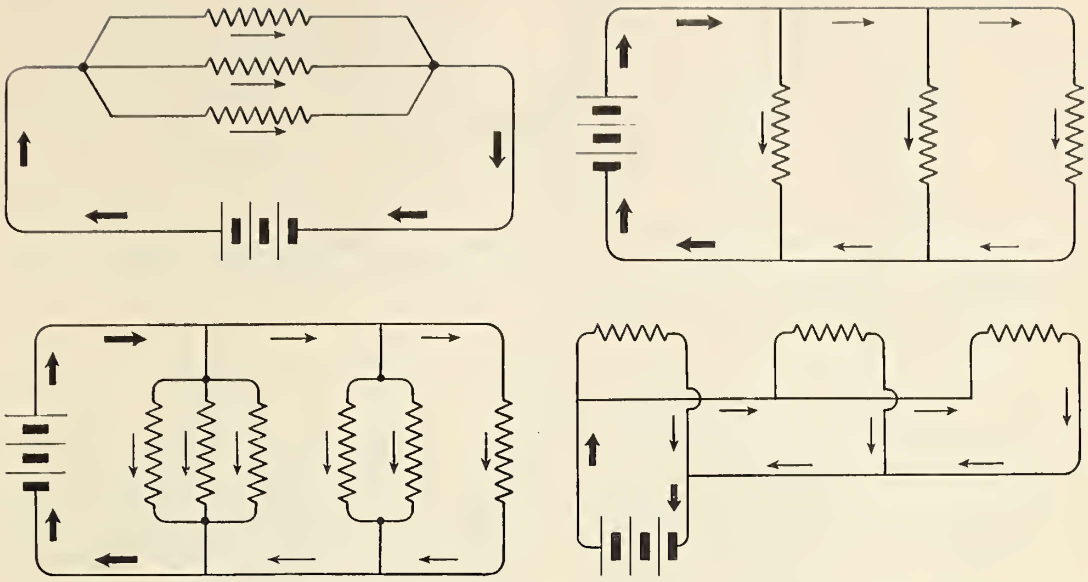


Figure 155 *shows four of the ways in which parallel circuits are usually indicated in electrical diagrams. Notice that in each case there are two or more paths for the current to follow through the parts of the circuit that are connected in parallel. The heavy arrows show the path followed by the total current, while the lighter arrows show the paths followed by the divided currents.*

Parallel Circuits

When parts of a circuit are connected so that the current can flow by several different paths and therefore is divided, the parts are said to be connected in parallel. This type of connection is also called a *divided, multiple,* or *shunt circuit*. Figure 155 shows different ways of diagraming a parallel circuit. The arrows show the direction of the current. In each of the circuits the current can travel by various paths through the circuit.

First we will consider the voltage in a parallel circuit and the voltage in each branch of the circuit. If you do Experiment 60, you will see how the voltages at different points of the circuit compare. The experiment shows that the voltage in the circuit is the same as the voltage at the lamps connected in parallel.

The voltage in a parallel circuit is the same in all branches of the circuit. Or it may be stated in this way: *The voltage in each branch of a parallel combination is the same as the voltage in the circuit.* For example, in Figure 156, a voltmeter connected from B to G will show the same voltage as when connected from C to F or from D to E. This statement holds true even when the resistances in the parallel branches are unequal. For example, if a lamp with a resistance of 220 ohms, a heater with a resistance of 10 ohms, and a toaster with a resistance of 20 ohms are connected in parallel in the same circuit, the voltage at each device is the same.

The distribution of current in a parallel circuit is shown in Experiment 60. This experiment shows that the current is different in different parts of the circuit. Figure 156 shows a similar circuit in which three lamps, each with a resistance of 220 ohms, are connected to a 110-volt generator. We can find the current through each lamp by the formula

$$I = \frac{E}{R} = \frac{110}{220} = .5 \text{ ampere}$$

The total current in the circuit is three times

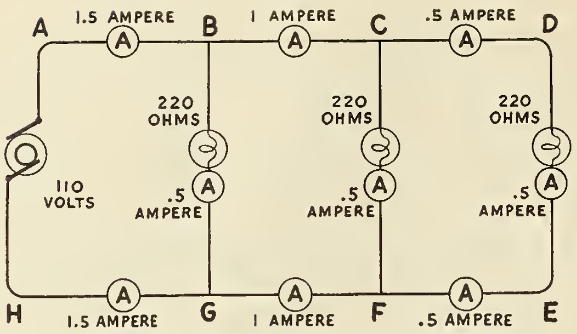


Figure 156 *shows the distribution of current and voltage in a parallel circuit having three branches of equal resistance. Notice that the total current flowing in the main part of the circuit is equal to the sum of the currents in the individual branches, while the voltage of the individual branches is the same as that of the circuit.*

this amount, or 1.5 amperes. Hence, the wire from A to B carries 1.5 amperes. The first lamp requires .5 ampere, and so the wire from B to C carries 1 ampere. The second lamp also requires .5 ampere, leaving .5 ampere in the circuit from C to D, through the third lamp to E, and back to F, where .5 ampere from the second lamp is added. The wire from F to G carries 1 ampere. At G .5 ampere more is added from the first lamp, and the current from G to H is 1.5 amperes.

Figure 157 shows three unequal resistances of 10, 5, and 15 ohms in parallel. In this circuit the current through each resistance can also be found by Ohm's Law. Since the voltage in all branches is the same, it is only necessary to divide the voltage by the resistance of the branch to find the current in the branch.

$$I_1 = \frac{E}{R_1} = \frac{110}{10} = 11 \text{ amperes}$$

$$I_2 = \frac{E}{R_2} = \frac{110}{5} = 22 \text{ amperes}$$

$$I_3 = \frac{E}{R_3} = \frac{110}{15} = 7.3 \text{ amperes}$$

The current in each branch of a parallel circuit depends upon the resistance in that individual branch; it is not affected by the resistance of other branches. The current in each branch is the voltage divided by the resistance of that branch.

In parallel circuits the current divides. *The total current flowing in the circuit is equal to the sum of the currents in the individual branches.* For example, in Figure 156, .5 ampere flows through each lamp. The total current is .5 + .5 + .5, or 1.5 amperes. In Figure 157, the sum of the currents in the branches is 11 + 22 + 7.3, or 40.3 amperes.

If the total current in a parallel circuit and the voltage are known, the resistance of the circuit can be determined by Ohm's Law. For example, in Figure 157, the voltage is 110 volts, and the total current is 40.3 amperes.

$$R = \frac{E}{I} = \frac{110}{40.3} = 2.7 \text{ ohms}$$

The resistance of a parallel circuit is equal to the voltage divided by the sum of the currents in the individual branches of the circuit. There is also another way of determining the resistance in the circuit when two known resistances are in parallel. The formula is

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

Such a circuit is shown in Figure 158. R_1 is 6 ohms, and R_2 is 8 ohms. Therefore

$$R = \frac{6 \times 8}{6+8} = \frac{48}{14} = 3.43 \text{ ohms}$$

This can be stated: *The joint resistance of two resistances in parallel is equal to their product divided by their sum.* (We use the term *joint resistance* for parallel circuits because the resistance of such circuits is not the sum of the individual resistances, as you can see.)

Figure 158 also shows the voltage and current.

Using the formula, $R = \frac{E}{I} = \frac{6}{1.75} = 3.43$ ohms

When possible, resistance should be determined by both methods in order to check the result.

Unlike the total resistance of a series circuit, which is greater than any one resistance, *the joint resistance of a parallel circuit is always less than the smallest individual resistance.* In the

Current in parallel circuits: The current in each branch of a parallel circuit is equal to the voltage divided by the resistance of the branch. The total current in a parallel circuit is equal to the sum of the currents in the individual branches.

Resistance in parallel circuits: The resistance of a parallel circuit is equal to the voltage divided by the sum of the currents in the individual branches.

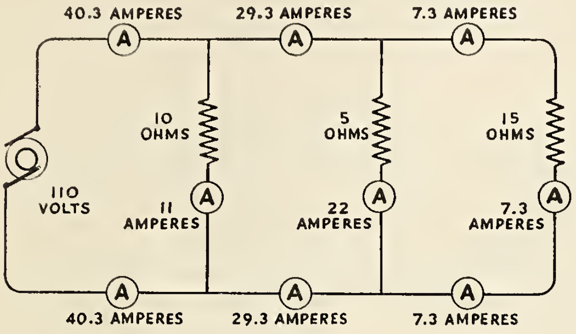


Figure 157 *shows the distribution of current in a parallel circuit having three branches of unequal resistance. Notice that the current in each branch depends entirely upon the resistance of that individual branch, that it is not affected by the resistance of the other branches. Hence, the current in any branch is equal to the voltage divided by the resistance of that branch.*

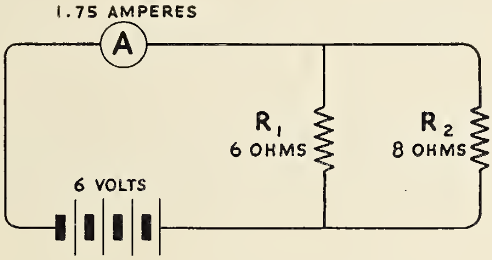


Figure 158. *This diagram shows that the joint resistance of two resistances in parallel is equal to their product divided by their sum. Thus, 48 (the product of 6 × 8) divided by 14 (the sum of 6 + 8) gives 3.43 ohms, the joint resistance.*

problem you just worked, the smallest resistance was 6 ohms, but the joint resistance of the circuit was just 3.43 ohms. This is always a good check to apply to problems dealing with parallel circuits.

When three or more resistances are connected in parallel, another method of determining joint resistance is ordinarily used. The formula is

$$\frac{1}{R}=\frac{1}{R_1}+\frac{1}{R_2}+\frac{1}{R_3}, \text{ etc.}$$

There are several kinds of problems to be solved in connection with parallel circuits. The commonest types and the methods of solving them follow:

1. *To find the resistance of a parallel circuit when the values of the individual resistances are known.* For example, two resistances of 6 and 3 ohms, respectively, are connected across a 6-volt battery. What is the resistance of the circuit? Use the formula

$$R=\frac{R_1 \times R_2}{R_1+R_2}=\frac{6\times 3}{6+3}=\frac{18}{9}=2 \text{ ohms}$$

If three or more resistances are in the circuit, use the formula $\frac{1}{R}=\frac{1}{R_1}+\frac{1}{R_2}+\frac{1}{R_3}$, etc.

2. *To find the current in a parallel circuit.* First find the joint resistance as shown in 1. Apply the formula $I=\frac{E}{R}$.

3. *To find the voltage required to force a certain current through a parallel circuit containing two resistances.* For example, what voltage is required to force 2 amperes through a parallel combination consisting of 2 ohms and 5 ohms?

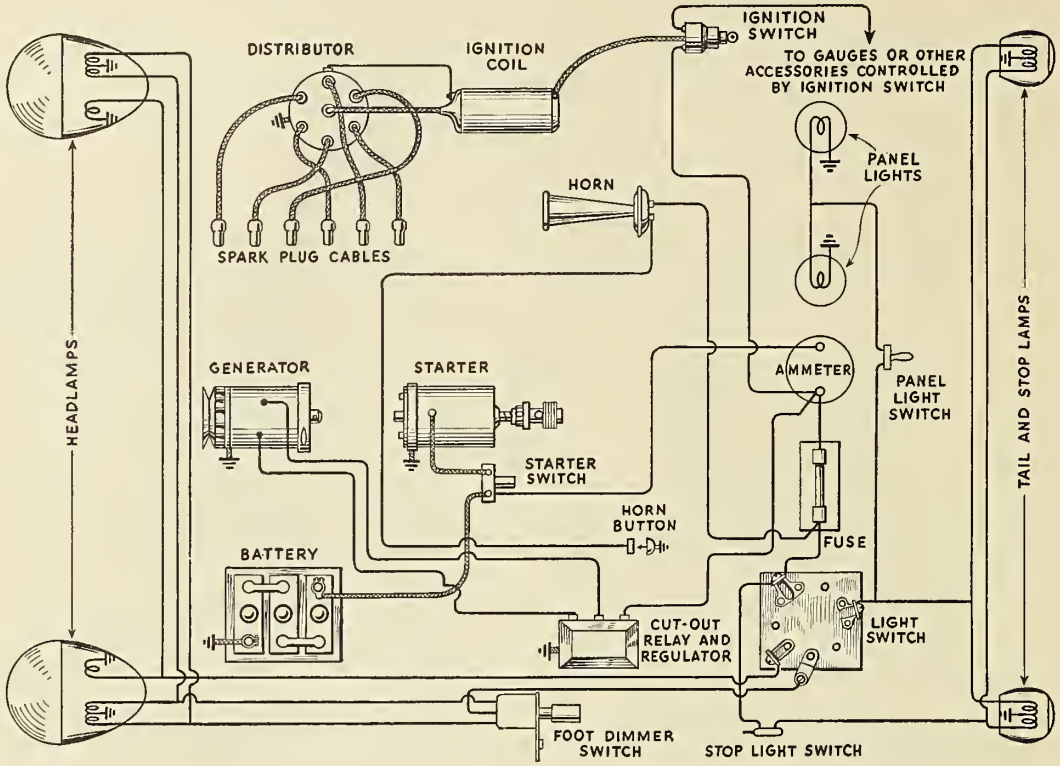


Figure 159. *A good example of a parallel circuit is shown in this diagram of the electrical system of an automobile. If you trace the various parts of the circuit, you will see that in parallel with the generator are the storage battery, starter motor, horn, ignition coil, and lights. Not shown, but also connected in parallel are such devices as electric windshield wipers, heater and defroster fan motors, radio, and spotlights.*

First find the resistance as shown in 1. Then apply the formula $E = IR$.

$$R = \frac{2 \times 5}{2 + 5} = \frac{10}{7} = 1.43 \text{ ohms}$$

$$E = 2 \times 1.43 = 2.86 \text{ volts}$$

4. *To find the current flowing through one resistance in a parallel circuit when the current through the other resistance is known.* For example, a circuit has a branch of 6 ohms resistance and a branch of 4 ohms resistance. A current of 3 amperes flows through the resistance of 6 ohms. What current flows through the resistance of 4 ohms?

The current through any branch can be found if the resistance and voltage are known. Since the voltage is the same at each resistance in a parallel circuit, if we find the voltage at one resistance, we will know the voltage at the other. The voltage at the 6-ohm resistance can be found by using the formula

$$E = IR = 3 \times 6 = 18 \text{ volts}$$

The current through the 4-ohm resistance can now be found by using the formula

$$I = \frac{E}{R} = \frac{18}{4} = 4.5 \text{ amperes}$$

These results can easily be checked. The total current is 4.5 + 3, or 7.5 amperes. The resistance is

$$R = \frac{E}{I} = \frac{18}{7.5} = 2.4 \text{ ohms}$$

Using the formula

$$R = \frac{R_1 \times R_2}{R_1 + R_2} = \frac{6 \times 4}{6 + 4} = \frac{24}{10} = 2.4 \text{ ohms}$$

Thus you prove the result.

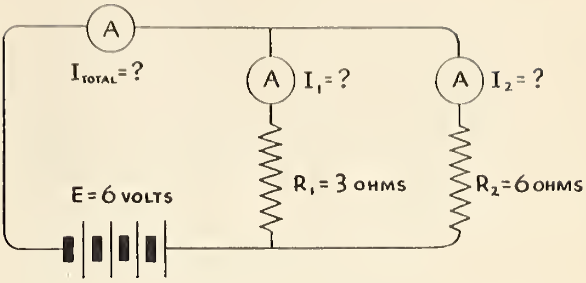
CHECKING WHAT YOU LEARNED

1. What is the difference between a parallel circuit and a series circuit?
2. Is the voltage at two branches of a parallel circuit the same, or does it depend upon the resistance of the branches? Explain.
3. **a.** How can you find the current distribution in a parallel circuit? **b.** How does the current distribution in a parallel circuit differ from that in a series circuit?
4. **a.** If the resistances in a parallel circuit have the same value, will the current flowing through the individual resistances be the same or different? **b.** What happens when the resistances have different values?
5. If you know the current flowing in the individual branches, how can you find the total current in a parallel circuit?
6. State two ways of finding the resistance of a parallel circuit.
7. **a.** If there are two branches in a parallel circuit, one with a resistance of 8 ohms and the other with a resistance of 5 ohms, what is the resistance of the circuit? **b.** If the voltage in the circuit is 12 volts, how much current flows?
8. How does the resistance of a parallel circuit compare with the smallest individual resistance? Why?
9. Why does more current flow in a parallel circuit when an additional resistance is added in parallel?

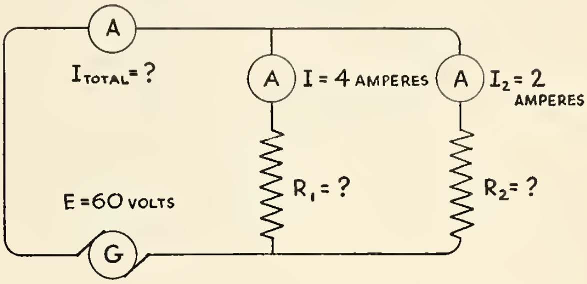
USING WHAT YOU LEARNED

1. Two resistances of 10 ohms and 15 ohms are connected in parallel in a 12-volt circuit. Draw the wiring diagram. Find the resistance of the circuit, the total current, and the current through each of the two branches. Place the values you obtain on your wiring diagram.

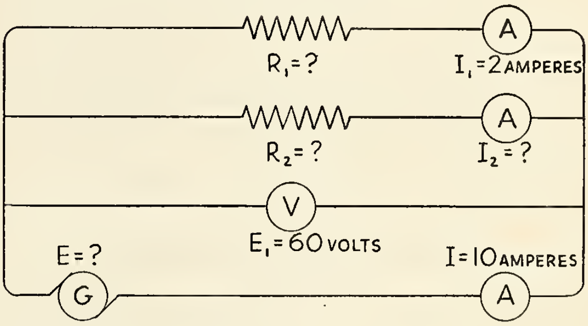
2. Find R_{joint}, I_{total}, I_1, and I_2.



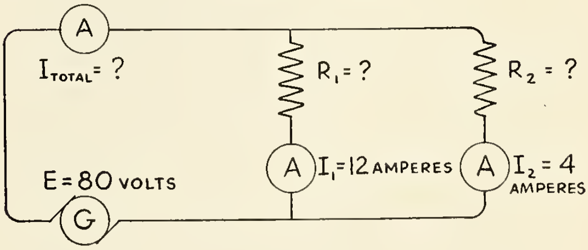
3. Find R_{joint}, I_{total}, R_1, and R_2.



4. Find I_2, R_1, R_2, E_{total}, and R_{joint}.



5. Find I_{total}, R_1, R_2, and R_{joint}.



Inductance and capacitance in parallel circuits: When coils are connected in parallel, the joint inductance can be determined from the formula:

$$\frac{1}{L}=\frac{1}{L_1}+\frac{1}{L_2}+\frac{1}{L_3}, \text{ etc.}$$

When condensers are connected in parallel, the total capacitance can be determined from the formula: $C=C_1+C_2+C_3$, etc.

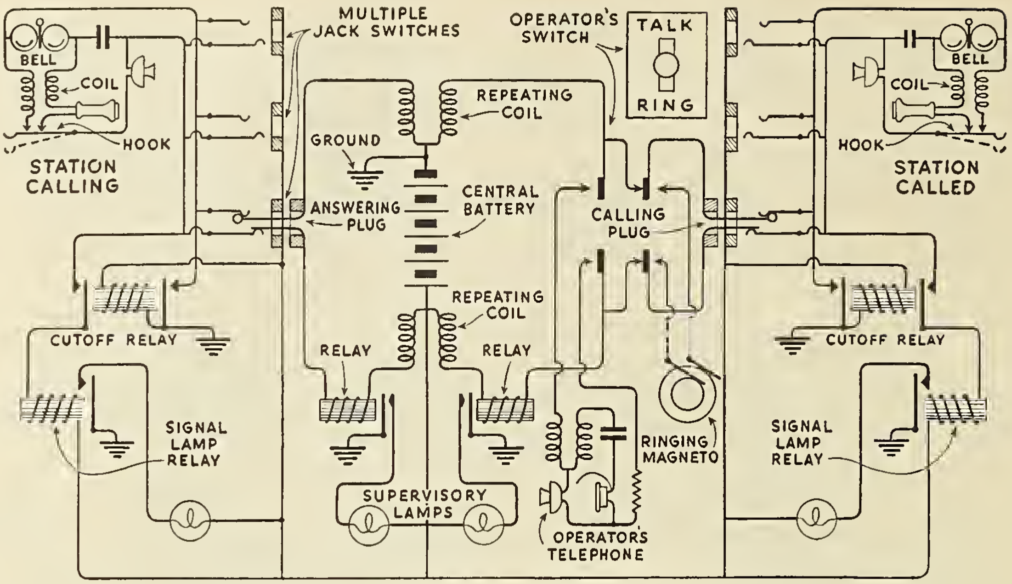


Figure 160. *This simplified central-battery telephone system has both series and parallel circuits. The multiple jack switches and cutoff relays are in parallel with plug circuits and battery, while the relays for the supervisory lamps are in series with the repeating coil. The operator's switch connects a telephone across the plug circuits or connects the ringing magneto in series with the condenser and bell of the called station.*

Series-Parallel Circuits

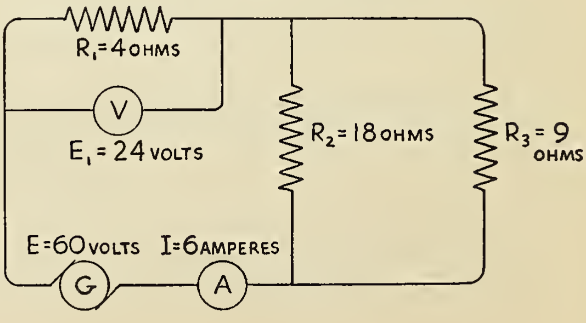
Many circuits are a combination of series and parallel circuits. For example, one common series-parallel circuit is the circuit for lighting a stage. The tiers of lamps are in parallel, but each tier is regulated by a rheostat in series with it. In a radio set, the tubes may be connected in parallel, and the voltage is sometimes regulated by a rheostat. In Experiment 61 you can measure the voltage and current in a series-parallel circuit, using various connections.

When a resistance is added in series to a parallel circuit, there will be a voltage drop through the series resistance. The amount of this drop will depend on the amount of resistance and the current flowing ($E = IR$). This voltage drop through the resistance in series must be subtracted from the voltage at the source in order to find the voltage at the parallel circuit.

An example will make this clear. In the diagram at the right, the ammeter shows 6 amperes. The voltage drop through R_1 is found by using the formula $E_1 = IR_1 = 4 \times 6 = 24$ volts. Since the pressure in the circuit is equal to 60 volts, the voltage at the parallel circuit must be equal to $60 - 24$ or 36 volts. The current through R_2 will be $I = \frac{E}{R} = \frac{36}{18} = 2$ amperes. The current through R_3 will be $\frac{36}{9} = 4$ amperes.

The total current will be the sum of the currents through the individual branches or

$$2 + 4 = 6 \text{ amperes}$$



The various kinds of problems involving series-parallel circuits and methods of solving them are:

1. *To find the voltage at a parallel combination when there is a resistance in series.* To solve this, the voltage drop through the series resistance must be known. To find this drop, the value of the resistance and the current must be known ($E = IR$). Subtracting E_1 from E_{total} will give the voltage at the parallel combination.

2. *To find the total resistance in a series-parallel circuit.* The total resistance in the circuit is equal to the sum of the resistance in series and the joint resistance of the parallel group. The formula for two resistances in parallel is

$$R_{joint} = \frac{R_1 \times R_2}{R_1 + R_2}$$

Using the values in the preceding diagram as an example $R_{joint} = \frac{18 \times 9}{18 + 9} = 6 \text{ ohms}$

R_1 is given as 4 ohms.

$$R_{total} = R_1 + R_{joint} = 4 + 6 = 10 \text{ ohms}$$

This answer can be checked by comparing the current with the value obtained from the formula

$$I = \frac{E}{R} = \frac{60}{10} = 6 \text{ amperes}$$

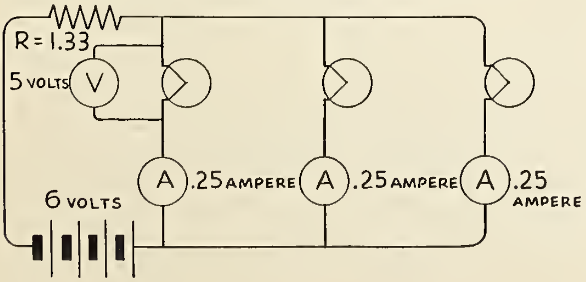
3. *To find the current through each parallel resistance.* If the resistance is given and the voltage of the circuit is known, the current can be found from the formula $I = \frac{E}{R}$

$$I_2 = \frac{36}{18} = 2 \text{ amperes}$$

$$I_3 = \frac{36}{9} = 4 \text{ amperes}$$

The sum of these two currents should check with the total current.

4. *To find the value of a series resistor needed to cut down voltage in a parallel circuit.* For example, suppose we want to operate three 5-volt vacuum tubes connected in parallel, each requiring .25 ampere, with a 6-volt storage battery. The following diagram shows such a circuit.



In this case we want to reduce 6 volts to 5 volts at the tubes. In other words, we need a 1-volt drop through the series resistor. To find the resistance necessary to secure a drop of 1 volt, we also need to know the current. Since each tube draws .25 ampere, the total current is .75 ampere. To find the resistance needed, we use the formula

$$R = \frac{E}{I} = \frac{1}{.75} = 1.33 \text{ ohms}$$

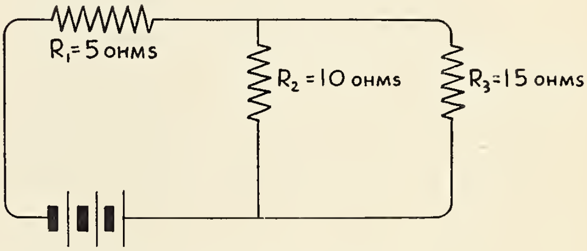
CHECKING WHAT YOU LEARNED

1. When a resistance is connected in series with a parallel circuit, what effect does it have upon the voltage of the parallel circuit? Why?
2. How is the total resistance in a series-parallel circuit determined?
3. When is it necessary to use a resistance in series with a parallel circuit? Explain.

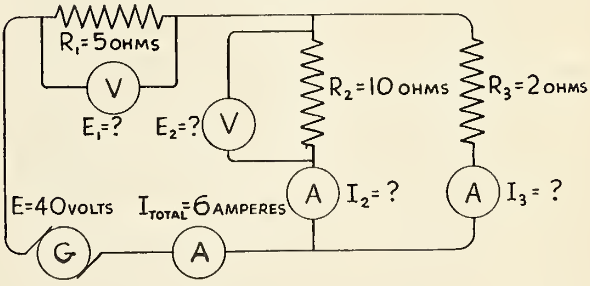
USING WHAT YOU LEARNED

Solve the following problems:

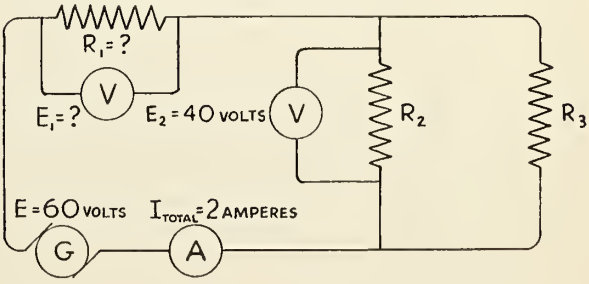
1. Find R_{total}.



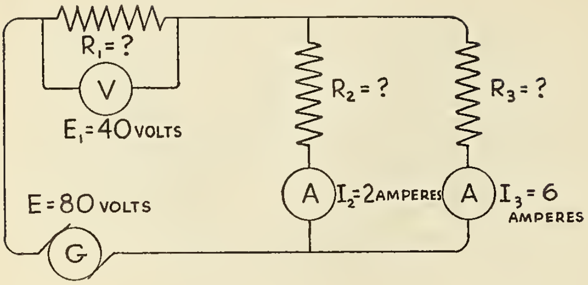
2. Find E_1, E_2, I_2, I_3, and R_{total}.



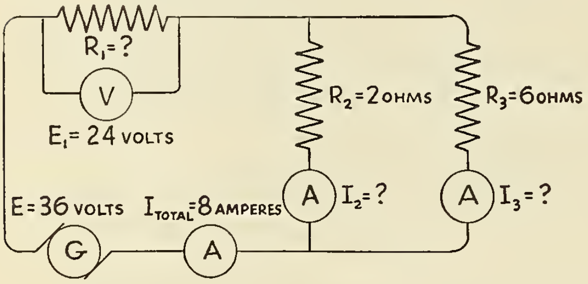
3. Find E_1 and R_1.



4. Find R_1, R_2, R_3, and R_{total}.



5. Find R_1, I_2, I_3, R_{joint}, and R_{total}.



Three-Wire Circuits

The lighting circuit of a home usually operates on 110 volts. Electric lamps are designed to operate on this voltage, and so are other devices. If current is used for motors or heat, a higher voltage than 110 is desirable. Large motors are usually designed to run on 220 volts. Electric water heaters are operated on 220 volts, and most electric ranges require both 110 and 220 volts. Two voltages are therefore necessary for the efficient operation of such appliances in the home.

Two voltages can be delivered to a user by means of three wires, instead of four, by using a system invented by Thomas Edison. To cut the cost of delivering direct current to consumers, Edison devised what is now called the *Edison three-wire system.* You will see, by referring to Figure 161, that two 110-volt D.C. generators are connected in series. When two generators are connected in series, the total voltage output from the outside terminals is the sum of the two voltages. A third wire is connected to the point where the two generators are connected. The voltage between the outer wires is 220 volts. The voltage between either outer wire and the center wire is 110 volts. The diagram shows you how three wires can thus do the work of four, saving 25 per cent in wire, insulators, and installation.

When alternating current is distributed, another type of installation is used. The power companies run high-voltage lines along streets and highways and, at convenient locations close to the customers, install step-down or *distribution transformers.* The high-voltage line may carry current at 1100, 2200, or even higher voltage, and the power losses are very low at such high pressures. At the distribution transformers the voltage is stepped down to 220 volts.

Each of the distribution transformers has a center tap on the secondary winding, and this center tap is grounded. Wires from the outside terminals of the secondary winding and from the center tap are run to each user's building. The diagram in Figure 162 shows how such a distribution system is wired.

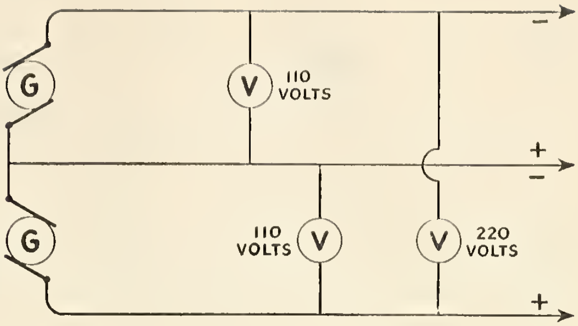
Figure 163 shows how most three-wire systems are arranged at the entrance to the building. The *service wires* enter a *service entrance box,* which contains a switch and fuses for the main circuit, a watt-hour meter, and the fuses for the branch circuits inside the building. In place of fuses, circuit breakers of the type described in Chapter 3 may be used.

In three-wire systems the center, or *neutral,* wire is run to a strip of copper, which is directly connected to the metal of the service entrance box. From this copper strip a heavy *ground wire* is run to a good ground connection, such as a cold-water pipe, and fastened securely to the ground with a *ground clamp.* You will see that as metal conduits are attached to the metal of the entrance box, they become automatically grounded through this same ground wire.

The neutral wire is never interrupted by fuses or switches, and in order to distinguish it, a white wire is used. The wires in cables and conduits are *color-coded* for convenience and safety. Each color stands for a particular type of wire. When there are two wires, they will be white and black; if there are three, the third will be red. The white wire is always grounded, and it is connected with the neutral, or center, wire of the three which enter the building.

With the ordinary 110-volt circuit, the white wire runs unbroken from the entrance box to each and every outlet. The black wire runs from its terminal in the entrance box to the various outlets. If switches and control devices are used, they are

Figure 161 *shows a diagram of the Edison three-wire system, whereby two different voltages can be supplied by means of three wires instead of four. The two D.C. generators are connected in series (+ to —) so that 220 volts are available between the outside wires, while 110 volts are available between either of the outside wires and the center wire, as indicated by the voltmeters.*



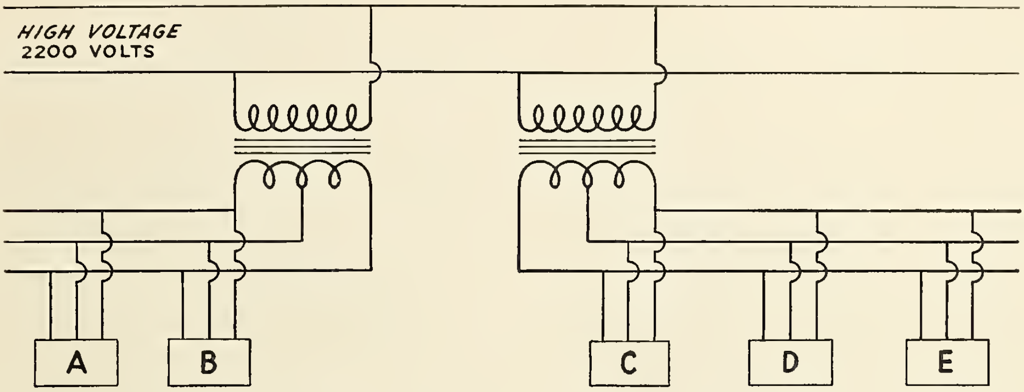


Figure 162. *On the wooden poles carrying electric current through cities and towns are step-down transformers that change the 2200 volts to 220 for use in homes, offices, and stores. This diagram shows how these transformers are connected so that either 220 or 110 volts are available at buildings A, B, C, D, and E if three wires are used.*

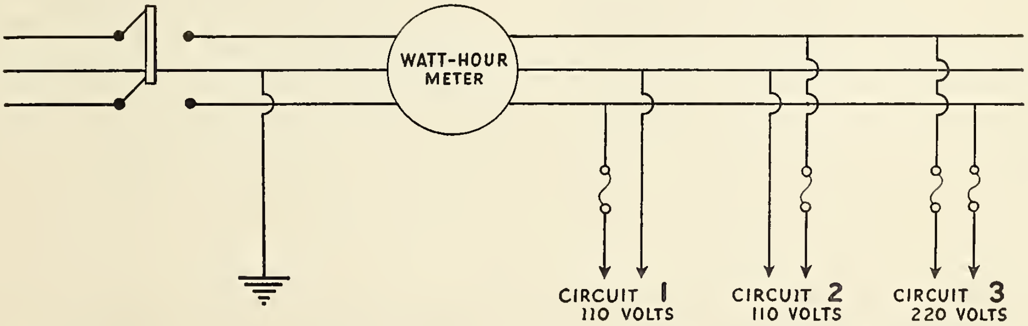


Figure 163 *shows a three-wire circuit as usually installed in a building. The center wire from the transformer is grounded and so is not broken by switch or fuse. Notice that 220-volt circuits use double-pole switches and two fuses, while 110-volt circuits use single-pole switches and one fuse. The grounded, or neutral, wire ordinarily has white insulation.*

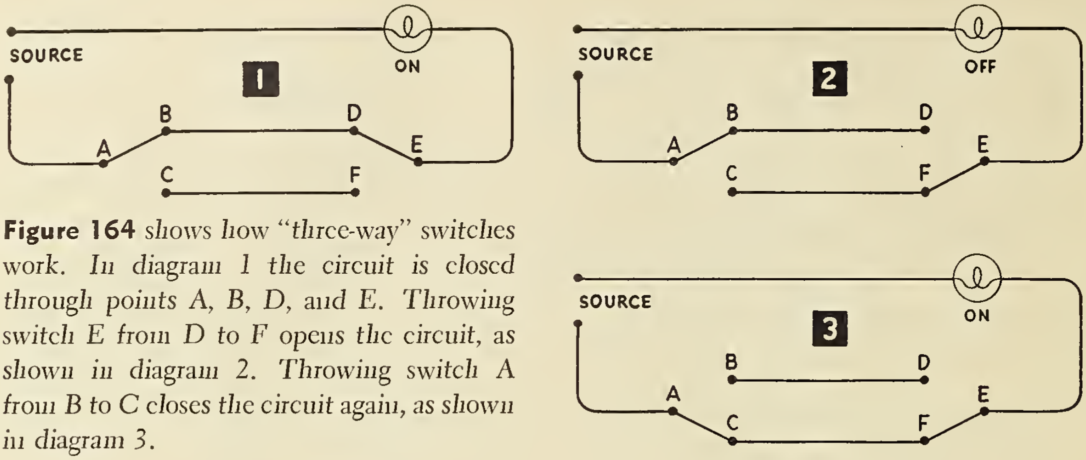


Figure 164 *shows how "three-way" switches work. In diagram 1 the circuit is closed through points A, B, D, and E. Throwing switch E from D to F opens the circuit, as shown in diagram 2. Throwing switch A from B to C closes the circuit again, as shown in diagram 3.*

placed in series with this black wire. With this arrangement the electrician always knows that the white wire is the neutral wire, while the black wire is the "hot," or ungrounded, wire.

An additional safety measure is provided by the fact that the *raceway* (the cable, conduit, or other enclosure for wires) is also grounded. If the "hot" wire should accidentally make contact with the conduit, a short circuit will result, and a fuse will blow. Then the whole circuit is dead. If the conduit were not grounded when the "hot" wire touched it, then the conduit itself would be carrying the current, and it would be a source of danger to anyone who touched it or any metallic fixture connected to it.

Using a white grounded wire and keeping one side of a circuit grounded is known as *polarizing*. *Polarized terminals* are terminals in which the connections are indicated by having one terminal painted white or made of nickel, tin, cadmium, or other white metal, while the other is either painted another color or made in natural brass or copper color. *Polarized plugs* are plugs that can be inserted in a socket in only one way so that the device can be connected in only one way.

Circuits with 220 volts. If you will refer again to the diagram in Figure 163, you will see that neither wire of the 220-volt circuit is grounded. Both are line or "hot" wires, and so devices using 220 volts are operated by switches that open both wires—double-pole switches. If a single-pole switch were used, one wire would remain "hot" and would be a source of danger to anyone touching it. For example, a man standing on a damp floor in a basement would offer a short path for a current at 110 volts from the "hot" wire to ground.

Another safety method used with 220-volt circuits is the grounding of equipment. Ordinarily, the metal frames of motors and all such devices are grounded. Otherwise, the device itself might easily become a source of danger in case either "hot" wire touched the framework of the device.

Usual voltages: The voltage supplied for residential purposes is commonly referred to as 110 volts, although it may actually be 115 volts or even higher. In many localities there is a decided trend toward supplying 115 volts, and most household devices are designed to operate at that voltage. If the voltage supplied is 110, 115, or 120, the high voltage available to the user is twice that pressure, that is, 220, 230, or 240 volts.

Voltage to ground: The maximum voltage between the grounded wire of a circuit and any ungrounded wire. If the circuit has no grounded wire, the voltage to ground is the maximum voltage between any two wires of the circuit.

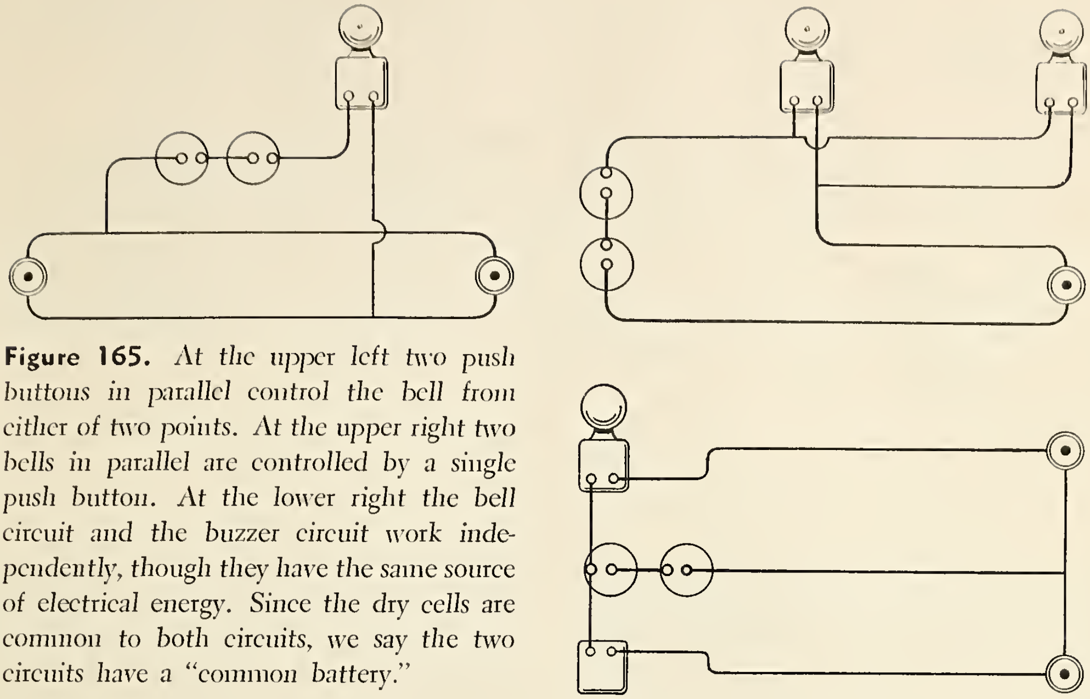


Figure 165. *At the upper left two push buttons in parallel control the bell from either of two points. At the upper right two bells in parallel are controlled by a single push button. At the lower right the bell circuit and the buzzer circuit work independently, though they have the same source of electrical energy. Since the dry cells are common to both circuits, we say the two circuits have a "common battery."*

Control of circuits by switches. The 110-volt circuits in house wiring are not always alike. Usually there is an appliance circuit with heavier wire than the ordinary lighting circuits. For the average circuit, No. 14 wire will carry the required amperage with less than 2 per cent drop in the voltage. For appliances, a circuit with conductors of No. 12 wire will generally be necessary.

The simplest type of house circuit is shown in Figure 1 (page 4). Of course such a circuit is not very convenient, since no provision is made for opening and closing it. By adding a single switch, as in Figure 2 (page 6), the circuit becomes controllable. All common circuits are adaptations of this fundamental arrangement of lamp (or outlet of any kind), switch, and source, with the necessary conductors.

The *three-way switch* offers a method of controlling a circuit from more than one point. For example, it is often desirable to control the same light from two floors, or from two different entrances to a room. The method of wiring such a switch circuit is simple if you will keep in mind the basic diagram shown in Figure 164. The switches used have three terminals (from which their name is taken), and usually one of the terminals is marked by being of a darker color than other terminals. This is the "common" terminal, for it corresponds to the center terminal of the switches shown in the basic diagram.

The diagrams in Figure 165 show cells as a source of electrical energy, push buttons as controls, and bells or buzzers as devices. They show one bell controlled by two push buttons at different points, two bells at different points controlled by one push button, and a bell and a buzzer with separate push buttons but the same battery for both circuits. The same methods of wiring can be used on a 110-volt circuit; the controls can be switches or thermostats, and the devices can be motors, lamps, or any other appliances. By changing the location of the devices and controls, you can see how similar circuits can be used under many different conditions.

CHECKING WHAT YOU LEARNED

1. State two reasons why a three-wire circuit is superior to a two-wire circuit.

Rectifier: A device for changing alternating current to direct current. There are various types, such as mechanical rectifiers, chemical rectifiers, and tube rectifiers.

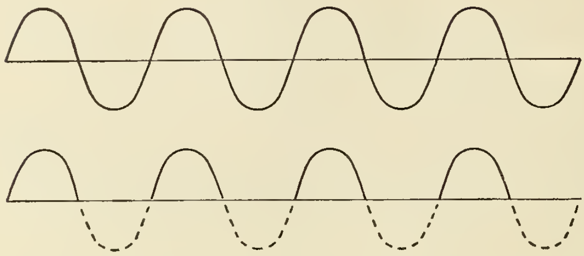


Figure 166. *The upper diagram represents an alternating current before it is rectified, and the lower diagram represents the same current after rectification. Dotted lines indicate the alternations suppressed by a "half-wave" rectifier.*

2. Why must two generators be used in a three-wire circuit if the current is direct current?
3. What method is used to provide two voltages in a three-wire system using alternating current?
4. Why are metal conduits grounded?
5. How can the electrician tell which of the wires is "hot"?
6. How can two voltages be obtained from a three-wire system?
7. Explain how a three-way switch operates.

USING WHAT YOU LEARNED

1. Make a drawing of a three-wire system in which four lamps are connected across the 110-volt source, and a motor and a hot-water heater are connected across the 220-volt source.
2. Make a drawing to show how four 60-watt lamps can be connected across the 110-volt source in a three-wire system so that no current flows in the neutral wire.
3. Design a method of connecting an outside garage to the house-wiring circuit so that the lights in the garage can be turned on or off at either the house or the garage.
4. How can you tell which of the wires at an outlet is the neutral wire?

Rectifier Circuits

Because transmission losses are low with high-voltage alternating current, this kind of current is most frequently available. But there are uses that require direct current. Battery charging, electroplating, and many industrial processes require direct current. Communication devices also use direct current. Accordingly, devices are needed to change alternating current into direct current. A **rectifier** is such a device, and the rectifier circuit is one type of electric circuit.

It is not difficult to understand rectifier eircuits if the principles of rectification are kept in mind. A rectifier changes alternating current into a pulsating direct current. If you will review pages 218 to 223 in Chapter 9, which deal with commutators, you will see that a commutator is a kind of rectifier. You can also think of a rectifier as a kind of automatic switch.

Mechanical rectifiers. A simple way to rectify an alternating current is to send it through a commutator that revolves at the correct speed. This is simply a motor-driven automatic switch that shifts terminals in perfect timing with the alternation of the current. It changes the alternating current to direct current, but the current is not a steady one; it pulsates between zero strength and full strength, just as alternating current does. Synchronous converters are rectifiers of this type.

The *vibrator* is another mechanical type of rectifier. The vibrator is placed between the poles of an electromagnet operated by the alternating current. As the polarity of the magnet alternates with the current, the vibrator is attracted and repelled by the poles as the current alternates. The back-and-forth motion of the vibrator makes

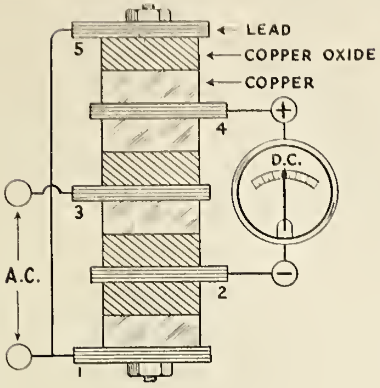
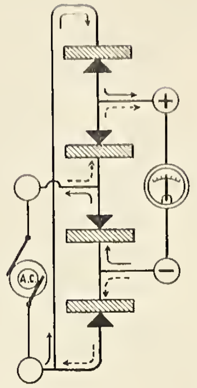


Figure 167. *At the left is shown the construction of a simple copper-oxide rectifier. The disks have been made thicker to show their arrangement on either side of the direct-current terminals. At the right is shown the flow of current through a full-wave copper-oxide rectifier. Solid arrows show the current flow during one half of the cycle, while dotted arrows show the flow during the other half of the cycle.*



and breaks contacts at each alternation in such a way as to act as an automatic switch.

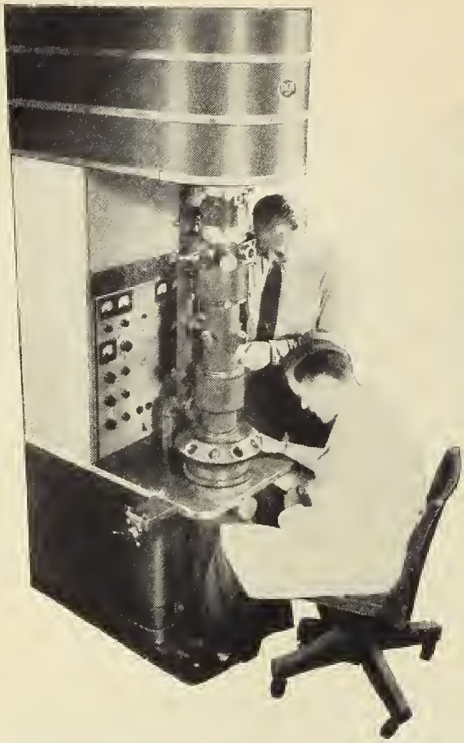
Chemical rectifiers. Other rectifiers make use of electrochemical effects. Perhaps the commonest kind is the *copper-oxide rectifier.* This rectifier is made of alternate layers of metallic copper and copper oxide (cuprous oxide). This combination of copper and copper oxide has the peculiar property of permitting an electric current to flow easily from the copper oxide to the copper, but of opposing its flow from the copper to the copper oxide. In other words, it acts as a one-way valve.

If you will look at Figure 166, you will see what happens to an alternating current that flows through such a rectifier. The upper diagram in Figure 166 shows the curving line, or wave form, of an alternating current. The lower part of the figure shows the rectified current graphically. The rectifier allows only half of the current to flow through. In other words, current in one direction flows through the rectifier, but current cannot flow in the opposite direction.

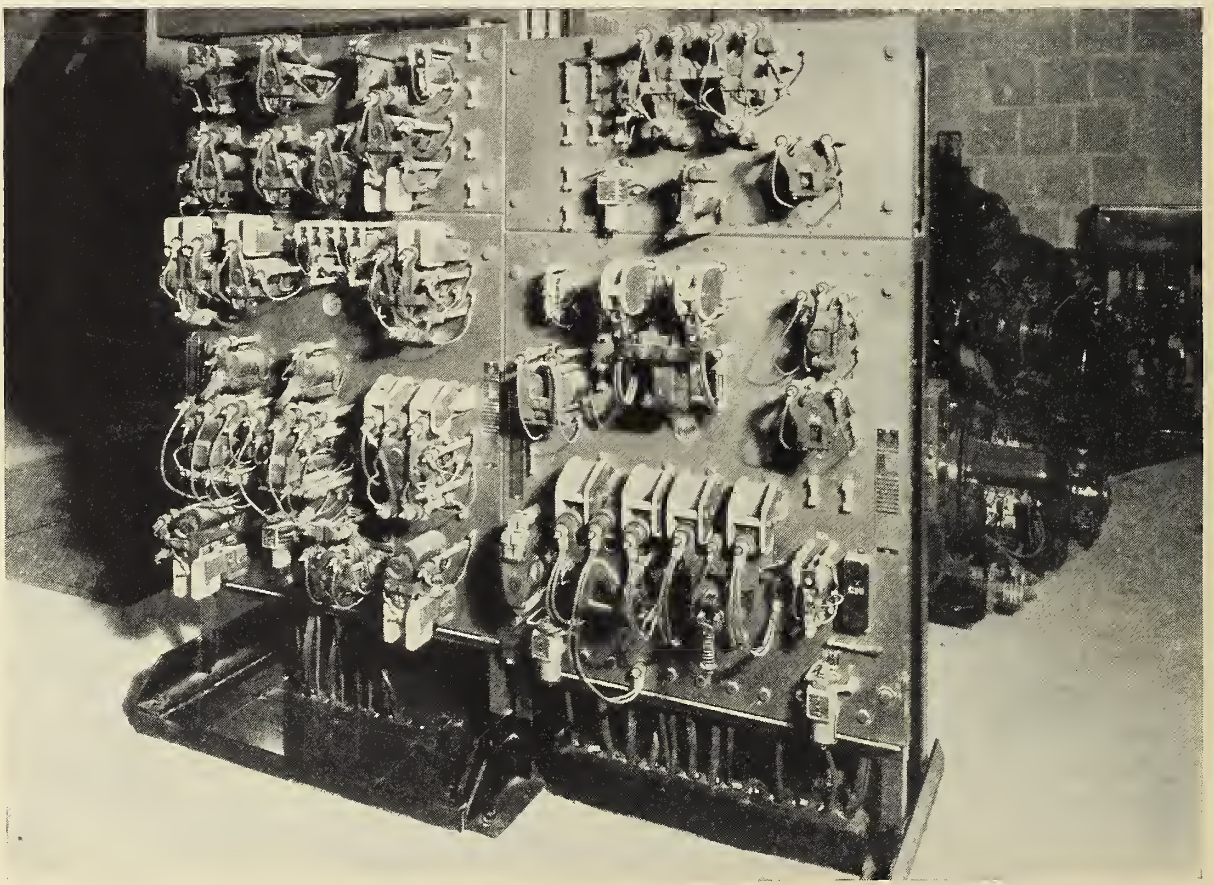
Such a rectified current pulsates too much for many uses. It reaches full strength for an instant, dies away, and then for a time there is no current whatever; then the current builds up, reaches full strength once more, dies away again, and so on. Half of the time there is no current. For this reason, this kind of rectification is called *half-wave* rectification. A much more even current can be obtained by connecting four copper-oxide rectifiers in a special circuit. Figure 167 shows how such a circuit provides *full-wave* rectification.

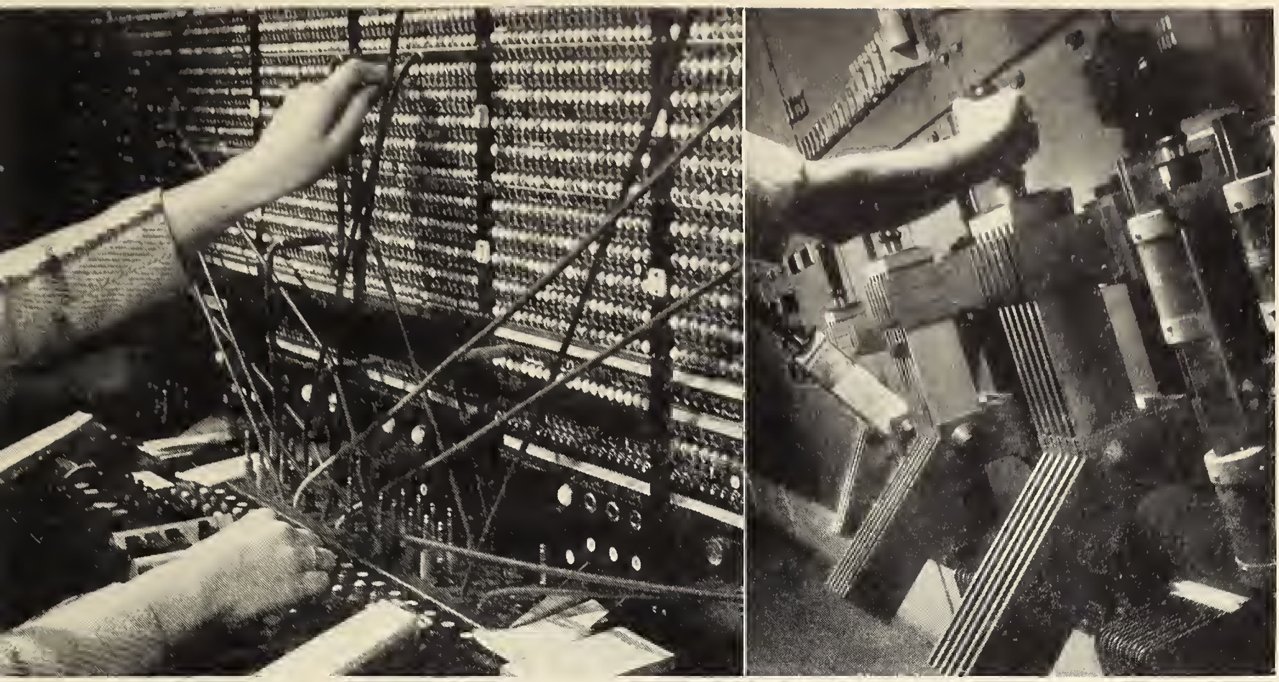
The ordinary copper-oxide rectifier is made up of alternate layers of copper, copper oxide, and lead washers, as shown in Figure 167. These parts are insulated from the bolt which is used to clamp them together. The lead washers make good contact with the copper-oxide and copper layers, and provide terminals for the connections. Terminals 1 and 5 are connected to one alternating-current terminal, and terminal 3 to the other alternating-current terminal. Terminal 2 is the negative terminal for the direct current, and terminal 4 is the positive terminal for the direct current. If you will check over these connections and compare them with the diagram of the rectifier circuit, you will see that this method of assembly is simply a convenient way to provide for rectification of both halves of the cycle.

Other rectifiers making use of similar properties of certain metals can be used in place of the copper-oxide rectifier. One such *electrolytic rectifier* is made of electrodes of aluminum and lead suspended in a container filled with an electrolyte, which is a water solution of ammonium phosphate. Current will pass readily from the lead electrode through the electrolyte to the aluminum electrode, but it will not pass from the aluminum electrode through the electrolyte to the lead electrode because of polarization. Rectifiers of this type will handle alternating currents up to 220 volts and will rectify both halves of the alternating-current cycle. Provision is usually made for removing the electrodes from the electrolyte so that the electrolyte does not deteriorate too rapidly.

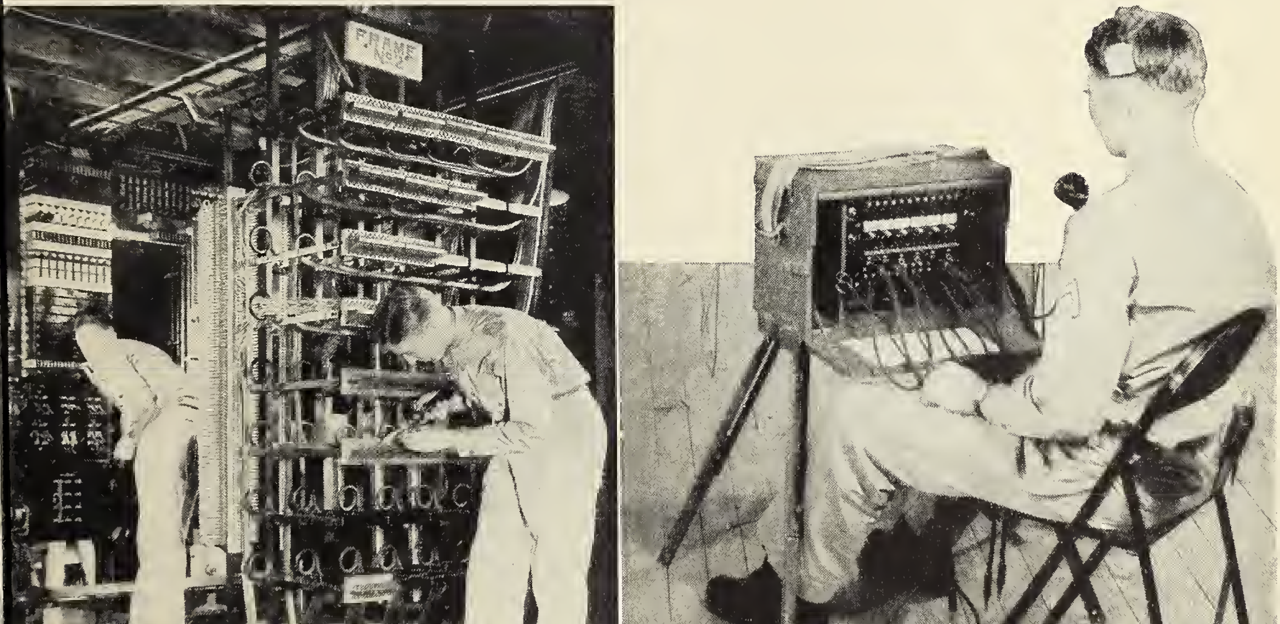


Capable of magnifications up to 100,000 diameters, the electron microscope at the upper left has special power-supply circuits to furnish the 60,000 volts required for its operation. Aided by a civilian instructor, the soldier at the upper right learns to measure the voltage drop through a series resistor. Below is shown the rear of a switchboard controlling the complex circuits needed for elevator motors.





At the upper left is a section of the switchboard for a central-battery telephone system. On the vertical panel are many signal lights and jack switches, some of which are connected by plugs and cords. Rated at 6000 amperes, the big knife switches at the upper right control the large direct currents supplied by generators and storage batteries to the many telephones. The two soldiers at the lower left are adjusting relays and soldering wires to one of the main terminal boards in a central station, while the one at the lower right is learning to operate a small field switchboard.



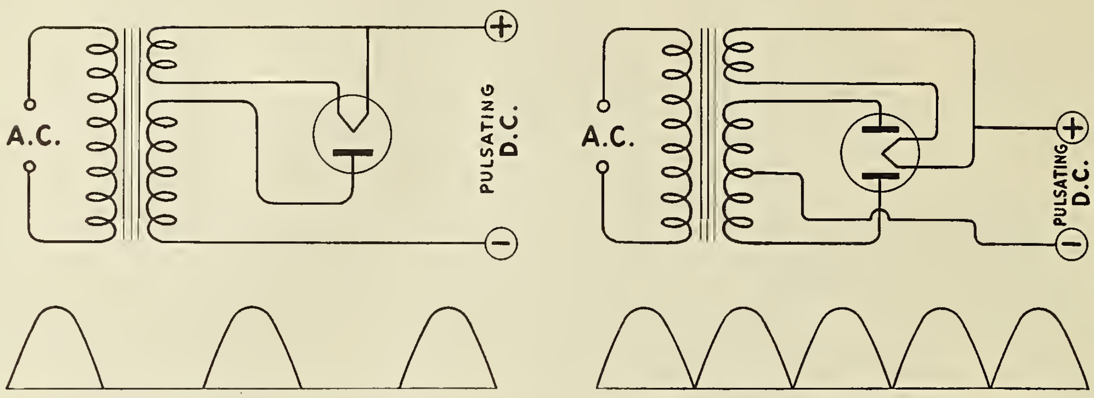


Figure 168. *At the left is shown a circuit containing a diode rectifier with a single plate. The rectified current pulsates 60 times a second. With two plates, as shown at the right, the rectified current pulsates 120 times a second. The lower diagrams represent this difference between half-wave and full-wave rectification.*

Tube rectifiers. A *diode* rectifying tube has two elements, a filament and a *plate*. When the filament is heated by a current, electrons are given off. (This was noticed by Thomas Edison and is called the *Edison effect.*) If the plate of the tube has a positive charge, electrons will pass from the filament to the plate. And when electrons flow, there is an electric current. Therefore, a current flows from the plate to the filament when the plate is positive. But if the plate has a negative charge, electrons from the filament are repelled, and no current will flow. Since the tube is operated by alternating current, you can see that the plate alternately has a positive and a negative charge. The diode tube, therefore, is a valve which allows current to flow in one direction but not in the other. Diode rectifying tubes range in size from small radio tubes to large tubes capable of handling many amperes. The "Tungar" rectifier, for example, has a heavy filament and a plate made of carbon to carry the large currents needed in charging storage batteries.

The circuit for a half-wave rectifier is shown at the left in Figure 168, and below it a diagram of the rectified current. With 60-cycle current, current flows from plate to filament only during the 60 times a second that the plate is positive. The result is a pulsating direct current.

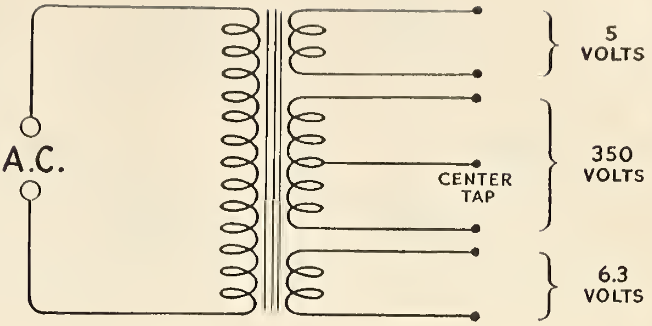
A pulsating current of this type is satisfactory for charging storage batteries, but it is too uneven for most communications work. Therefore, a rectifying tube with two plates is often used to give full-wave rectification. The circuit for this type of rectifier is shown at the right in Figure 168. If you examine this circuit, you will see that the plates are alternately positive and negative. When one is positive, the other is negative, and they change simultaneously as the current alternates. Therefore, a current is always flowing from one or the other of the plates to the filament.

Power is lost when a current is rectified, but this loss can be reduced by using a *mercury-vapor rectifier*. This rectifier is similar to the diode just described, except that a small quantity of mercury is put into the tube. The mercury vaporizes under the heat and ionizes when current flows from the plate. Because of their low resistance, mercury-vapor rectifiers are used in power circuits. Some large radio sets contain such rectifiers.

Radio power supply. Since this is the last section in this book, it would be a good idea to consider a circuit which applies practically everything you have learned in the book. For this reason, we will take up the power circuit of a radio set operating from 110-volt alternating current.

A radio set needs two kinds of current, a low-

Figure 169 *shows the symbol often used for the transformer in a radio power supply. This transformer has three secondary windings. The 5-volt winding is for the filament of the rectifier tube, while the high-voltage winding supplies 350 volts to each of the two plates. The 6.3-volt winding is for the other radio-tube filaments.*



voltage alternating current to heat the filaments of the tubes, and a higher-voltage direct current to supply the plate circuit of the vacuum tubes. The power supply includes a transformer, a rectifier, a filter, and a voltage divider.

To obtain the low-voltage current to heat the filaments of the tubes, we must use a step-down transformer. The rectifier tube that is ordinarily used requires 5 volts on the filament, so a transformer ratio of 22 to 1 will step down 110 volts to 5 volts. A secondary coil is therefore wound on the transformer to supply that voltage. The other tubes in the set may require 6.3 volts for efficient operation. Therefore, another secondary coil is wound on the same transformer in order to secure this voltage.

Next, to supply the high voltage needed for the plates of the tubes, the 110-volt current must be stepped up. For small sets the usual voltage is about 350 volts. The transformer must have a third secondary winding to step up the voltage.

The power transformer, therefore, has one primary winding, to which the 110-volt alternating current is connected, and it has three secondary windings. Two of the three secondary windings are low-voltage step-down windings, while the third is a high-voltage step-up winding. The usual way of showing such a transformer is given in Figure 169.

The two low-voltage alternating currents can be used without further change to heat the filaments of the tubes. But the high-voltage alternating current from the step-up winding of the transformer must be rectified before it can be used. In a radio power supply, this is usually accomplished by means of a rectifying tube with two plates, such as shown in Figure 168.

Filters. This full-wave rectification produces a direct current, such as the one shown graphically in Figure 168. However, it is not even and smooth enough to use for the plates of the vacuum tubes in a radio set. Therefore, it is smoothed out by means of a *filter circuit*, which changes the current into one that is smooth and even.

A filter circuit usually consists of a combination of coils and condensers. Figure 170 (page 300) shows one type of filter circuit. You will remember that a coil has self-induction that may produce a back E.M.F. As the current from the rectifier flows through the filter, the back E.M.F. of a coil prevents the current from rising to its peak value. Part of the current is "choked" back by a coil, which is also known as a *choke coil*. At the same time the condenser becomes charged. Each time the current from the rectifier dies down, the condenser discharges and supplies E.M.F. to keep current flowing in the circuit. In this way the peaks of the waves are blocked by the coil, and the hollows of the waves are filled out by the discharge of the condenser. This action is repeated in each following section of the filter until finally a smooth, non-pulsating current is produced. An extra condenser is usually placed last in the circuit to act as a storage condenser.

Experiment 62 shows how coils and condensers operate. Figure 171 (page 300) shows a 15-watt lamp in series with a coil and a reversing switch by which the coil and lamp can be connected with either 110-volt direct current or 110-volt alternating current. When the switch is thrown so as to

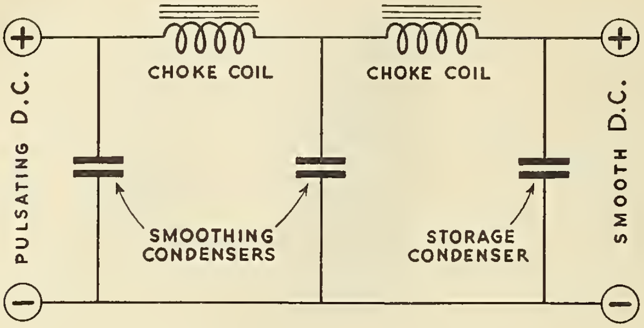


Figure 170 *shows a typical two-section filter of the type used in a radio power supply to smooth out the pulsations of the rectified current. Each section consists of a large condenser and a "choke" coil. The storage condenser supplies extra current during brief overloads.*

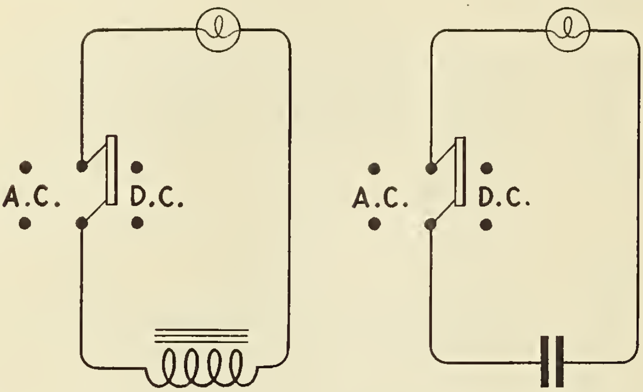


Figure 171 *shows the circuits to be used in Experiment 62. At the left a choke coil is placed in series with a 15-watt lamp for Part* **a** *of the experiment. At the right a condenser replaces the choke coil for Part* **b** *of the experiment. A double-pole, double-throw switch is used to connect the circuits to either alternating or direct current.*

supply the circuit with direct current, the lamp lights up. The lamp is perhaps a little dimmer than it would be if the coil were not in the circuit, but otherwise the coil seems to have no effect. When the switch is thrown so as to supply the circuit with alternating current, the lamp lights but with much less brilliance.

If you will review some of the information learned in Chapter 7, you will remember that, when the direction of the current flow in a coil is changed, an E.M.F. is induced in the coil and that this self-induced E.M.F. opposes the flow of the current in the coil, in accordance with Lenz's Law. In the choke coil the direction of current flow is changed with each alternation of the current. The self-induced E.M.F. in the coil opposes the rising strength of the alternating current. The stronger the alternating current becomes, the stronger becomes the self-induced E.M.F. that opposes its flow. The self-induced E.M.F. resists any change in the current passing through the coil.

The self-induced E.M.F. not only resists changes in the alternating current when that current increases in strength, but it resists a change in the current when the alternating current begins to weaken. In other words, the self-induced E.M.F. tends to weaken the increasing current and strengthen the decreasing one.

If you will use the same circuit as before, but in place of the choke coil use an 8-microfarad condenser, you can see how a condenser operates in a circuit. With the switch thrown to deliver direct current to the circuit, the lamp does not light. Very obviously, the condenser prevents the passage of direct current. Now if you throw the switch to provide the circuit with alternating current, the filament will light. It will not be so brilliant, but it will light. You might jump to the conclusion that the condenser was passing alternating current; but this is not so. If you will study the diagram for a moment, and remember that the direction of the current is being reversed 120 times

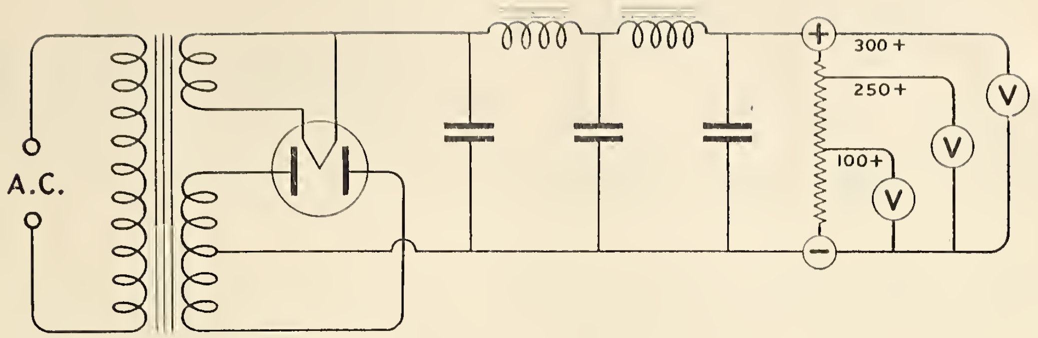


Figure 172 *shows a diagram of a complete radio power supply from transformer, through rectifier and filter, to the voltage divider.*

a second, you will see that the condenser is being charged and discharged with great rapidity. It acts as a reservoir, storing a charge on each alternation. Current flows into and out of the condenser but not through it.

A filter circuit makes use of coils and condensers to smooth out pulsating direct current. Of course, the action of coils and condensers is more easily observed with alternating current. That is why alternating current was used in the experiment.

Similar filter circuits are sometimes used in telegraph and telephone circuits. In radio circuits, where the vacuum tubes must be operated with smooth, even direct current, two or three such filters are used. Each filter, however, consists of the same two elements—a condenser and a choke coil. To further smooth out the current and to provide storage for brief overloads, a final condenser is added, as shown in Figure 170.

Voltage divider. The voltage of the current leaving the filter of the average radio set is about 300 volts. This is the voltage usually required to operate the tube which supplies the loud-speaker. The plates of the other tubes are usually operated at 250 volts, while certain ones may also require about 100 volts. Different voltages must therefore be provided for the different tubes. This is accomplished by means of a device known as a *voltage divider.*

A voltage divider is simply a tapped resistance. It is an example of a series-parallel circuit. Figure 172 shows a typical voltage-divider circuit. The tube requiring 300 volts is connected to the output of the filter, receiving the full voltage. Enough resistance is added to secure a voltage drop of 50 volts. The voltage at the second tap will then measure 250 volts. Enough more resistance is then added to secure another voltage drop of 150 volts. Then the voltage at the third tap will measure 100 volts.

CHECKING WHAT YOU LEARNED

1. List several important uses of direct current and tell why it is used.
2. What is the principle of operation on which the action of the copper-oxide rectifier is based?
3. **a.** Describe the output of a single copper-oxide rectifier. **b.** How can this output be changed to produce a smoother direct current?
4. List the four parts of a radio power supply and tell what each part must do.
5. Tell how low voltages and high voltages are provided by a single power transformer.
6. Explain how a diode tube changes alternating current into direct current.
7. Why must the rectifier output be filtered for use in a radio set?
8. How does a filter work?

9. Explain how different voltages are provided for the various tubes in a radio set.

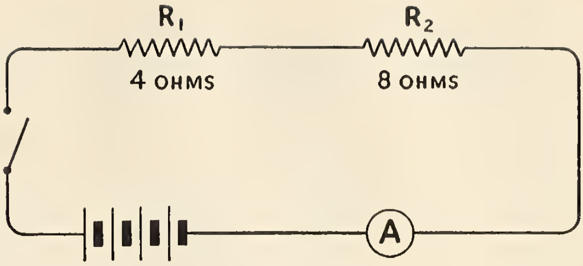
USING WHAT YOU LEARNED

1. In what different ways can alternating current be rectified?
2. How is a single-tube rectifier designed to provide full-wave rectification?
3. Why do battery-operated radio sets need no transformer?
4. The diode rectifier described in the text is a half-wave rectifier; it operates on only half of the alternating current. Draw a circuit employing two such tubes that will rectify both halves of the alternating-current cyle.

THINKING OVER WHAT YOU LEARNED

1. On a sheet of paper write down the main topics of this chapter, leaving a space after each topic. In complete sentences state the big ideas or principles you have learned in studying each topic.
2. Show in some way that you understand the meaning of the following terms. You may use a definition or a sentence to do this. **a.** diode, **b.** divided circuit, **c.** rectifier, **d.** filter, **e.** shunt circuit, **f.** polarized plug, **g.** three-wire circuit, **h.** "hot" wire, **i.** multiple circuit, **j.** three-way switch, **k.** choke coil, **l.** voltage divider, **m.** neutral wire, **n.** half-wave, **o.** color-coded, **p.** full-wave.

Figure 173 *shows a diagram of the circuit to be used in Experiment 59.*



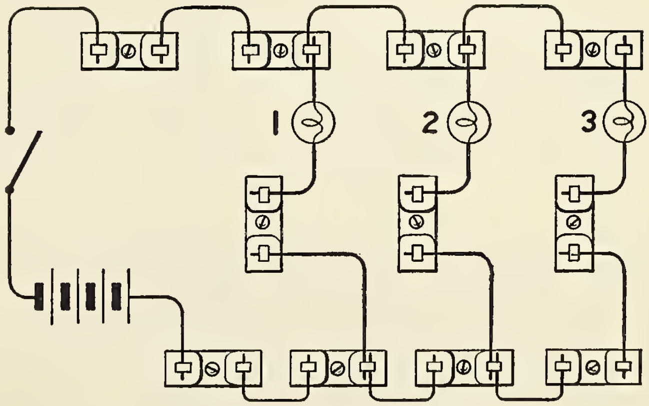
Experiment 59: **Voltage Drops in a Series Circuit**

THINGS NEEDED: Four No. 6 dry cells. Two resistors, 4 and 8 ohms. 0-10 D.C. ammeter. 0-10 D.C. voltmeter. Single-pole, single-throw switch.
WHAT TO DO: Connect the two resistors and the ammeter in series with the switch and 6-volt battery of 4 cells, as shown in Figure 173. (Keep the switch open except when you are taking meter readings.) Read the current. Now measure the voltage drop through the 4-ohm resistor. Then measure the voltage drop through the 8-ohm resistor. Add the voltage drops through the two resistors. How does the sum of these two voltage drops compare with the voltage in the circuit as measured at the battery terminals?

Experiment 60: **Voltage and Current in a Parallel Circuit**

THINGS NEEDED: Four No. 6 dry cells. Three 6-volt lamps and sockets. 0-10 D.C. ammeter. 0-10 D.C. voltmeter. Double Fahnestock clips or brass bolts. Wooden base (about 18 x 10 inches). Screwdriver. No. 18 insulated copper wire. Wood screws. Single-pole, single-throw switch.
WHAT TO DO: **a.** Arrange a circuit as shown in Figure 174. If Fahnestock clips are available, fasten them with a screw in the center of each clip to a wooden base about 18 x 10 inches. If clips are not available, brass bolts can be used. Substitute one bolt for each clip. Use two nuts on each bolt, one to fasten the bolt, the other to fasten down the connecting wires. The spaces between the clips or bolts are used to connect the ammeter in different parts of the circuit. Short pieces of wire should be used to connect all clips except the ones to which the meter is attached. The four cells should be connected in series. (Keep the switch open except when taking meter readings.)

Figure 174 *shows a diagram of the circuit to be used in Experiment 60, Parts* **a** *and* **b.**



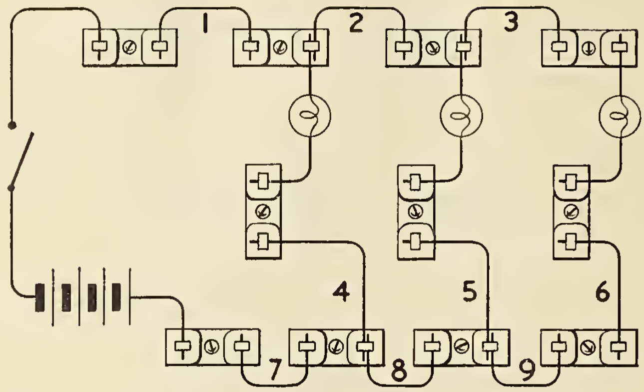


Figure 175 *shows a diagram of the circuit to be used in Experiment 60, Part* **c.**

b. First measure the voltage in the circuit. To do this, touch the wires from the voltmeter to the terminals of the battery. Next measure the voltage at lamp 1. To do this, touch the wires from the voltmeter to the clips connected with the terminals of the lamp. Repeat with lamps 2 and 3. How does the voltage in the circuit compare with the voltage at each lamp? What conclusion can you make?

c. Now connect the ammeter at point 1, as shown in Figure 175, and read the current. Make a drawing of the circuit and write the ammeter reading at the correct point on your drawing. Disconnect the ammeter and connect a wire in its place. Connect the ammeter at point 2. Take a reading and write it down on the diagram you drew. Take readings at points 3, 4, 5, 6, 7, 8, and 9. When you have completed the readings, you should have a complete record of the current distribution in a parallel circuit. Is the current the same in all parts of the line? How do you account for this?

Experiment 61: **Voltage and Current in a Series-Parallel Circuit**

THINGS NEEDED: Four No. 6 dry cells. Four small resistors (2 to 10 ohms) of different values. 0-10 D.C. ammeter. 0-10 D.C. voltmeter. Circuit board used in Experiment 60.

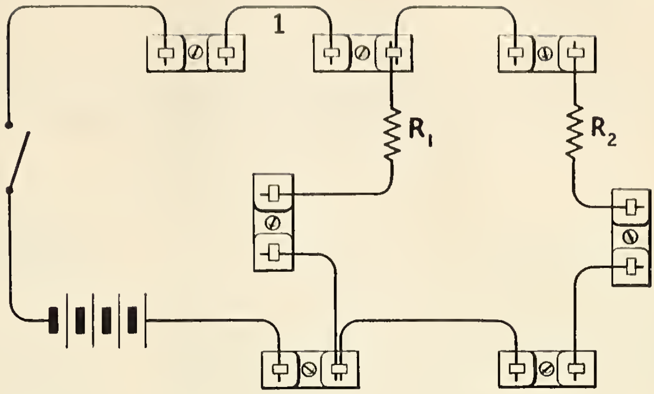
WHAT TO DO: Make connections as shown in Figure 176. Measure the voltage in the circuit by touching the wires from the voltmeter to the terminals of the battery. Then measure the voltage at R_1 and R_2 by touching the wires from the voltmeter to the ends of the resistors. As you already know, all of these voltages should be the same. If you get the same voltages, you will know that the experiment is correctly set up. Now remove the wire at 1 (called a *jumper wire*), and connect a resistor in its place. Then measure the voltage drop through the resistance. Now measure the voltage drops through R_1 and R_2. What effect does the resistance in series have upon the voltage drops at R_1 and R_2? How does the sum of the voltage drops through the series resistance and through the resistances in parallel compare with the voltage in the circuit?

Experiment 62: **A.C. and D.C. with a Coil or Condenser**

THINGS NEEDED: Reversing switch (double-pole, double-throw). Choke coil (5-henry, .15-ampere). 15-watt 110-volt lamp and socket. Alternating current and direct current at 110 volts. Insulated wire. 8-microfarad condenser.

WHAT TO DO: **a.** Connect the lamp in series with the choke coil, as shown in Figure 171. Then attach the wires from the lamp and coil to the reversing switch so that they can be supplied with either alternating current or direct current. Throw

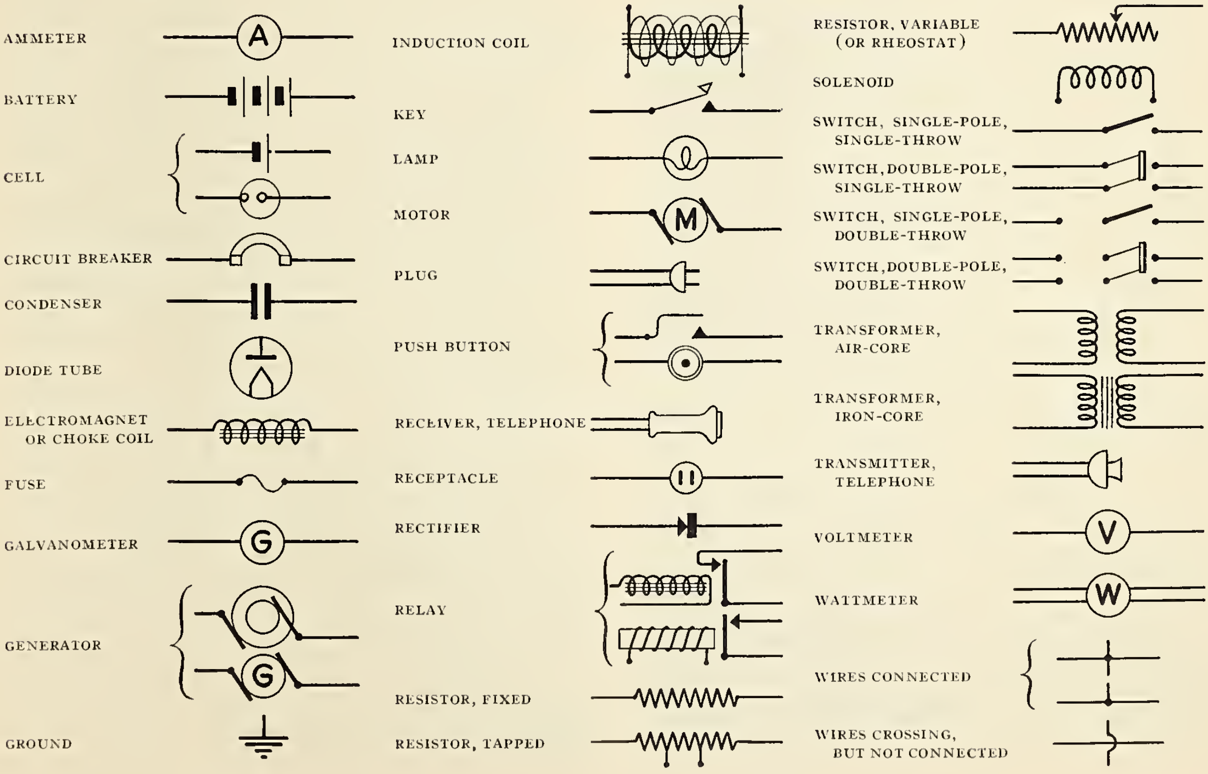
Figure 176 *shows a diagram of the circuit to be used in Experiment 61.*



the switch so that direct current is provided. Notice that the lamp lights up to almost full brilliance. Now throw the switch so that alternating current is supplied. What happens? How can you explain this result?

b. Using the same circuit as in Part **a**, replace the choke coil with the condenser, as shown in Figure 171. Throw the handle of the reversing switch to the side that connects direct current to the circuit. What happens? Then throw the switch to the side that furnishes alternating current to the circuit. What happens now? Explain the results. Does current flow through the condenser? Why?

SYMBOLS USED IN DIAGRAMS OF ELECTRIC CIRCUITS



INDEX

Page numbers in italic type refer to definitions or explanations at the top or bottom of the pages mentioned. For example, Alternation, *174* refers to a definition on page 174 of the text. Exp. after a page number refers to an experiment on the page mentioned.