33 Electric Fields and Potential

The space around a strong magnet is different from how it would be if the magnet were not there. Put a paper clip in the space and you'll see the paper clip move. The space around a black hole is different from how it would be if the black hole were not there. Put yourself in the space, and that will be the last thing you do. Similarly, the space around a concentration of electric charge is different from how it would be if the charge were not there. If you walk by the charged dome of an electrostatic machine—a Van de Graaff generator, for example—you can sense the charge. Hair on your body stands out—just a tiny bit if you're more than a meter away, and more if you're closer. The space that surrounds each of these things—the magnet, the black hole, and the electric charge—is altered. The space is said to contain a *force field*.

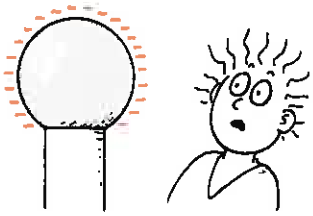

Fig. 33–1 You can sense the force field that surrounds a charged Van de Graaff generator.

33.1 Electric Fields

The force field that surrounds a mass is a gravitational field. If you throw a ball into the air, it follows a curved path. Earlier chapters showed that it curves because there is an interaction between the ball and the earth—between their centers of gravity, to be exact. Their centers of gravity are quite far apart, so this is "action at a distance."

The idea that things not in contact could exert forces on one another bothered Isaac Newton and many others. The concept of a force field eliminates the distance factor. The ball is in contact with the field all the time. We can say the ball curves because it interacts with the earth's gravitational field. It is common to think of distant rockets and space probes as interacting with gravitational fields rather than with the masses of the earth and other astronomical bodies that are responsible for the fields.

Just as the space around the earth and every other mass is filled with a gravitational field, the space around every electric charge is filled with an **electric field**—a kind of aura that extends through space. In Figure 33–2, a gravitational force holds a satellite in orbit about a planet, and an electrical force holds an electron in orbit about a proton. In both cases there is no contact between the objects, and the forces are "acting at a distance." Putting this in terms of the field concept, we can say that the orbiting satellite and electron interact with the force fields of the planet and the proton and are everywhere in contact with these fields. In other words, the force that one electric charge exerts on another can be described as the interaction between one charge and the electric field set up by the other.

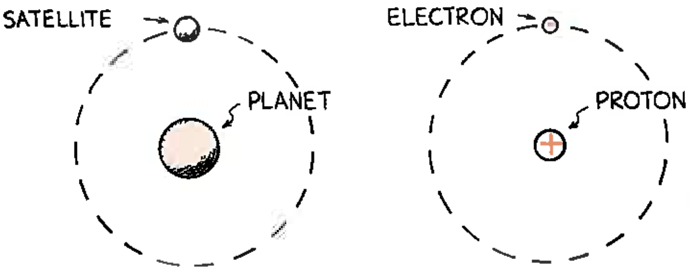

Fig. 33–2 The satellite and the electron both experience forces; they are both in force fields.

An electric field has both magnitude and direction. Its magnitude (strength) can be measured by its effect on charges located in the field. Imagine a small positive "test charge" that is placed in an electric field. Where the force is greatest on the test charge, the field is strongest. Where the force on the test charge is weak, the field is small.*

The direction of the electric field at any point, by convention, is the direction of the electrical force on a small *positive* test charge placed at that point. Thus, if the charge that sets up the field is positive, the field points away from that charge. If the charge that sets up the field is negative, the field points toward that charge. (Be sure to distinguish between the hypothetical small test charge and the charge that sets up the field.)

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* The strength of an electric field is a measure of how great a force will be exerted on a small test charge placed in the field. (The test charge must be small enough that it doesn't push the original charge around and thus alter the field we are trying to measure). If a test charge q experiences a force F at some point in space, then the electric field E at that point is

$$E = \frac{F}{q}$$

Electric field strength can be measured in units of newtons per coulomb (N/C). The next chapter will show that it has equivalent units of volts per meter (V/m).

33.2 Electric Field Lines

Since an electric field has both magnitude and direction, it is a *vector quantity* and can be represented by vectors. The negatively charged particle in Figure 33–3 top is surrounded by vectors that point toward the particle. (If the particle were positively charged, the vectors would point away from the particle. The vectors always point in the direction of the force that would act on a positive test charge.) The magnitude of the field is indicated by the length of the vectors. The electric field is greater where the vectors are long than where the vectors are short. To represent a complete electric field by vectors, you would have to show a vector at every point in the space around the charge. Such a diagram would be totally unreadable!

A more useful way to describe an electric field is with electric *field lines*, also called *lines of force* (Figure 33-3 bottom). Where the lines are farther apart, the field is weaker. For an isolated charge, the lines extend to infinity, while for two or more opposite charges, the lines emanate from a positive charge and terminate on a negative charge. Some electric field configurations are shown in Figure 33–4.

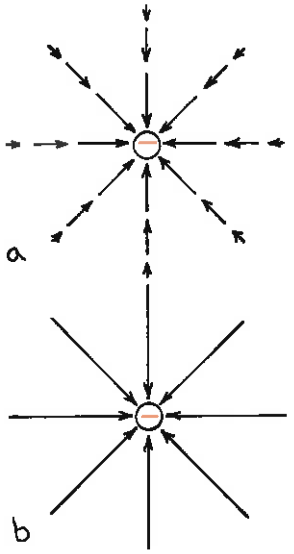

Fig. 33–3 Electric field representations about a negative electric charge. (a) A vector representation; (b) a lines-of-force representation.

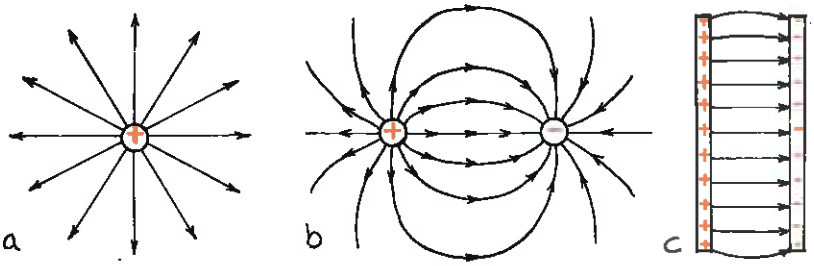

Fig. 33–4 Some electric field configurations. (a) Field lines around a single positive charge. (b) Field lines for a pair of equal but opposite charges. Note that the lines emanate from the positive charge and terminate on the negative charge. (c) Evenly spaced field lines between two oppositely charged parallel plates.

Photographs of field patterns are shown in Figure 33–5. The photographs show bits of thread that are suspended in an oil bath surrounding charged conductors. The ends of the bits of thread are charged by induction and tend to line up end-to-end with the field lines, like iron filings in a magnetic field. Notice that between the plates the threads are aligned parallel to each other. The field has a constant strength between the plates. Also, notice the threads inside the cylinder are unaligned. There is no electric field in the space inside a conductor. The conductor shields the space from the field outside.

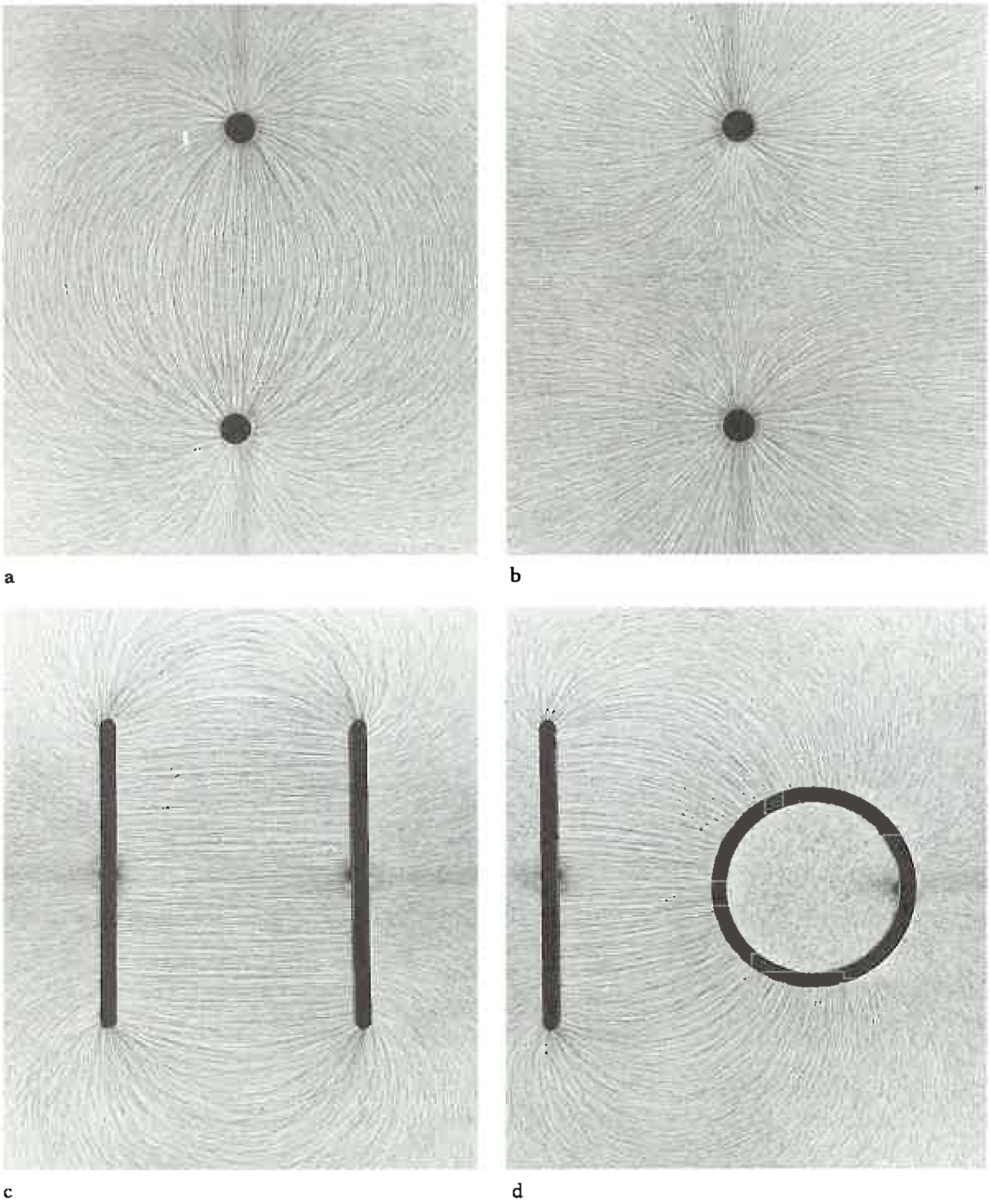

Fig. 33–5 Bits of fine thread suspended in an oil bath surrounding charged conductors line up end-to-end along the direction of the field. (a) Equal and opposite charges. (b) Equal like charges. (c) Oppositely charged plates. (d) Oppositely charged cylinder and plate.

If our only concern for electrical forces were limited to isolated point charges, the electric field concept would be of limited use. The force between point charges is adequately described by Coulomb's law. But charges most often are spread out over a wide variety of surfaces. Charges also move. This motion is communicated to neighboring charges by changes in the electric field that emanate at the speed of light.

As later chapters will show, the electric field is a storehouse of energy. The energy can be transported over long distances by an electric field, which may be directed through and guided by metal wires or directed through empty space.

▸ **Question**

Suppose that a beam of electrons is produced at one end of a glass tube and lights up a phosphor screen on the inner surface of the other end. When the beam is straight, it produces a spot of light in the middle of the screen. If the beam passes through the electric field of a pair of oppositely charged plates, it is deflected, say to the left. If the charge on the plates is reversed, in what direction would deflection occur?

33.3 Electric Shielding

The dramatic photo in Figure 33–6 shows a car being struck by lightning. Yet the occupant inside the car is completely safe. This is because the electrons that shower down upon the car are mutually repelled to the outer metal surface before moving to the ground. The configuration of electrons on the car's surface at any moment is such that the electric field contributions inside the car cancel to zero. This is true of any charged conductor. The electric field inside a conductor is normally zero.

This internal field cancellation is more easily understood by considering a charged metal sphere (Figure 33–7). Because of mutual repulsion, the electrons have spread as far apart from one another as possible. They distribute themselves uniformly over

Fig. 33–6 Electrons from the lightning bolt mutually repel to the outer metal surface. Although the electric field they set up may be great *outside* the car, the overall electric field *inside* the car cancels to zero.

▸ **Answer**

When the charge on the plates is reversed, the electric field will be in the opposite direction, so the electron beam would be deflected to the right. If the field is made to oscillate, the beam will be swept back and forth. With a second set of plates and further refinements it could sweep a picture onto the screen and be a television set.

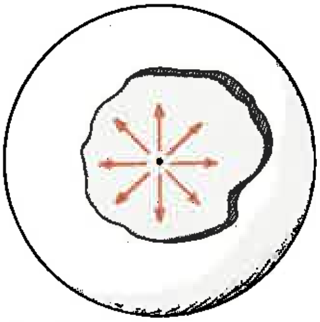

Fig. 33–7 The forces on a test charge located inside a charged hollow sphere cancel to zero.

the surface of the sphere. A positive test charge located exactly in the middle of the sphere would feel no force. The electrons on the left side of the sphere, for example, would tend to pull the test charge to the left, but the electrons on the right side of the sphere would tend to pull the test charge to the right equally hard. The net force on the test charge would be zero. Thus, the electric field is also zero. Interestingly enough, complete cancellation will occur *anywhere* inside the conducting sphere. Why this is true involves some geometry and will not be treated in this text.

If the conductor is not spherical, then the charge distribution will not be uniform. If it is a cube, for example, then most of the charge is located at the corners. The neat thing is this: The exact charge distribution over the surfaces and corners of a conducting cube is such that the electric field everywhere inside the cube is zero. Look at it this way: If there were an electric field inside a conductor, then free electrons inside the conductor would be set in motion. How far would they move? Until equilibrium is established, which is to say, when the positions of all the electrons produce a zero field inside the conductor.

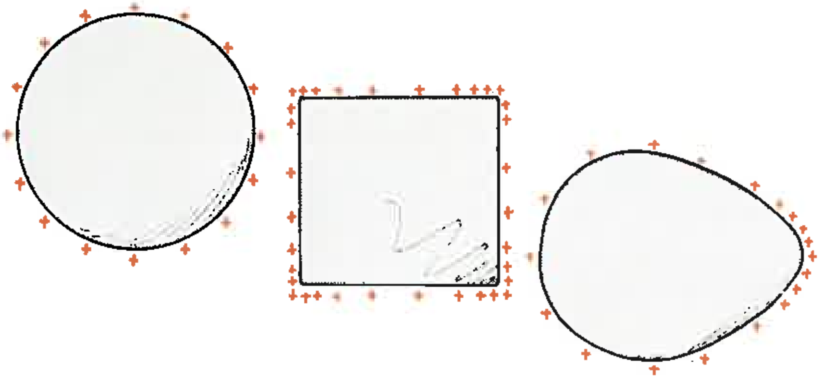

Fig. 33–8 The charges are distributed on the surface of all conductors in a way such that the electric field inside the conductor is zero.

Fig. 33–9 The metal cover shields the internal electrical components from external electric fields. Similarly, the metal cover also shields the coaxial cable.

There is no way to shield gravity, because gravity only attracts. There are no repelling parts of gravity to offset attracting parts. Shielding electric fields, however, is quite simple. Surround yourself or whatever you wish to shield with a conducting surface. Put this surface in an electric field of whatever field strength. The free charges in the conducting surface will arrange themselves on the surface of the conductor in a way such that all field contributions inside cancel one another. That's why certain electronic components are encased in metal boxes, and why certain cables have a metal covering—to shield them from all outside electrical activity.

▶ **Question**

It is said that a gravitational field, unlike an electric field, cannot be shielded. But the gravitational field at the center of the earth cancels to zero. Isn't this evidence that a gravitational field *can* be shielded?

33.4 Electric Potential Energy

Recall from Chapter 8 the relation between work and potential energy. Work is done when a force moves something in the direction of the force. An object has potential energy by virtue of its location, say in a force field. For example, if you lift an object, you apply a force equal to its weight. When you raise it through some distance, you are doing work on the object. You are also increasing its gravitational potential energy. The greater the distance it is raised, the greater is the increase in its gravitational potential energy. Doing work increases its gravitational potential energy (Figure 33–10).

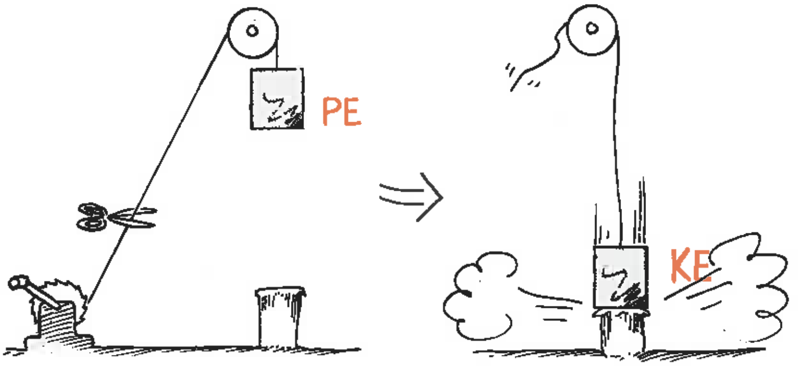

Fig. 33–10 Work is done to lift the ram of the pile driver against the gravitational field of the earth. In an elevated position, the ram has gravitational potential energy. When released, this energy is transferred to the pile below.

▶ **Answer**

No. Gravity can be cancelled inside a planet or between planets, but it cannot be *shielded* by a planet or by any arrangement of masses. During a lunar eclipse, for example, when the earth is directly between the sun and the moon, there is no shielding of the sun's field to affect the moon's orbit. Even a very slight shielding would accumulate over a period of years and show itself in the timing of subsequent eclipses. Shielding requires a combination of repelling and attracting forces, and gravity only attracts.

In a similar way, a charged object can have potential energy by virtue of its location in an electric field. Just as work is required to lift an object against the gravitational field of the earth, work is required to push a charged particle against the electric field of a charged body. (It may be more difficult to visualize, but the physics of both the gravitational case and the electrical case is the same.) The electric potential energy of a charged particle is increased when work is done to push it against the electric field of something else that is charged.

Figure 33–11 top shows a small positive charge located at some distance from a positively charged sphere. If we push the small charge closer to the sphere (Figure 33–11 bottom), we will expend energy to overcome electrical repulsion. Just as work is done in compressing a spring, work is done in pushing the charge against the electric field of the sphere. This work is equivalent to the energy gained by the charge. The energy the charge now possesses by virtue of its location is called **electric potential energy**. If the charge is released, it will accelerate in a direction away from the sphere, and its electric potential energy will transform to kinetic energy.

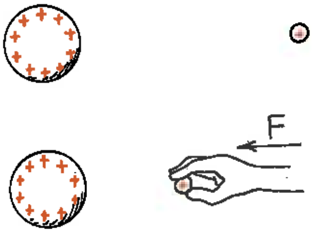

Fig. 33–11 The small positive charge has more potential energy when it is closer to the positively charged sphere because work is required to move it to the closer location.

33.5 Electric Potential

If in the preceding discussion we push two charges instead, we do twice as much work. The two charges in the same location will have twice the electric potential energy as one; three charges will have three times the potential energy; a group of ten charges will have ten times the potential energy; and so on.

Rather than deal with the total potential energy of a group of charges, it is convenient when working with electricity to consider the *electric potential energy per charge*. The electric potential energy per charge is the total electric potential energy divided by the amount of charge. At any location the potential energy *per charge*—whatever the amount of charge—will be the same. For example, an object with ten units of charge at a specific location has ten times as much energy as an object with a single unit of charge. But it also has ten times as much charge, so the potential energy per charge is the same. The concept of electric potential energy per charge has a special name, **electric potential**.

$$\text{electric potential} = \frac{\text{electric potential energy}}{\text{charge}}$$

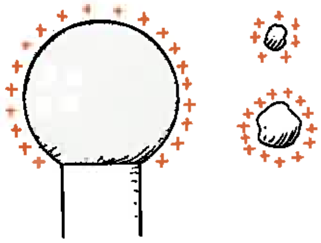

Fig. 33–12 An object of greater charge has more electric potential energy in the field of the charged dome than an object of less charge, but the *electric potential* of any amount of charge at the same location is the same.

▶ Question

If there were twice as much charge on one of the charged objects near the charged sphere in Figure 33–12, would the electric potential energy of the object in the field of the charged sphere be the same or would it be twice as great? Would the electric potential of the object be the same or would it be twice as great?

The SI unit of measurement for electric potential is the **volt**, named after the Italian physicist Allesandro Volta (1745–1827). The symbol for volt is V. Since potential energy is measured in joules and charge is measured in coulombs,

$$1 \text{ volt} = 1 \frac{\text{joule}}{\text{coulomb}}$$

Thus, a potential of 1 volt equals 1 joule of energy per coulomb of charge; 1000 volts equals 1000 joules of energy per coulomb of charge. If a conductor has a potential of 1000 volts, it would take 1000 joules of energy per coulomb to bring a small charge from very far away and add it to the charge on the conductor.* (Since the small charge would be much less than one coulomb, the energy required would be much less than 1000 joules. For example, to add the charge of one proton, 1.6×10^{-19} C, would take only 1.6×10^{-16} J of energy.)

Since electric potential is measured in volts, it is commonly called **voltage**. In this book the names will be used interchangeably. The significance of voltage is that a definite value for it can be assigned to a location whether or not a charge exists at that location. We can speak about the voltages at different locations in an electric field whether or not any charges occupy those locations.

▶ Answer

Twice as much charge would cause the object to have twice as much electric potential energy, because it would have taken twice as much work to put the object at that location. But the electric potential would be the same, because the electric potential is total electric potential energy divided by total charge. In this case, twice the energy divided by twice the charge gives the same value as the original energy divided by the original charge. Electric potential is not the same thing as electric potential energy. Be sure you understand this before you study further.

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* It is common practice to assign a zero electric potential to places infinitely far away from any charges. As the next chapter discusses, for electric currents the value zero is assigned to the potential of the ground.

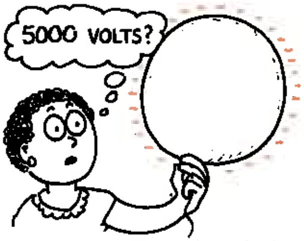

Fig. 33–13 Although the voltage of the charged balloon is high, the electric potential energy is low because of the small amount of charge.

Rub a balloon on your hair and the balloon becomes negatively charged, perhaps to several thousand volts! If the charge on the balloon were one coulomb, it would take several thousand joules of energy to give the balloon that voltage. However, one coulomb is a relatively large amount of charge; the charge on a balloon rubbed on hair is typically much less than a millionth of a coulomb. Therefore, the amount of energy associated with the charged balloon is very, very small—about a thousandth of a joule. A high voltage requires great energy only if a great amount of charge is involved. This example highlights the difference between electric potential energy and electric potential.

33.6 The Van de Graaff Generator

A common laboratory device for building up high voltages is the *Van de Graaff generator*. This is the lightning machine that "evil scientists" used in old science fiction movies. A simple model of the Van de Graaff generator is shown in Figure 33–14. A large hollow metal sphere is supported by a cylindrical insulating stand. A motor-driven rubber belt inside the support stand moves past a comb-like set of metal needles that are maintained at a

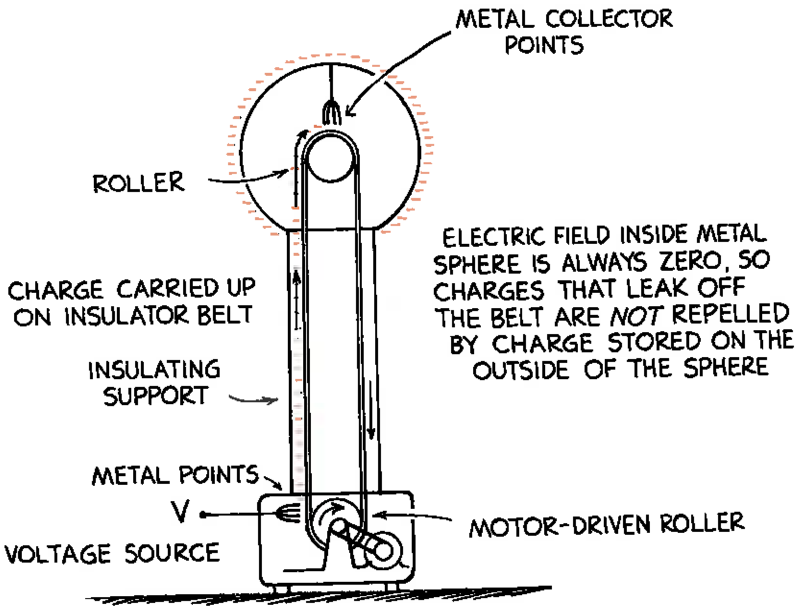

Fig. 33–14 A simple model of a Van de Graaff Generator.

Fig. 33–15 The physics enthusiasts and the dome of the Van de Graaff generator are charged to a high voltage. Why does their hair stand out?

high electric potential. A continuous supply of electrons is deposited on the belt through electric discharge by the points of the needles and is carried up into the hollow metal sphere. The electrons leak onto metal points (which act like tiny lightning rods) attached to the inner surface of the sphere. Because of mutual repulsion, the electrons move to the outer surface of the conducting sphere. (Remember, static charge on any conductor is on the outside surface.) This leaves the inside surface uncharged and able to receive more electrons as they are brought up the belt. The process is continuous, and the charge builds up to a very high electric potential—on the order of millions of volts.

A sphere with a radius of 1 m can be raised to a potential of 3 million volts before electrical discharge occurs through the air (because breakdown occurs in air when the electric field strength is about 3×10^6 V/m). The voltage can be further increased by increasing the radius of the sphere or by placing the entire system in a container filled with high-pressure gas. Van de Graaff generators can produce voltages as high as 20 million volts. These devices accelerate charged particles used as projectiles for penetrating the nuclei of atoms. Touching one can be a hair-raising experience (Figure 33–15).

Before electricity became commonplace, it was regarded by most people as a terrifying phenomenon. To help dispel this fear, Nikola Tesla (who was the chief proponent of alternating current when Thomas Edison was promoting direct current) would sit indifferently in the midst of a high-voltage sparking demonstration (Figure 33–16).

Fig. 33–16 Time exposure of Nikola Tesla quietly reading while sparks leap between conductors around him.

33 Chapter Review

Concept Summary

An electric field fills the space around every electric charge.

- The field is strongest where it would exert the greatest electrical force on a test charge.
- The direction of the field at any point is the direction of the electrical force on a positive test charge.
- An electric field can be represented by electric field lines.
- The electric field inside a conductor is zero; any static net charge is all on the outside surface.

A charged object has electric potential energy by virtue of its location in an electric field.

- The electric potential, or voltage, at any point in an electric field is the electric potential energy per charge for a charged object at that point.

Important Terms

electric field (33.1)
electric potential energy (33.4)
electric potential (33.5)
volt (33.5)
voltage (33.5)

Review Questions

1. What is meant by the expression *action at a distance*? (33.1)

2. How does the concept of a field eliminate the idea of action at a distance? (33.1)

3. How are a gravitational and an electric field similar? (33.1)

4. Why is an electric field considered a vector quantity? (33.2)

5. a. What are electric field lines?
   b. How do their directions compare with the direction of the force that acts on a positive test charge in the same region? (33.2)

6. How is the strength of an electric field indicated with field lines? (33.2)

7. How do the electric field lines appear when the field has the same strength at all points in a region? (33.2)

8. Why will an occupant inside a car struck by lightning be safe? (33.3)

9. What is the size of the electric field inside any charged conductor? (33.3)

10. a. Can gravity be shielded?
    b. Can electric fields be shielded? (33.3)

11. What is the relationship between the amount of work you do on an object and its potential energy? (33.4)

12. How can the electric potential energy of a charged particle in an electric field be increased? (33.4)

13. What will happen to the electric potential energy of a charged particle in an electric field when the particle is released and free to move? (33.4)

14. Clearly distinguish between *electric potential energy* and *electric potential*. (33.5)

15. If you do more work to move more charge a

certain distance against an electric field, and increase the electric potential energy as a result, why do you not also increase the electric potential (33.5)?

16. The SI unit for electric potential energy is the joule. What is the SI unit for electric potential? (33.5)

17. Charge must be present at a location in order for there to be electric potential energy. Must charge also be present at a location for there to be electric potential? (33.5)

18. How can electric potential be high when electric potential energy is relatively low? (33.5)

19. How does the amount of charge on the inside surface of the sphere of a charged Van de Graaff generator compare to the amount on the outside? (33.6)

20. About how large a voltage can be built up on a Van de Graaff generator before electrical discharge occurs through the air? (33.6)

Think and Explain

1. How is an electric field different from a gravitational field?

2. The vectors for the gravitational field of the earth point *toward* the earth; the vectors for the electric field of a proton point *away* from the proton. Explain.

3. If a "free" electron and "free" proton were placed in an electric field, how would their accelerations and directions of travel compare?

4. Suppose that the strength of the electric field about an isolated point charge has a certain value at a distance of 1 m. How will the electric field strength compare at a distance of 2 m from the point charge? What law guides your answer?

5. When a conductor is charged, the charge moves to the outer surface of the conductor. Why is this so?

6. Suppose that a metal file cabinet is charged. How will the charge concentration at the corners of the cabinet compare to the charge concentration on the flat parts of the cabinet? Defend your answer.

7. a. If you do 12 J of work to push 0.001 C of charge into an electric field, by how much will its voltage increase?
   b. When the charge is released, what will be its kinetic energy as it flies past its starting position? What principle guides your answer?

8. a. If you do 24 J of work to push 0.002 C of charge into an electric field, by how much will its voltage increase?
   b. When the charge is released, what will be its kinetic energy as it flies past its starting position?

9. Is it correct to say that an object with twice the electric potential as another has twice the electric potential energy? Defend your answer. (*Hint*: Is it correct to say that an object with twice the temperature as another has twice the internal energy?)

10. Why does your hair stand out when you are charged by a device such as a Van de Graaff generator?

34 Electric Current

The last chapter discussed the concept of electric potential, or voltage. This chapter will show that voltage is an "electrical pressure" that can produce a flow of charge, or *current*, within a conductor. The flow is restrained by the *resistance* it encounters. When the flow takes place along one direction, it is called *direct current* (dc); when it flows to and fro, it is called *alternating current* (ac). The rate at which energy is transferred by electric current is *power*. You'll note here that there are many terms to be sorted out. This is easier (and more meaningful) to do when you have some understanding of the ideas these terms represent. In turn, the ideas are better understood if you know how they relate to one another. Let's begin with the flow of electric charge.

34.1 Flow of Charge

Recall in your study of heat and temperature that heat flows through a conductor when a difference in temperature exists across its ends. Heat flows from the end of higher temperature to the end of lower temperature. When both ends reach the same temperature, the flow of heat ceases.

In a similar way, when the ends of an electrical conductor are at different electric potentials, charge flows from the higher potential to the lower potential. Charge flows when there is a **potential difference**, or difference in potential (voltage), across the ends of a conductor. The flow of charge will continue until both ends reach a common potential. When there is no potential difference, no flow of charge will occur.

As an example, if one end of a wire were connected to the ground and the other end placed in contact with the sphere of a

Van de Graaff generator charged to a high potential, a surge of charge would flow through the wire. The flow would be brief, however, for the sphere would quickly reach a common potential with the ground.

To attain a sustained flow of charge in a conductor, some arrangement must be provided to maintain a difference in potential while charge flows from one end to the other. The situation is analagous to the flow of water from a higher reservoir to a lower one (Figure 34–1 left). Water will flow in a pipe that connects the reservoirs only as long as a difference in water level exists. (This is implied in the saying, "Water seeks its own level.") The flow of water in the pipe, like the flow of charge in the wire that connects the Van de Graaff generator to the ground, will cease when the pressures at each end are equal. In order that the flow be sustained, there must be a suitable pump of some sort to maintain a difference in water levels (Figure 34–1 right). Then there will be a continual difference in water pressures and a continual flow of water. The same is true of electric current.

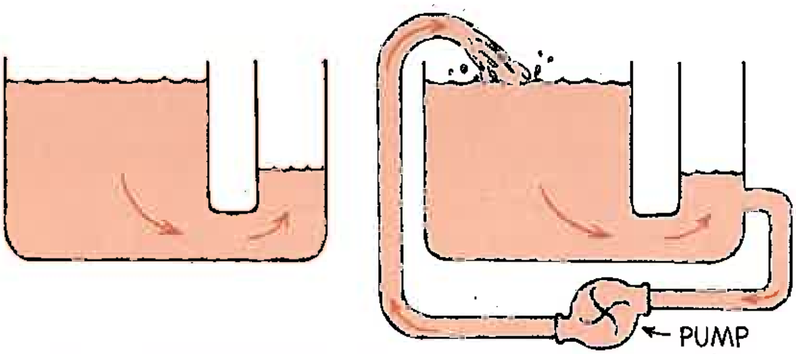

Fig. 34-1 (Left) Water flows from the reservoir of higher pressure to the reservoir of lower pressure. The flow will cease when the difference in pressure ceases. (Right) Water continues to flow because a difference in pressure is maintained with the pump.

34.2 Electric Current

Electric current is simply the flow of electric charge. In solid conductors, it is the electrons that carry the charge through the circuit. This is because the electrons are free to move throughout the atomic network. These electrons are called *conduction electrons*. Protons, on the other hand, are bound inside atomic nuclei that are more or less locked in fixed positions. In fluids, however, positive and negative ions as well as electrons may compose the flow of electric charge.

Electric current is measured in **amperes**, symbol A.* An ampere is the flow of one coulomb of charge per second. (Recall that one coulomb, the standard unit of charge, is the electric charge of 6.25 billion billion electrons.) In a wire that carries a current of 5 amperes, for example, 5 coulombs of charge pass any cross section in the wire each second. So that's a lot of electrons! In a wire that carries 10 amperes, twice as many electrons pass any cross section each second.

Note that a current-carrying wire does not have a *net* electric charge. Negative electrons swarm through the atomic network that is composed of positively charged atomic nuclei. Under ordinary conditions, the number of electrons in the wire is equal to the number of positive protons in the atomic nuclei. So the net charge of the wire is normally zero at every moment.

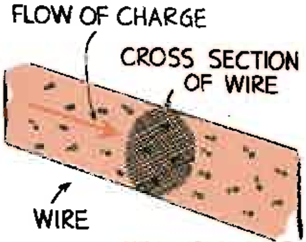

Fig. 34-2 When the rate of flow of charge past any cross section is one coulomb (6.25 billion billion electrons) per second, the current is one ampere.

34.3 Voltage Sources

Charges do not flow unless there is a potential difference. A sustained current requires a suitable "electrical pump" to provide a sustained potential difference. Something that provides a potential difference is known as a **voltage source**. If you charge a metal sphere positively, and another negatively, you can develop a large voltage between them. This voltage source is not a good electrical pump because when the spheres are connected by a conductor, the potentials equalize in a single brief surge of moving charges. It is not practical. Dry cells, wet cells, and generators, however, are capable of maintaining a steady flow. (A battery is just two or more cells wired together.)

Dry cells, wet cells, and generators supply energy that allows charges to move. In dry cells and wet cells, energy released in a chemical reaction that takes place inside the cell is converted to electric energy.** Generators convert mechanical energy to electric energy, as discussed in Chapter 37. The electric potential energy produced by whatever means is available at the terminals of the cell or generator. The potential energy per coulomb of charge available to electrons that move from one terminal to the other equals the potential difference (voltage) that provides the "electrical pressure" to move electrons through a circuit joined to these terminals.

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* The SI symbol for ampere is A. However, an older symbol still in common usage is amp. People often speak of a current of, say, "5 amps."

** A description of the chemical reactions inside dry cells and wet cells can be found in almost any chemistry textbook.

Fig. 34-3 Each coulomb of charge that is made to flow in a circuit that connects the ends of this 1.5-volt flashlight cell is energized with 1.5 joules.

Power utilities use electric generators to provide the 120 volts that is delivered to home outlets. The potential difference between the two holes in the outlet is 120 volts. When the prongs of a plug are inserted into the outlet, an electrical "pressure" of 120 volts is placed across the circuit connected to the prongs. This means that 120 joules of energy is supplied to each coulomb of charge that is made to flow in the circuit.

There is often some confusion between charge flowing *through* a circuit and voltage being impressed *across* a circuit. To distinguish between these ideas, consider a long pipe filled with water. Water will flow *through* the pipe if there is a difference in pressure *across* or between its ends. Water flows from the high-pressure end to the low-pressure end. Only the water flows, not the pressure. Similarly, you say that charges flow *through* a circuit because of an applied voltage *across* the circuit.* You don't say that voltage flows through a circuit. Voltage doesn't go anywhere, for it is the charges that move. Voltage causes current.

34.4 Electrical Resistance

The amount of current that flows in a circuit depends on the voltage provided by the voltage source. It also depends on the resistance that the conductor offers to the flow of charge, or the **electrical resistance.** This is similar to the rate of water flow in a pipe, which depends not only on the pressure behind the water but on the resistance offered by the pipe itself. The resistance of a wire depends on the *conductivity* of the material (that is, how well it conducts) and also on the thickness and length of the wire.

Electrical resistance is less in thick wires. The longer the wire, of course, the greater the resistance. In addition, electrical resistance depends on temperature. The greater the jostling about of atoms within the conductor, the greater resistance the conductor offers to the flow of charge. For most conductors, increased temperature means increased resistance.** The resistance of some metals approaches zero at very low temperatures. These are the superconductors discussed briefly in Chapter 32.

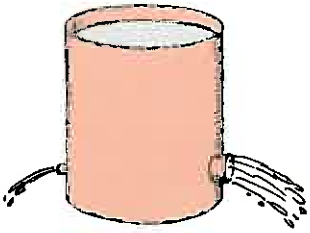

Fig. 34-4 For a given pressure, more water passes through a large pipe than a small one. Similarly, more electric current passes through a large-diameter wire than a small one.

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* It is conceptually simpler to say that current flows through a circuit, but don't say this around somebody who is "picky" about grammar, for the expression "current flows" is redundant. More properly, charge flows, which *is* current.

** Carbon is an interesting exception. At high temperatures, electrons are shaken from the carbon atom, which increases electric current. Carbon's resistance, in effect, lowers with increasing temperature. This behavior, along with its high melting temperature, accounts for the use of carbon in arc lamps.

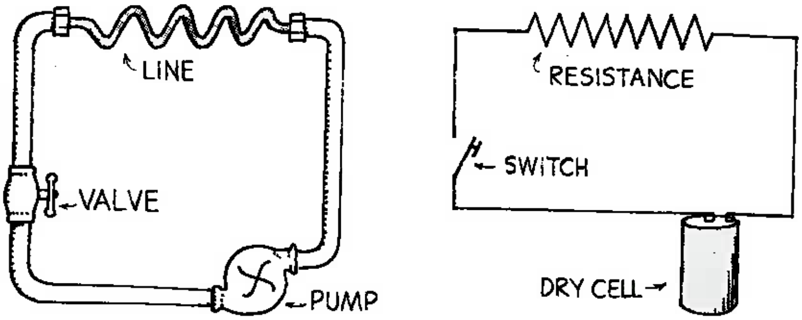

Fig. 34-5 Analogy between a simple hydraulic circuit and an electric circuit.

Electrical resistance is measured in units called **ohms**,* after Georg Simon Ohm, a German physicist who tested different wires in circuits to see what effect the resistance of the wire had on the current.

34.5 Ohm's Law

Ohm discovered that the amount of current in a circuit is directly proportional to the voltage impressed across the circuit, and is inversely proportional to the resistance of the circuit. In short,

$$\text{current} = \frac{\text{voltage}}{\text{resistance}}$$

This relationship between voltage, current, and resistance is called **Ohm's law**.**

The relationship between the units of measurement for these three quantities is:

$$1 \text{ ampere} = 1 \frac{\text{volt}}{\text{ohm}}$$

So for a given circuit of constant resistance, current and voltage are proportional. This means that you'll get twice the current for twice the voltage. The greater the voltage, the greater the current. But if the resistance is doubled for a circuit, the current will be half what it would be otherwise. The greater the resistance, the less the current. Ohm's law makes good sense.

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* The Greek letter omega (Ω) is usually used as a symbol for ohm.

** Many texts use V for voltage, I for current, and R for resistance, and express Ohm's law as $V = IR$. It then follows that $I = V/R$, or $R = V/I$, so if any two variables are known, the third can be found.

Using specific values, a potential difference of 1 volt impressed across a circuit that has a resistance of 1 ohm will produce a current of 1 ampere. If a voltage of 12 volts is impressed across the same circuit, the current will be 12 amperes.

The resistance of a typical lamp cord is much less than 1 ohm, while a typical light bulb has a resistance of about 100 ohms. An iron or electric toaster has a resistance of 15 to 20 ohms. The low resistance permits a large current, which produces considerable heat. Inside electrical devices such as radio and television receivers, the current is regulated by circuit elements called *resistors*, whose resistance may range from a few ohms to millions of ohms.

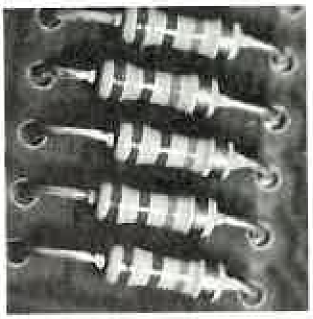

Fig. 34-6 Resistors. The stripes are color coded to indicate the resistance in ohms.

▶ **Questions**

1. What is the resistance of an electric frying pan that draws 12 amperes of current when connected to a 120-volt circuit?
2. How much current is drawn by a lamp that has a resistance of 100 ohms when a voltage of 50 volts is impressed across it?

34.6 Ohm's Law and Electric Shock

What causes electric shock in the human body—current or voltage? The damaging effects of shock are the result of current passing through your body. From Ohm's law, we can see that this current depends on the voltage applied, and also on the electrical resistance of the human body.

The resistance of your body depends on its condition and ranges from about 100 ohms if you're soaked with salt water to about 500 000 ohms if your skin is very dry. If you touched the

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▶ **Answers**

1. The resistance is 10 ohms.

resistance = (voltage)/(current) = (120 volts)/(12 amperes) = 10 ohms

An electrical device is said to *draw* current when voltage is impressed across it, just as water is said to be drawn from a well or a faucet. In this sense, to draw is not to attract, but to *obtain*.

2. The current is 0.5 ampere.

current = (voltage)/(resistance) = (50 volts)/(100 ohms) = 0.5 ampere two electrodes of a battery with dry fingers, the resistance your body would normally offer to the flow of charge would be about 100 000 ohms. You usually would not feel 12 volts, and 24 volts would just barely tingle. If your skin were moist, on the other hand, 24 volts could be quite uncomfortable. Table 34–1 describes the effects of different amounts of current on the human body.

Table 34–1 Effect of Various Electric Currents on the Body

Current in amperes	Effect
0.001	Can be felt
0.005	Painful
0.010	Involuntary muscle contractions (spasms)
0.015	Loss of muscle control
0.070	Through the heart, serious disruption, probably fatal if current lasts for more than 1 second

▶ **Questions**

1. If the resistance of your body were 100 000 ohms, how much current would be produced in your body if you touched the terminals of a 12-volt battery?
2. If your skin were very moist so that your resistance was only 1000 ohms, and you touched the terminals of a 24-volt battery, how much current would you draw?

Many people are killed each year by current from common 120-volt electric circuits. If you touch a faulty 120-volt light fixture with your hand while your feet are on the ground, there is a 120-volt "electric pressure" between your hand and the ground. Resistance to current flow is usually greatest between your feet and the ground, so the current is usually not enough to do serious harm. But if your feet and the ground are wet, there is a low-resistance electrical bond between you and the ground.

▶ **Answers**

1. The current in your body would be:

$$\text{current} = (\text{voltage})/(\text{resistance}) = (12\ \text{V})/(100\ 000\ \Omega) = 0.00012\ \text{A}$$

2. You would draw (24 V)/(1000 Ω), or 0.024 A, a dangerous amount of current!

Your overall resistance is so lowered that the 120-volt potential difference across your body may produce a harmful current in your body.

Drops of water that collect around the on-off switch of devices such as a hair dryer can conduct current to the user. Although distilled water is a good insulator, the ions in ordinary water greatly reduce the electrical resistance. Dissolved materials, especially small amounts of salt, reduce the resistance even more. There is usually a layer of salt left from perspiration on your skin, which when wet lowers your skin resistance to a few hundred ohms or less. Handling electrical devices while taking a bath is extremely dangerous.

Fig. 34-7 Handling a wet hair dryer can be like sticking your fingers into a live socket.

You have seen birds perched on high-voltage wires. Every part of their bodies is at the same high potential as the wire, and they feel no ill effects. For the bird to receive a shock, there must be a *difference* in electric potential between one part of its body and another part. Most of the current will then pass along the path of least electrical resistance connecting these two points.

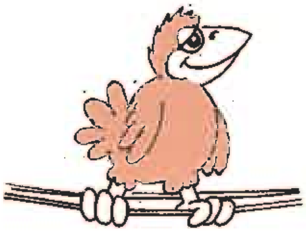

Fig. 34-8 The bird can stand harmlessly on one wire of high potential, but it had better not reach over and grab a neighboring wire! Why not?

Suppose you fell from a bridge and managed to grab onto a high-voltage power line, halting your fall. So long as you touch nothing else of different potential, you will receive no shock at all. Even if the wire is several thousand volts above ground potential and even if you hang by it with two hands, no charge will flow from one hand to the other. This is because there is no difference in electric potential between your hands. If, however, you reach over with one hand and grab onto a wire of different potential, ZAP!!

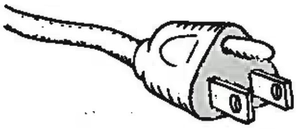

Fig. 34-9 The third prong connects the body of the appliance directly to ground. Any charge that builds up on an appliance is therefore conducted to the ground.

Mild shocks occur when the surfaces of electrical appliances are at a different electric potential from the surfaces of other nearby devices. If you touch surfaces of different potentials, you become the pathway to equilibrium. Sometimes the effect is more than mild. To prevent this problem, the outsides of electrical appliances are connected to a ground wire, which is connected to the round third prong of a three-wire electrical plug (Figure 34–9). All ground wires in all plugs are connected together through the wiring system of the house. The two flat prongs are for the current-carrying double wire, part of which is live and the other neutral. If the live wire accidentally comes in contact with the metal surface of an appliance, the current will be directed to ground rather than shocking you if you handle it.

Electric shock overheats tissues in the body or disrupts normal nerve functions. It can upset the nerve center that controls breathing. In rescuing victims, the first thing to do is clear them from the electric supply with a wooden stick or some other nonconductor so that you don't get electrocuted yourself. Then apply artificial respiration.

▶ **Question**
What causes electric shock—current or voltage?

34.7 Direct Current and Alternating Current

Electric current may be *dc* or *ac*. By *dc*, we mean **direct current**, which refers to a flow of charge that is *always in one direction*. A battery produces direct current in a circuit because the terminals of the battery always have the same sign of charge. Electrons always move through the circuit in the same direction, from the repelling negative terminal and toward the attracting positive terminal. Even if the current moves in unsteady pulses, so long as it moves in one direction only, it is dc.

Alternating current (ac) acts as the name implies. Electrons in the circuit are moved first in one direction and then in the opposite direction, alternating to and fro about relatively fixed positions. This is accomplished by alternating the polarity of voltage at the generator or other voltage source. Nearly all commercial ac circuits in North America involve voltages and currents that alternate back and forth at a frequency of 60 cycles per second. This is 60-hertz current. In some places, 25-hertz, 30-hertz, or 50-hertz current is used.

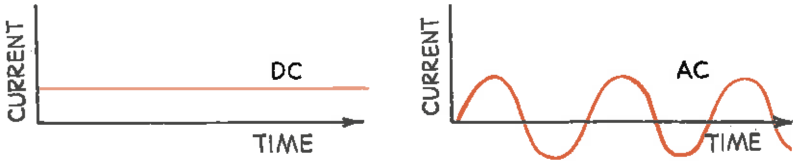

Fig. 34-10 Direct current (dc) does not change direction over time. Alternating current (ac) cycles back and forth.

The popularity of ac arises from the fact that electric energy in the form of ac can be transmitted great distances with easy voltage step-ups that result in lower heat losses in the wires. Why this is so will be discussed in Chapter 37.

The primary use of electric current, whether dc or ac, is to transfer energy quietly, flexibly, and conveniently from one place to another.

▶ **Answer**
Electric shock *occurs* when current is produced in the body, which is *caused* by an impressed voltage.

34.8 The Speed of Electrons in a Circuit

When you flip on the light switch on your wall and the circuit is completed, the light bulb appears to glow immediately. When you make a telephone call, the electrical signal carrying your voice travels through the connecting wires at seemingly infinite speed. This signal is transmitted through the conductors at nearly the speed of light. It is *not* the electrons that move at this speed but the signal.

At room temperature, the electrons inside a metal wire have an average speed of a few million kilometers per hour due to their thermal motion. This does not produce a current because the motion is random. There is no flow in any one direction. But when a battery or generator is connected, an electric field is established inside the wire. It is the electric field that travels through a circuit at nearly the speed of light. The electrons continue their random motions while simultaneously being nudged through the wire by the electric field.

The conducting wire acts as a guide or "pipe" to the electric field lines that are established at the voltage source (Figure 34–11). If the voltage source is dc, like the battery shown in Figure 34–11, the electric field lines are maintained in one direction in the conductor.

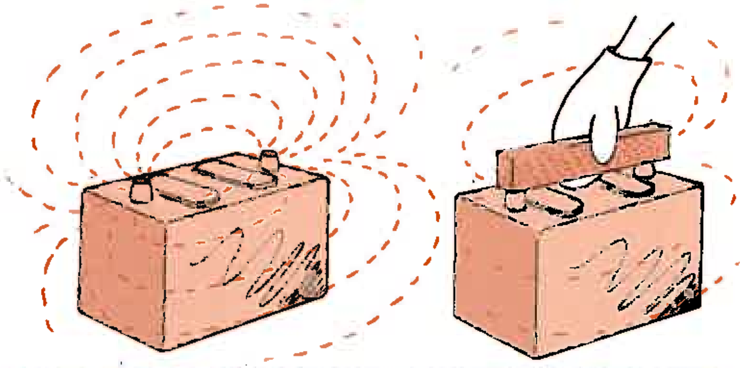

Fig. 34-11 The electric field lines between the terminals of a battery are directed through a conductor, which joins the terminals. A metal bar is shown here, but the conductor is usually an electric circuit.

Conduction electrons are accelerated by the field in a direction parallel to the field lines. Before they gain appreciable speed, they "bump into" the anchored metallic ions in their paths and lose some of their kinetic energy to them. This is why current-carrying wires become hot. These collisions interrupt the motion of the electrons so that their actual *drift speed*, or *net* *speed* through the wire due to the field, is extremely low. In a typical dc circuit, in the electrical system of an automobile, for example, electrons have a net average drift speed of about 0.01 cm/s. At this rate it would take more than three hours for an electron to travel through 10 meters of wire.

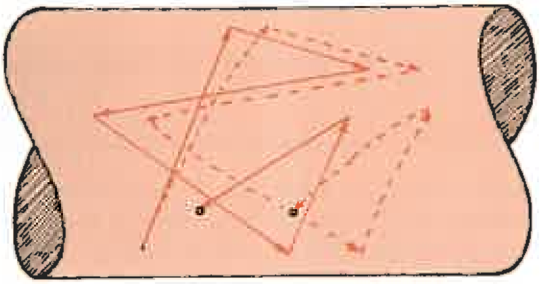

Fig. 34-12 The solid lines depict a possible random path of an electron bouncing off atomic nuclei in a conductor. Instantaneous speeds are about 1/200 the speed of light. The dashed lines show an exaggerated view of how this path may be altered when an electric field is applied. The electron drifts toward the right with an average speed much less than a snail's pace.

In an ac circuit, the conduction electrons don't go anywhere. They oscillate rhythmically to and fro about relatively fixed positions. When you talk to your friend on the telephone, it is the *pattern* of oscillating motion that is carried across town at nearly the speed of light. The electrons already in the wires vibrate to the rhythm of the traveling pattern.

34.9 The Source of Electrons in a Circuit

Some people think that the electrical outlets in the walls of their homes are a source of electrons. They think that electrons flow from the power utility through the power lines and into the wall outlets of their homes. This is not true. The outlets in homes are ac. Electrons do not travel through a wire in an ac circuit, but instead vibrate to and fro about relatively fixed positions.

When you plug a lamp into an outlet, *energy* flows from the outlet into the lamp, not electrons. Energy is carried by the electric field and causes vibratory motion of the electrons that already exist in the lamp filament. If 120 volts are impressed on a lamp, then 120 joules of energy are given to each coulomb of charge that is made to vibrate. Most of this electrical energy is transformed into heat while some of it takes the form of light. Power utilities do not sell electrons. They sell *energy*. *You* supply the electrons.

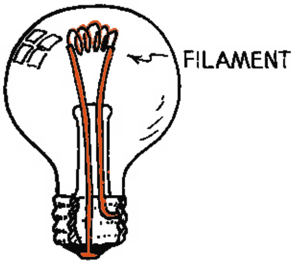

Fig. 34-13 The conduction electrons that surge to and fro in the filament of the lamp do not come from the voltage source. They are in the filament to begin with. The voltage source simply provides them with surges of energy.

Thus, when you are jolted by an electric shock, the electrons making up the current in your body originate in your body. Electrons do not come out of the wire and through your body and into the ground. Energy does. The energy simply causes free electrons in your body to vibrate in unison. Small vibrations tingle. Large vibrations can be fatal.

34.10 Electric Power

When a charge moves in a circuit, it does work. Usually this results in heating the circuit or in turning a motor. The rate at which work is done, that is, the rate at which electric energy is converted into another form such as mechanical energy, heat, or light is called **electric power**. Electric power is equal to the product of current and voltage.[*]

$$\text{electric power} = \text{current} \times \text{voltage}$$

If the voltage is expressed in volts and the current in amperes, then the power is expressed in watts. So in units form,

$$1 \text{ watt} = (1 \text{ ampere}) \times (1 \text{ volt})$$

If a lamp rated at 120 watts operates on a 120-volt line, you can see that it will draw a current of 1 ampere, since 120 watts = (1 ampere) × (120 volts). A 60-watt lamp draws 0.5 ampere on a 120-volt line. This relationship becomes a practical matter when you wish to know the cost of electrical energy, which varies from 1 cent to 10 cents per kilowatt-hour depending on locality.

A *kilowatt* is 1000 watts, and a *kilowatt-hour* represents the amount of energy consumed in 1 hour at the rate of 1 kilowatt.[**]

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[*] Note that this follows from the definitions of current and voltage:

$$\text{current} \times \text{voltage} = \frac{\cancel{\text{charge}}}{\text{time}} \times \frac{\text{energy}}{\cancel{\text{charge}}} = \frac{\text{energy}}{\text{time}} = \text{power}$$

[**] Since power = (energy)/(time), simple rearrangement gives energy = power × time; hence, energy can be expressed in units of kilowatt-hours.

Physicists measure energy in *joules*, but utility companies customarily sell energy in units of *kilowatt-hours* (kW·h), where $1 \text{ kW·h} = 3.6 \times 10^6$ J. This duplication of units added to an already long list of units unfortunately makes the study of physics more difficult. It will be enough for you to become familiar with and be able to distinguish between the units *coulombs*, *volts*, *ohms*, *amperes*, *watts*, *kilowatts*, and *kilowatt-hours* here. Mastering them requires laboratory work and the help of more advanced textbooks. An understanding of electricity takes considerable time and effort, so be patient with yourself if you find this material difficult.

Therefore, in a locality where electric energy costs 5 cents per kilowatt-hour, a 100-watt electric light bulb can be run for 10 hours at a cost of 5 cents, or a half cent for each hour. A toaster or iron, which draws more current and therefore more power, costs several times as much to operate for the same time.

Fig. 34-14 The power and voltage on the light bulb read "60 W 120 V." How much current in amperes will flow though the bulb?

▶ **Questions**

1. How much power is used by a calculator that operates on 8 volts and 0.1 ampere? If it is used for one hour, how much energy does it use?
2. Will a 1200-watt hairdryer operate on a 120-volt line if the current is limited to 15 amperes by a safety fuse? Can two hairdryers operate on this line?

▶ **Answers**

1. Power = current × voltage = (0.1 A) × (8 V) = 0.8 W. If it is used for one hour, then energy = power × time = (0.8 W) × (1 h) = 0.8 watt-hour, or 0.0008 kilowatt-hour.
2. One 1200-watt hairdryer can be operated because the circuit can provide (15 A) × (120 V) = 1800 watts. But there is inadequate power to operate two hairdryers of combined power 2400 watts. This can be seen also from the amount of current involved. Since 1 watt = (1 ampere) × (1 volt), note that (1200 watts)/(120 volts) = 10 amperes; so the hair dryer will operate when connected to the circuit. But two hairdryers on the same plug will require 20 amperes and blow the fuse.

34 Chapter Review

Concept Summary

Electric current is the flow of electric charge that occurs when ~~there is a potential difference across the ends of~~ an electrical conductor.

- The flow continues until both ends reach a common potential.
- Dry cells, wet cells, and electric generators are voltage sources that maintain a potential difference in a circuit.

The amount of current that flows in a circuit depends on the voltage and the electrical resistance that the conductor offers to the flow of charge.

- An increased temperature or a longer wire increases resistance.
- Increasing the thickness of the wire decreases resistance.

Ohm's law states that the amount of current is directly proportional to the voltage and inversely proportional to the resistance.

- Resistors are used in many electrical devices to control the considerable heat formed by a large current.
- Electric shock is caused by the electric current that passes through the body when there is a voltage difference between two parts of the body.

Direct current (dc) is electric current in which the charge flows in one direction only; electrons in an alternating current (ac) alternate their direction of flow.

- Batteries produce direct current.
- Alternating current allows electrical transmission across great distances.

Electric fields travel through circuits at nearly the speed of light, but the electrons themselves do not.

- In a dc circuit, electrons have a low drift speed within the electric field.
- In ac circuits, energy, not electrons, flows from the outlet; the electrons vibrate rhythmically in fixed positions.

Electric power, the rate at which electric energy is converted into another form of energy, is equal to the product of current and voltage.

Important Terms

alternating current (34.7)
ampere (34.2)
direct current (34.7)
electrical resistance (34.4)
electric current (34.2)
electric power (34.10)
ohm (34.4)
Ohm's law (34.5)
potential difference (34.1)
voltage source (34.3)

Review Questions

1. What condition is necessary for the flow of heat? What analagous condition is necessary for the flow of charge? (34.1)

2. What is meant by the term potential? Potential difference? (34.1)

3. What condition is necessary for the sustained flow of water in a pipe? What analogous condition is necessary for the sustained flow of charge in a wire? (34.1)

4. What is electric current? (34.2)

5. What is an ampere? (34.2)

6. What two devices commonly separate charges to provide an "electrical pressure"? (34.3)

7. How many joules per coulomb are given to charges that flow in a 120-volt circuit? (34.3)

8. Does charge flow through a circuit or into a circuit? (34.3)

9. Does voltage flow through a circuit, or is voltage established across a circuit? (34.3)

10. What is electrical resistance? (34.4)

11. Is electrical resistance greater in a short fat wire or a long thin wire? Explain. (34.4)

12. What is Ohm's law? (34.5)

13. If the voltage impressed across a circuit remains constant while the resistance doubles, what change occurs in the current? (34.5)

14. If the resistance of a circuit remains constant while the voltage across the circuit decreases to half its former value, what change occurs in the current? (34.5)

15. How does wetness affect the resistance of your body? (34.6)

16. Is water usually an insulator or a conductor? Does it vary? (34.6)

17. Why is it that a bird can perch without harm on a high voltage wire? (34.6)

18. What is the function of the third prong in a household electric plug? (34.6)

19. Distinguish between dc and ac. Which is produced by a battery and which is usually produced by a generator? (34.7)

20. Exactly what is it that travels at the speed of light in an electric circuit? (34.8)

21. What is a typical "drift" speed of electrons that make up a current in a typical dc circuit? In a typical ac circuit? (34.8)

22. From where do the electrons originate that flow in a typical electric circuit? (34.9)

23. What is power? (34.10)

24. Which of these is a unit of power and which is a unit of electrical energy: a watt, a kilowatt, or a kilowatt-hour? (34.10)

25. How many amperes flow through a 60 watt bulb when 120 volts are impressed across it? (34.10)

Activity

Batteries are made up of electric cells, which are composed of two unlike pieces of metal separated by a conducting solution. A simple 1.5-volt cell, equivalent to a flashlight cell, can be made by placing a strip of copper and a strip of zinc in a moist vegetable or piece of fruit as shown in Figure A. A lemon or banana works fine. Hold the ends of the strips close together, but not touching, and place the ends on your tongue. The slight tingle you feel and the metallic taste you experience result from a slight current of electricity pushed by the cell through the metal strips when your moist tongue closes the circuit. Try this and compare the results for different metals and different fruits and vegetables.

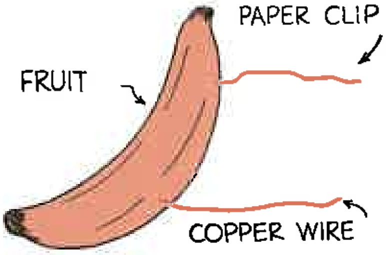

Fig. A

Think and Explain

1. Do an *ampere* and a *volt* measure the same thing, or different things? What are those things, and which is a flow and which is the cause of the flow?

2. Ten coulombs of charge pass a point in 5 seconds. What is the current at that point?

3. A battery does 18 joules of work on 3 cou-

lombs of charge. What voltage does it supply?

4. How much voltage is required to make 1 ampere flow through a resistance of 8 ohms?

5. What is the effect on current in a circuit if both the voltage and the resistance are doubled? If both are halved? Explain.

6. How much current moves through your fingers (resistance = 1200 ohms) when you place them against the terminals of a 6-volt battery?

7. Why do wires heat up when they carry electric current?

8. Why are thick wires rather than thin wires used to carry large currents?

9. Would you expect to find dc or ac in the dome lamp in an automobile? In a lamp in your home? Explain.

10. How many amperes flow in a 60-watt bulb that is rated for 120 volts when it is connected to a 120-volt circuit? How many amperes would flow if it were connected to 240 volts?

11. Use the relationship power = current × voltage to find out how much current is drawn by a 1200-watt hair dryer when it operates on 120 volts. Then use Ohm's law to find the resistance of the hair dryer.

12. The useful life of an automobile battery without recharging is given in terms of ampere-hours. A typical 12-volt battery has a rating of 60 ampere-hours, which means that a current of 60 amperes can be drawn for 1 hour, 30 amperes can be drawn for 2 hours, 15 amperes can be drawn for 4 hours, and so forth. Suppose you forget to turn off the headlights in a parked automobile. If each of the two headlights draws 3 amperes, how long will it be before the battery is "dead"?

35 Electric Circuits

Mechanical things seem to be easier to figure out for most people than electrical things. Maybe this is because most people have had experience playing with blocks and mechanical toys when they were children. If you are among the many who have had far less direct experience with the inner workings of electrical devices, as compared to mechanical gadgets, you are encouraged to put extra effort into the laboratory part of this course. This is because an understanding of electric circuits is helped by hands-on experience. This experience can be fun.

35.1 A Battery and a Bulb

Take apart a flashlight, the ordinary kind shown in Figure 35-1. If you don't have any spare pieces of wire around, cut some strips from some aluminum foil that you probably have in one of your kitchen drawers. Try to light up the bulb with a single battery* and a couple of pieces of wire or foil.

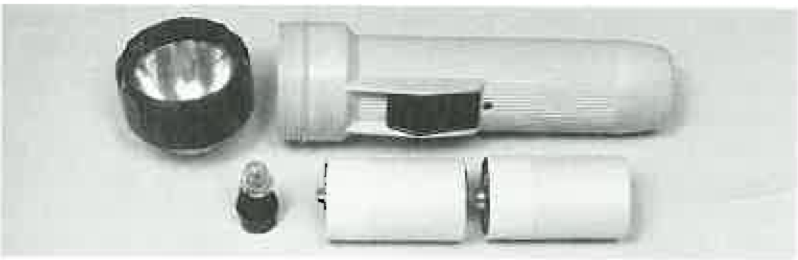

Fig. 35-1 A flashlight taken apart.

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* Strictly speaking, a battery consists of two or more cells. What most people call a flashlight battery is more properly called a flashlight dry cell. To conform with popular usage, this chapter uses the term *battery* to mean either a single cell or series of cells.

Some of the ways you *can* light the bulb and some of the ways you *can't* light it are shown in Figure 35-2. The important thing to note is that there must be a complete path, or **circuit**, from the positive terminal at the top of the battery to the negative terminal, which is the bottom of the battery. Electrons flow from the negative part of the battery through the wire or foil to the bottom (or side) of the bulb, through the filament inside the bulb, and out the side (or bottom) and through the other piece of wire or foil to the positive part of the battery. The current then passes through the interior of the battery to complete the circuit.

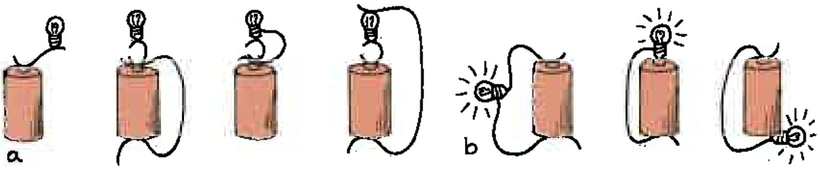


Fig. 35-2 (a) Unsuccessful ways to light a bulb. (b) Successful ways to light a bulb.

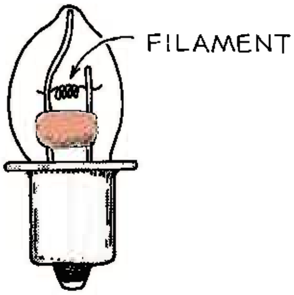


Fig. 35-3 Electrons do not pile up inside a bulb, but instead flow through its filament.

It is a bit misleading to say that electrons flow "out of" the battery, or "into" the bulb; a better description is to say they flow *through* these devices. The flow of charge in a circuit is analogous to the flow of water in a closed system of pipes. The battery is analogous to a pump, the wires to the pipes, and the bulb to any device that operates when the water is flowing. The water flows through both the pump itself and the circuit it connects. It doesn't "squash up" and concentrate in certain regions, but flows continuously. Electric current behaves the same way.

35.2 Electric Circuits

Any path along which electrons can flow is a circuit. For a continuous flow of electrons, there must be a complete circuit with no gaps. A gap is usually provided by an electric switch that can be opened or closed to either cut off or allow electron flow.

The water analogy is quite useful for gaining a conceptual understanding of electric circuits, but it does have some limitations. An important one is that a break in a water pipe results in water spilling from the circuit, whereas a break in an electric circuit results in a complete stop in the flow of electricity. Another difference has to do with turning current off and on. When you *close* an electrical switch that connects the circuit, you allow current to flow in much the same way as you allow water to flow by *opening* a faucet. Opening a switch stops the flow of electricity. An electric circuit must be closed for electricity to flow. Opening a water faucet, on the other hand, starts the flow of water. Except for these and some other differences, thinking of electric current in terms of water current is a useful way to study electric circuits.

Most circuits have more than one device that receives electrical energy. These devices are commonly connected in a circuit in two ways, *series* or *parallel*. When connected **in series**, they form a single pathway for electron flow between the terminals of the battery, generator, or wall socket (which is simply an extension of these terminals). When connected **in parallel**, they form branches, each of which is a separate path for the flow of electrons. Both series and parallel connections have their own distinctive characteristics. This chapter briefly treats circuits with these two types of connections.

35.3 Series Circuits

Figure 35-4 shows three lamps connected in series with a battery. This is an example of a simple **series circuit**. When the switch is closed, a current exists almost immediately in all three lamps. The current does not "pile up" in any lamp but flows *through* each lamp. Electrons that make up this current leave the negative terminal of the battery, pass through each of the resistive filaments in the lamps in turn, and then return to the positive terminal of the battery (the same amount of current passes through the battery). This is the only path of the electrons through the circuit. A break anywhere in the path results in an open circuit, and the flow of electrons ceases. Burning out of one of the lamp filaments or simply opening the switch could cause such a break.

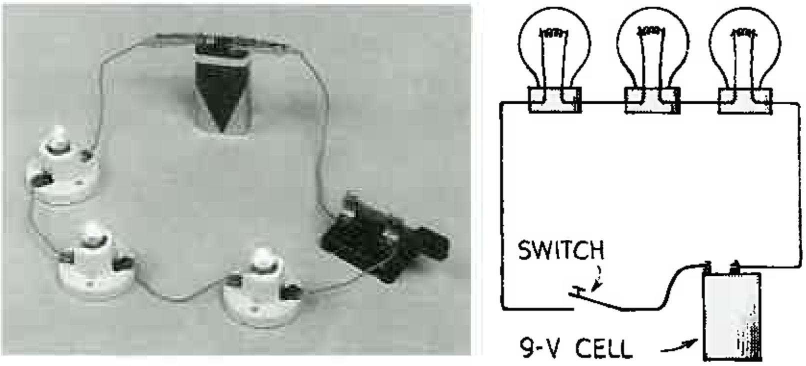


Fig. 35-4 A simple series circuit. The 9-volt battery provides 3 volts across each lamp.

The circuit shown in Figure 35-4 illustrates the following important characteristics of series connections:

1. Electric current has but a single pathway through the circuit. This means that the current passing through the resistance of each electrical device is the same.
2. This current is resisted by the resistance of the first device, the resistance of the second, and the third also, so that the total resistance to current in the circuit is the sum of the individual resistances along the circuit path.
3. The current in the circuit is numerically equal to the voltage supplied by the source divided by the total resistance of the circuit. This follows Ohm's law.
4. The *voltage drop*, or potential difference, across each device is proportional to its resistance. This follows from the fact that more energy is used to move a unit of charge through a large resistance than through a small resistance.
5. The total voltage impressed across a series circuit divides among the individual electrical devices in the circuit so that the sum of the voltage drops across each individual device is equal to the total voltage supplied by the source. This follows from the fact that the amount of energy used to move each unit of charge through the entire circuit equals the sum of the energies used to move that unit of charge through each electrical device in turn.

▶ Questions

1. What happens to current in other lamps if one lamp in a series circuit burns out?
2. What happens to the light intensity of each lamp in a series circuit when more lamps are added to the circuit?

It is easy to see the main disadvantage of a series circuit: if one device fails, current in the whole circuit ceases. Some cheap Christmas tree lights are connected in series. When one lamp burns out, it's "fun and games" (or frustration) trying to find which bulb to replace.

▶ Answers

1. If one of the lamp filaments burns out, the path connecting the terminals of the voltage source will break and current will cease. All lamps will go out.
2. The addition of more lamps in a series circuit results in a greater circuit resistance. This decreases the current in the circuit and therefore in each lamp, which causes dimming of the lamps. Energy is divided among more lamps so the voltage drop across each lamp will be less.

Most circuits are wired so that it is possible to operate electrical devices independently of each other. In your home, for example, a lamp can be turned on or off without affecting the operation of other lamps or electrical devices. This is because these devices are connected not in series but in parallel to one another.

35.4 Parallel Circuits

Figure 35-5 shows three lamps connected to the same two points A and B. This is an example of a simple **parallel circuit**. Electrical devices connected in parallel are connected to the same two points of an electric circuit. Electrons leaving the negative terminal of the battery need travel through only *one* lamp filament before returning to the positive terminal of the battery. In this case, current branches into three separate pathways from A to B. A break in any one path does not interrupt the flow of charge in the other paths. Each device operates independently of the other devices.

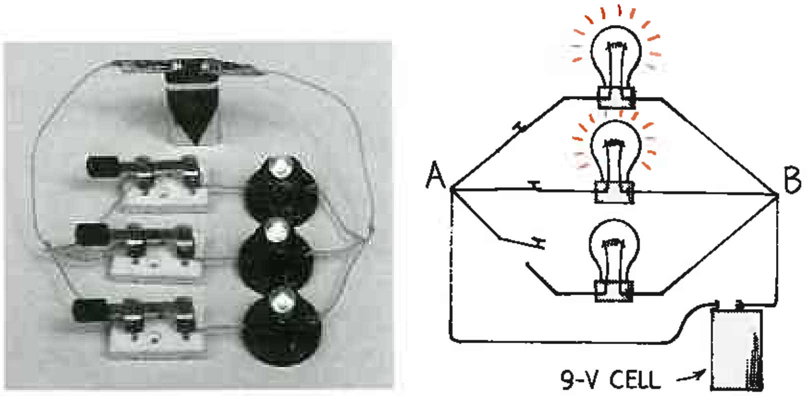
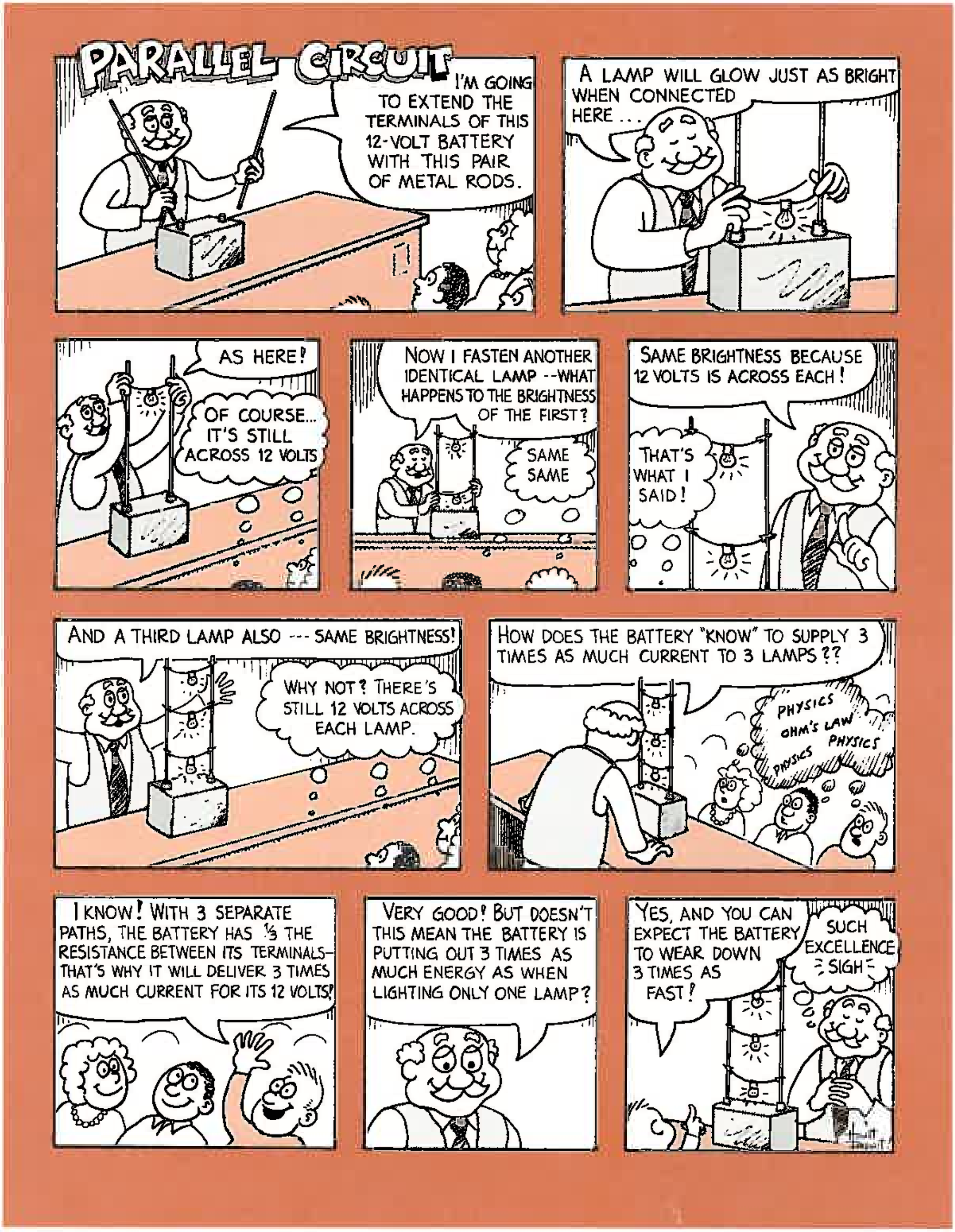


Fig. 35-5 A simple parallel circuit. A 9-volt battery provides 9 volts across each lamp.

The circuit shown in Figure 35-5 illustrates the following major characteristics of parallel connections:

1. Each device connects the same two points A and B of the circuit. The voltage is therefore the same across each device.
2. The total current in the circuit divides among the parallel branches. Current passes more readily into devices of low resistance, so the amount of current in each branch is inversely proportional to the resistance of the branch. This follows Ohm's law.


PARALLEL CIRCUIT
I'M GOING TO EXTEND THE TERMINALS OF THIS 12-VOLT BATTERY WITH THIS PAIR OF METAL RODS.
A LAMP WILL GLOW JUST AS BRIGHT WHEN CONNECTED HERE . . .
AS HERE!
OF COURSE... IT'S STILL ACROSS 12 VOLTS
NOW I FASTEN ANOTHER IDENTICAL LAMP --WHAT HAPPENS TO THE BRIGHTNESS OF THE FIRST?
SAME SAME
SAME BRIGHTNESS BECAUSE 12 VOLTS IS ACROSS EACH!
THAT'S WHAT I SAID!
AND A THIRD LAMP ALSO --- SAME BRIGHTNESS!
WHY NOT? THERE'S STILL 12 VOLTS ACROSS EACH LAMP.
HOW DOES THE BATTERY "KNOW" TO SUPPLY 3 TIMES AS MUCH CURRENT TO 3 LAMPS??
PHYSICS OHM'S LAW PHYSICS PHYSICS
I KNOW! WITH 3 SEPARATE PATHS, THE BATTERY HAS ⅓ THE RESISTANCE BETWEEN ITS TERMINALS— THAT'S WHY IT WILL DELIVER 3 TIMES AS MUCH CURRENT FOR ITS 12 VOLTS!
VERY GOOD! BUT DOESN'T THIS MEAN THE BATTERY IS PUTTING OUT 3 TIMES AS MUCH ENERGY AS WHEN LIGHTING ONLY ONE LAMP?
YES, AND YOU CAN EXPECT THE BATTERY TO WEAR DOWN 3 TIMES AS FAST!
SUCH EXCELLENCE ⁼SIGH⁼

3. The total current in the circuit equals the sum of the currents in its parallel branches.
4. As the number of parallel branches is increased, the overall resistance of the circuit is *decreased*. Overall resistance is lowered with each added path between any two points of the circuit. This means the overall resistance of the circuit is less than the resistance of any one of the branches.

▶ **Questions**

1. What happens to the current in other lamps if one of the lamps in a parallel circuit burns out?
2. What happens to the light intensity of each lamp in a parallel circuit when more lamps are added in parallel to the circuit?

35.5 Schematic Diagrams

Electric circuits are frequently described by simple diagrams, called **schematic diagrams**, that are similar to those of the last two figures. Some of the symbols used to represent certain circuit elements are shown in Figure 35-6. Resistance is shown by a zigzag line, and ideal resistanceless wires are shown with solid straight lines. A single cell battery is represented with a set of short and long parallel lines. The convention is to represent the

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▶ **Answers**

1. If one lamp burns out, the other lamps will be unaffected. The current in each branch, according to Ohm's law, is equal to (voltage)/(resistance), and since neither voltage nor resistance is affected in the branches, the current in those branches is unaffected. The total current in the overall circuit (the current through the battery) however, is decreased by an amount equal to the current drawn by the lamp in question before it burned out. But the current in any other single branch is unchanged.
2. The light intensity for each lamp is unchanged as other lamps are introduced (or removed). Only the total resistance and total current in the total circuit changes, which is to say, the current in the battery changes. (There is resistance in a battery also, which we assume is negligible here.) As lamps are introduced, more paths are available between the battery terminals, which effectively decreases total circuit resistance. This decreased resistance is accompanied by an increased current, the same increase that feeds energy to the lamps as they are introduced. Although changes of resistance and current occur for the circuit as a whole, no changes occur in any individual branch in the circuit.

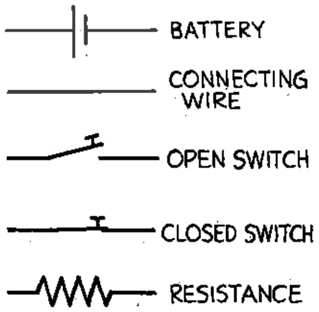

Fig. 35-6 Symbols of some common circuit devices.

positive terminal of the battery with a long line and the negative terminal with a short line. A two-cell battery is represented with a pair of such lines, a three-cell with three, and so on. Figure 35-7 shows schematic diagrams for the circuits of Figures 35-4 and 35-5.

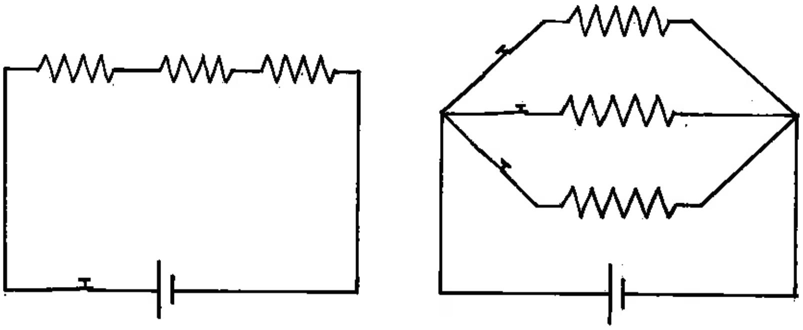

Fig. 35-7 Schematic diagrams. (Left) The circuit of Figure 35-4, with three lamps in series. (Right) The circuit of Figure 35-5, with three lamps in parallel.

35.6 Combining Resistors in a Compound Circuit

Sometimes it is useful to know the *equivalent resistance* of a circuit that has several resistors in its network. The equivalent resistance is the value of the single resistor that would comprise the same load to the battery or power source. The equivalent resistance can be found by the rules for adding resistors in series and parallel. For example, the equivalent resistance for a pair of 1-ohm resistors in series is simply 2 ohms.

The equivalent resistance for a pair of 1-ohm resistors in parallel is 0.5 ohm. (The equivalent resistance is *less* because the current has "twice the path width" when it takes the parallel path. In a similar way, the more doors that are open in an auditorium of people trying to exit, the *less* will be the resistance to migration.) The equivalent resistance for a pair of equal resistors in parallel is half the value of either resistor.

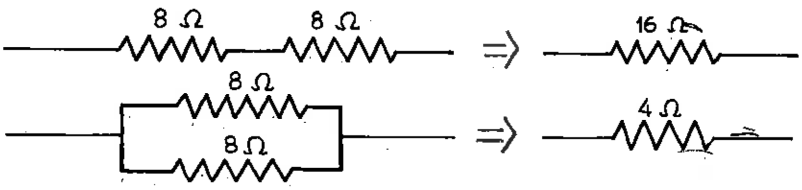

Fig. 35-8 (a) The equivalent resistance of two 8-ohm resistors in series is 16 ohms. (b) The equivalent resistance of two 8-ohm resistors in parallel is 4 ohms.

Figure 35-9 shows a combination of three 8-ohm resistors. The two in parallel are equivalent to a single 4-ohm resistor, which is in series to the 8-ohm resistor and adds to produce an equivalent resistance of 12 ohms. If a 12-volt battery were connected to these resistors, can you see from Ohm's law that the current through the battery would be 1 ampere? (In practice it would be less, for there is resistance inside the battery as well, called the *internal resistance*.)

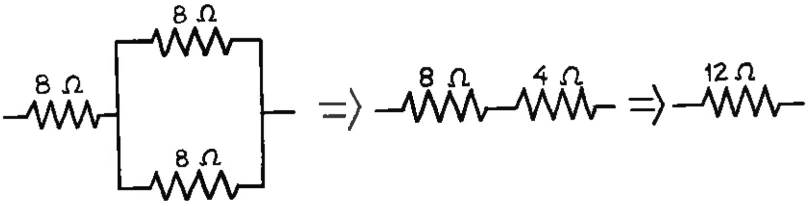

Fig. 35-9 The equivalent resistance of the circuit is found by combining resistors in successive steps.

Two more complex combinations are broken down in successive equivalent combinations in Figures 35-10 and 35-11. It's like a game: combine resistors in series by adding; combine a pair of equal resistors in parallel by halving.* The value of the single resistor left is the equivalent resistance of the combination.

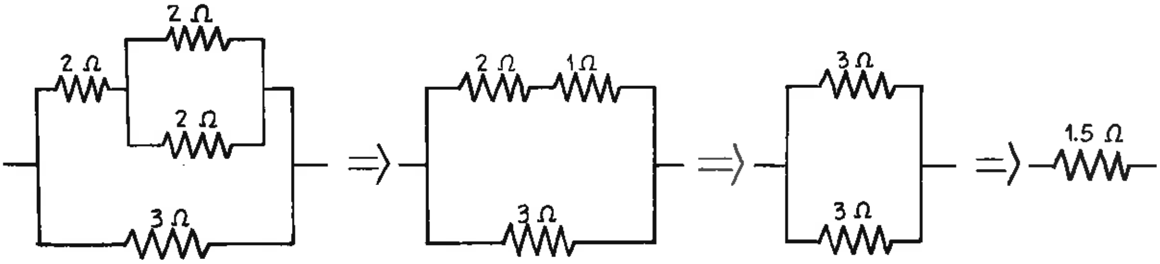

Fig. 35-10 The equivalent resistance of the top branch is 3 ohms, which is in parallel with the 3-ohm resistance of the lower branch. The overall equivalent resistance is 1.5 ohms.

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* For a pair of non-equal resistors in parallel, the equivalent resistance is found by taking the product of the pair and dividing by the sum of the pair. That is:

$$R_{\text{equivalent}} = \frac{R_1 R_2}{R_1 + R_2}$$

This rule of "product divided by sum" holds only for two resistors in parallel. For three or more parallel resistors, you can do a pair at a time (as is done in Figures 35-10 and 35-11), or use the more general formula:

$$1/R_{\text{equivalent}} = 1/R_1 + 1/R_2 + 1/R_3 \text{ and so on}$$

Details can be found in other physics textbooks.

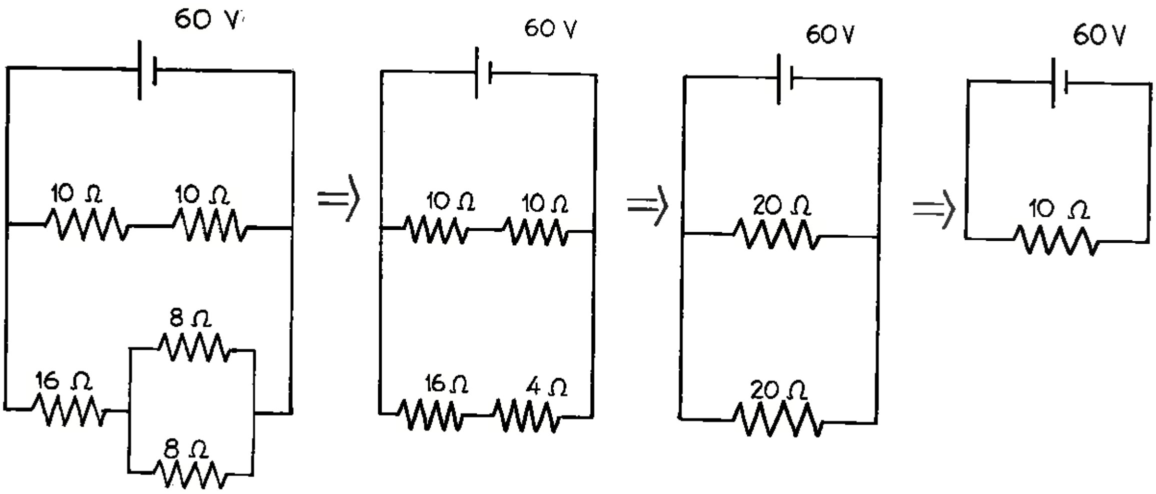

Fig 35-11 Schematic diagrams for an arrangement of various electric devices. The equivalent resistance of the circuit is 10 ohms.

▶ **Questions**

The following questions are based on the schematic diagrams in Figure 35-11.

1. What is the current in amperes through the battery? (Neglect the internal resistance of the battery.)
2. What is the current in amperes through the pair of 10-ohm resistors?
3. What is the current in amperes through each of the 8-ohm resistors?
4. How much power is provided by the battery?

▶ **Answers**

1. The current in the battery (or total current in the circuit) is 6 A. You can get this from Ohm's law: current = (voltage)/(resistance) = (60 V)/(10 ohms) = 6 A. You know that the equivalent resistance of the circuit is 10 ohms from step (d) in the figure.
2. Half the total circuit current, 3 A, will flow through the pair of 10-ohm resistors. You know this because you can see in step (c) of the figure that both branches have equal resistances. This means that the total circuit current will divide equally between the upper and lower branches.
3. The current through the pair of 8-ohm resistors is 3 A, and the current through each is therefore 1.5 A. This is because the 3-A current divides equally through these equal resistances.
4. The battery supplies 360 watts. This is from the relationship

$$\text{power} = \text{current} \times \text{voltage} = (6\text{ A}) \times (60\text{ V}) = 360\text{ watts}$$

This power will be dissipated among all the resistors in the circuit.

35.7 Parallel Circuits and Overloading

Electricity is usually fed into a home by way of two lead wires called *lines*. These lines are very low in resistance and are connected to wall outlets in each room. About 110 to 120 volts are impressed on these lines by generators at the power utility. This voltage is applied to appliances and other devices that are connected in parallel by plugs to these lines.

As more devices are connected to the lines, more pathways are provided for current. What effect do the additional pathways produce? The answer is, a lowering of the combined resistance of the circuit. Therefore, a greater amount of current occurs in the lines. Lines that carry more than a safe amount of current are said to be *overloaded*. The resulting heat may be sufficient to melt the insulation and start a fire.

You can see how overloading occurs by considering the circuit in Figure 35-12. The supply line is connected to an electric toaster that draws 8 amperes, to an electric heater that draws 10 amperes, and to an electric lamp that draws 2 amperes. When only the toaster is operating and drawing 8 amperes, the total line current is 8 amperes. When the heater is also operating, the total line current increases to 18 amperes (8 amperes to the toaster and 10 amperes to the heater). If you turn on the lamp, the line current increases to 20 amperes. Connecting any more devices increases the current still more.

To prevent overloading in circuits, *fuses* are connected in series along the supply line. In this way the entire line current must pass through the fuse. The fuse shown in Figure 35-13 is constructed with a wire ribbon that will heat up and melt at a given current. If the fuse is rated at 20 amperes, it will pass 20 amperes, but no more. A current above 20 amperes will melt the fuse, which "blows out" and breaks the circuit. Before a blown fuse is replaced, the cause of overloading should be determined and remedied. Often, insulation that separates the wires in a circuit wears away and allows the wires to touch. This effectively shortens the path of the circuit, and is called a *short circuit*. A short circuit draws a dangerously large current because it bypasses the normal circuit resistance.

Circuits may also be protected by *circuit breakers*, which use magnets or bimetallic strips to open the switch. Utility companies use circuit breakers to protect their lines all the way back to the generators. Circuit breakers are used instead of fuses in modern buildings because they do not have to be replaced each time the circuit is opened. Instead, the switch can simply be moved back to the "on" position after the problem has been corrected.

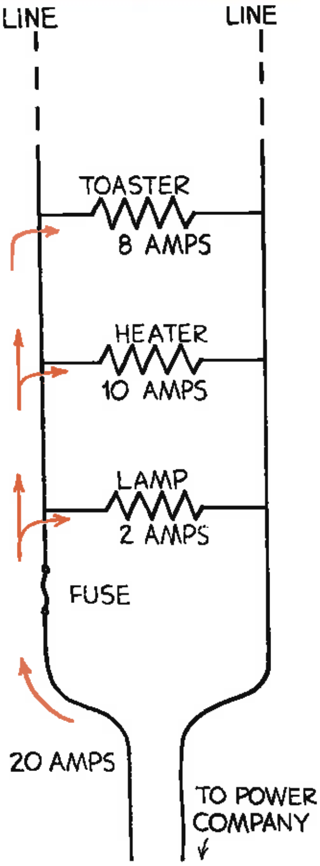

Fig. 35-12 Circuit diagram for appliances connected to a household supply line.

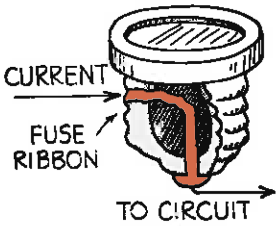

Fig. 35-13 A safety fuse.

35 Chapter Review

Concept Summary

Any path along which electrons can flow is a circuit.

- A complete circuit is needed to maintain a continuous electron flow.

In a series circuit, electrical devices form a single pathway for electron flow.

- A break anywhere in the path stops the electron flow in the entire circuit.
- The total resistance is equal to the sum of individual resistances along the current path.
- The current is equal to the voltage divided by the total resistance.
- The voltage drop across each device is proportional to its resistance.
- The sum of voltage drops across the resistance of each individual device is equal to the total voltage.

In a parallel circuit, electrical devices form branches, each of which provides a separate path for the flow of electrons.

- Each device connects the same two points of the circuit; the voltage is the same across each device.
- The amount of current in each branch is inversely porportional to the resistance of the branch.
- The total current is equal to the sum of the currents in each branch.

Electric circuits are often described by schematic diagrams, in which each element of the circuit is represented by a symbol.

In a circuit with several resistors, the equivalent resistance is the value of the single resistor that would comprise the same load to the battery or power source.

- For resistors in series, the equivalent resistance is the sum of their values.
- For resistors in parallel, the equivalent resistance is less than the value of any individual resistor.

Lines carrying an unsafe amount of current are overloaded.

- To prevent overloading, fuses are connected in series. Any current above the rating of the fuse will "blow out" the fuse and break the circuit.
- A short circuit is often caused by faulty wire insulation.

Important Terms

circuit (35.1)
in parallel (35.2)
in series (35.2)
parallel circuit (35.4)
schematic diagram (35.5)
series circuit (35.3)

Review Questions

1. Do electrons flow from a battery into a circuit or through both the battery and the circuit it connects? (35.1)

2. Why must there be no gaps in an electric circuit? (35.1)

3. Distinguish between a series circuit and a parallel circuit. (35.2)

4. If three lamps are connected in series to a 6-volt battery, how many volts are impressed across each lamp? (35.3)

5. If one of three lamps blows out when connected in series, what happens to the current in the other two? (35.3)

6. If three lamps are connected in parallel to a 6-volt battery, how many volts are impressed across each lamp? (35.4)

7. If one of three lamps blows out when connected in parallel, what happens to the current in the other two? (35.4)

8. a. In which case will there be more current in each of three lamps—if they are connected to the same battery in series or in parallel?
   b. In which case will there be more voltage across each lamp? (35.4)

9. What happens to the total circuit resistance when more devices are added to a series circuit? To a parallel circuit? (35.6)

10. What is the equivalent resistance of a pair of 8-ohm resistors in series? In parallel? (35.6)

11. Why does the total circuit resistance decrease when more devices are added to a parallel circuit? (35.6)

12. What does it mean to say that lines in a home are overloaded? (35.7)

13. What is the function of fuses in a circuit? (35.7)

14. Why will too many electrical devices operating at one time often blow a fuse? (35.7)

15. What is meant by a short circuit? (35.7)

Think and Explain

1. Sometimes you hear someone say that a particular appliance "uses up" electricity. What is it that the appliance actually "uses up," and what becomes of it?

2. Why are household appliances almost never connected in series?

3. As more and more lamps are connected in series to a flashlight battery, what happens to the brightness of the lamps?

4. As more and more lamps are connected in parallel to a battery, and if the current does not produce heating inside the battery, what happens to the brightness of the lamps?

5. When excessive charge flows in a battery, battery resistance increases. This lowers the voltage that is supplied to the external circuit. If too many lamps are connected in parallel across a battery, will their brightness diminish? Explain.

6. Consider the combination series and parallel circuit shown in Figure A.
   a. Identify the parallel part of the circuit. What is the equivalent resistance of this part? In other words, what single resistance could take their place and not change the total current from the battery?
   b. What is the equivalent resistance of all the resistors? In other words, what single resistance could take their place without changing the current from the battery?

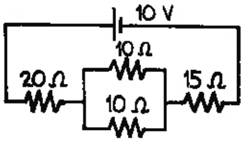

Fig. A

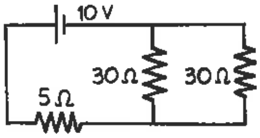

Fig. B

7. What is the current in the battery of the circuit shown in Figure B? (What must you find before you can calculate the current?)

8. The rear window defrosters on automobiles are made up of several strips of heater wire connected in parallel. Consider the case of four wires, each of 6 ohms resistance, connected to 12 volts.
   a. What is the equivalent resistance of the four wires? (Consider the wires to be two groups of two.)
   b. What is the total current drawn?

9. How does the line current compare to the total currents of all devices connected in parallel?
   Line current = sum of currents in branches.

10. Why should you not use a copper penny in place of a safety fuse that blows out?

36 Magnetism

Magnets are fascinating. Bring a pair close together and they snap together and stick. Turn one of the magnets around and they will repel each other. A magnet will stick to a refrigerator door, but it won't stick to an aluminum pan. Magnets come in all shapes and sizes. They are popular as toys, are utilized as compasses, and are essential elements in electric motors and generators. Magnetism is very common to all that you see, for it is an essential ingredient of light itself.

The term *magnetism* stems from certain metallic rocks called *lodestones* found by the early Greeks more than 2000 years ago in the region of Magnesia. In the twelfth century, the Chinese were using them for navigating ships. In the eighteenth century, the French physicist Charles Coulomb demonstrated that they obeyed the inverse-square law.

Magnetism was thought to be independent of electricity until 1820 when a Danish physics professor named Hans Christian Oersted made a remarkable discovery. Oersted discovered in a classroom demonstration that an electric current deflects a compass needle. He was the first to announce that magnetism was related to electricity.* This discovery ushered in a whole new technology, including electric power, radio, and television.

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* We can only speculate about how often such relationships become evident when they "aren't supposed to" and are dismissed as "something wrong with the apparatus." Oersted, however, had the insight characteristic of a good physicist to see that nature was revealing another of its secrets.