34 ELECTRIC CURRENT

THE BIG IDEA Electric current is related to the voltage that produces it and the resistance that opposes it.

The previous chapter discussed the concept of electric potential, or voltage, in terms of energy per charge. We'll see in this chapter that voltage can be thought of as an "electric pressure" that produces 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 the charges flow to and fro, it is called *alternating current* (AC). The rate at which energy is transferred by electric current is *power*. These ideas are better understood if you know how they relate to one another. Let's begin with the flow of electric charge.

discover!

How Can You Make a Simple Voltage Source?

1. Soak a piece of paper towel in a salt solution or vinegar and place it between a dime and a penny.
2. Attach one lead from a galvanometer to each of the coins.
3. Now attach the lead that was originally attached to the dime to the penny, and vice versa.

Analyze and Conclude

1. **Observing** Describe the galvanometer reading when the leads were brought in contact with the coins. What happened when the leads were reversed?
2. **Predicting** What do you think would happen if a number of these dime-and-penny cells were connected in series? (That is, placed end to end with dimes touching pennies.)
3. **Making Generalizations** How do you think voltage sources such as the batteries used in portable electronic devices are constructed?

34.1 Flow of Charge

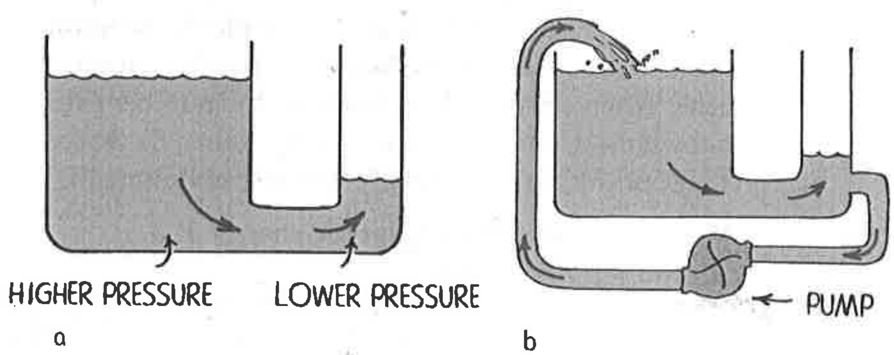
Recall that heat flows through a conductor when a difference in temperature exists between its ends. Heat flows from the end of higher temperature to the end of lower temperature. When both ends reach the same temperature, the flow of heat ceases.

Charge flows in a similar way. **When the ends of an electric conductor are at different electric potentials, charge flows from one end to the other.** Charge flows when there is a **potential difference,** or difference in potential (voltage), between the ends of a conductor. The flow of charge will continue until both ends reach a common potential. When there is no potential difference, there is no longer a flow of charge through the conductor. 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 that is charged to a high potential, a surge of charge would flow through the wire. The flow would be brief, however, for the sphere of the generator 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 keep one end at a higher potential than the other. The situation is analogous to the flow of water from a higher reservoir to a lower one, as shown in Figure 34.1a. Water will flow in a pipe that connects the reservoirs only as long as a difference in water level exists. 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 the two ends 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, as shown in Figure 34.1b. Then there will be a continual difference in water pressures and a continual flow of water. The same is true of electric current.

CONCEPT CHECK: What happens when the ends of a conductor are at different electrical potentials?

Electrons in a wire are like water in a pipe; whenever a little water enters one end, almost immediately the same amount of water exits the other end.



◀ **FIGURE 34.1**
a. Water flows from higl pressure to lower pressu The flow will cease wher the difference in pressur ceases. **b.** Water contin to flow because a differe in pressure is maintainec with the pump.

34.2 Electric Current

Electric current is the flow of electric charge. In solid conductors the electrons carry the charge through the circuit because they 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 within the conductor. In fluids, such as the electrolyte in a car battery, positive and negative ions as well as electrons may compose the flow of electric charge.

Measuring Current Electric current is measured in **amperes,** for which the SI unit is symbol A.[34.2] An ampere is the flow of 1 coulomb of charge per second. (Recall that 1 coulomb, the standard unit of charge, is the electric charge of 6.24 billion billion electrons.) In a wire that carries a current of 5 amperes, for example, 5 coulombs of charge pass through any cross section in the wire each second. That's a lot of electrons! In a wire that carries 10 amperes, twice as many electrons pass any cross section each second. Figure 34.2 shows a simplified view of electrons flowing in a wire.

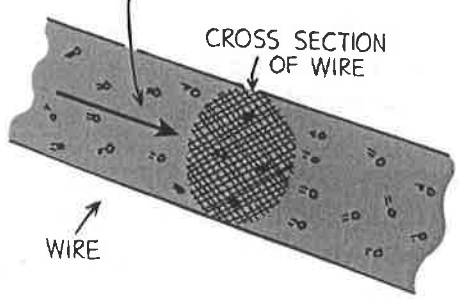


FIGURE 34.2 ▶ When the rate of flow of charge past any cross section is 1 coulomb (6.24 billion billion electrons) per second, the current is 1 ampere.

Net Charge of a Wire ✓ **A current-carrying wire has a net electric charge of zero.** While the current is flowing, 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. When electrons flow in a wire, the number entering one end is the same as the number leaving the other. So we see that the net charge of the wire is normally zero at every moment.

CONCEPT CHECK What is the net flow of electric charge in a current-carrying wire?

34.3 Voltage Sources

Charges do not flow unless there is a potential difference. A sustained current requires a suitable "electric 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 is not a good voltage source because when the spheres are connected by a conductor, the potentials equalize in a single brief surge of moving charges. It is not practical. Batteries and generators, however, are capable of maintaining a continuous flow.

FIGURE 34.3 ▲
Each coulomb of charge that is made to flow in a cuit that connects the er of this 1.5-volt flashlight is energized with 1.5 jou

Steady Voltage Sources ✓ **Voltage sources such as batteries and generators supply energy that allows charges to move steadily.** In a battery, a chemical reaction occurring inside releases electrical energy.[34.3.1] Generators—such as the alternators in automobiles—convert mechanical energy to electrical energy, as will be discussed in Chapter 37. The electrical potential energy produced by whatever means is available at the terminals of the battery or generator. The potential energy per coulomb of charge available to electrons moving between terminals is the voltage (sometimes called the *electromotive force,* or *emf*). The voltage provides the "electric pressure" to move electrons between the terminals in a circuit.

Power utilities use electric generators to provide the 120 volts delivered to home outlets. The alternating potential difference between the two holes in the outlet averages 120 volts. When the prongs of a plug are inserted into the outlet, an average electric "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.

Distinguishing Between Current and Voltage 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* the pipe or between its ends. Water flows from the high-pressure end to the low-pressure end. Only the water flows, not the pressure. Similarly, charges flow *through* a circuit because of an applied voltage *across* the circuit.[34.3.2] 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.

CONCEPT CHECK **What are two voltage sources used to provide the energy that allows charges to move steadily?**

Go Online
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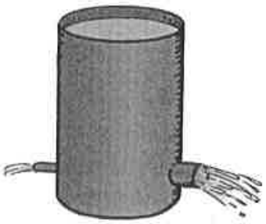
For: Links on batteries
Visit: www.SciLinks.org
Web Code: csn – 3403

ɜURE 34.4 ▼
r a given pressure, more ter passes through a ge pipe than a small one. nilarly, for a given volt- e, more electric current sses through a large- ımeter wire than a small- ımeter one.

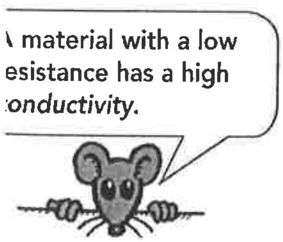


34.4 Electric Resistance

The amount of charge that flows in a circuit depends on the voltage provided by the voltage source. The current also depends on the resistance that the conductor offers to the flow of charge—the **electric resistance.** This is similar to the rate of water flow in a pipe, which depends not only on the pressure difference between the ends of the pipe but on the resistance offered by the pipe itself, as shown in Figure 34.4. ✅ **The resistance of a wire depends on the *conductivity* of the material used in the wire (that is, how well it conducts) and also on the thickness and length of the wire.**

Thick wires have less resistance than thin wires. Longer wires have more resistance than short wires. In addition, electric 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.[34.4.1]

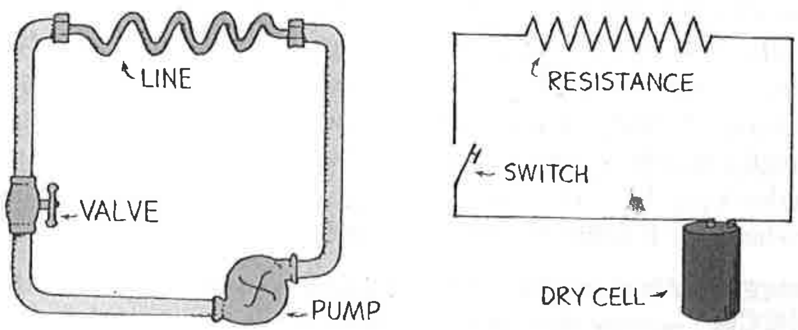
The resistance of some materials becomes zero at very low temperatures, a phenomenon known as **superconductivity.** Certain metals acquire superconductivity (zero resistance to the flow of charge) at temperatures near absolute zero. Since 1987, superconductivity at "high" temperatures (above 100 K) has been found in a variety of nonmetallic compounds. Once electric current is established in a superconductor, the electrons flow indefinitely.



Electric resistance is measured in units called **ohms,**[34.4.2] after Georg Simon Ohm (1789–1854), a German physicist who tested different wires in circuits to see what effect the resistance of the wire had on the current.

CONCEPT CHECK **What factors affect the resistance of a wire?**

FIGURE 34.5 ▶
A simple hydraulic circuit is analogous to an electric circuit. A circuit is any complete path along which charge can flow.



34.5 Ohm's Law

The relationship among voltage, current, and resistance is called **Ohm's law.**[34.5] **Ohm's law states that the 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,

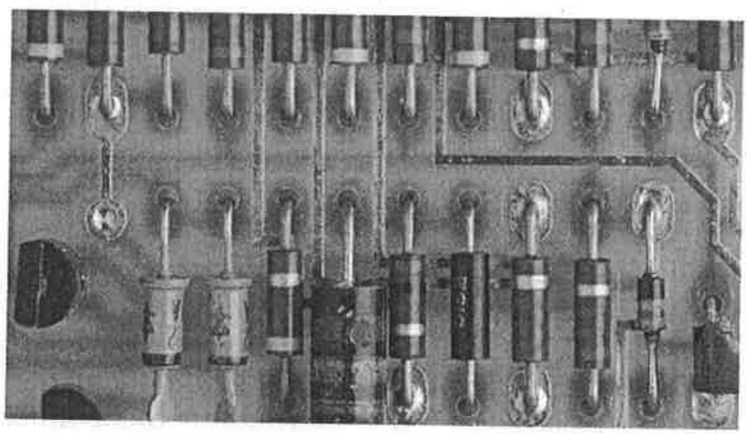
$$\text{current} = \frac{\text{voltage}}{\text{resistance}}$$

Using *I* for current, *V* voltage, and *R* for res tance, Ohm's law reac $I = V/R$.

The relationship among the units of measurement for these three quantities is as follows:

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

For a given circuit of constant resistance, current and voltage are proportional. This means that you'll get twice the current through a circuit for twice the voltage across the circuit. 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.



◀ **FIGURE 34.6**
The stripes on these resistors are color coded to indicate the resistance in ohms.

Using specific values, a potential difference of 1 volt impressed (imposed) 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 lightbulb 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. The current inside electric devices such as radio and television receivers is regulated by circuit elements called *resistors,* whose resistance may range from a few ohms to millions of ohms.

think!

How much current is drawn by a lamp that ha a resistance of 100 ohms when a voltage of 50 vol is impressed across it?
Answer: 34.5

CONCEPT CHECK **What does Ohm's law state?**

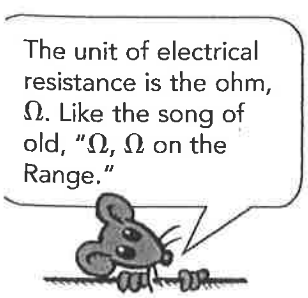
34.6 Ohm's Law and Electric Shock

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

The Body's Resistance 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 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 (amperes)	Effect
0.001	Can be felt
0.005	Painful
0.010	Involuntary muscle contractions (spasms)
0.015	Loss of muscle control
0.070	If through the heart, serious disruption; probably fatal if current lasts for more than 1 second



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 you are standing on the ground, there is a 120-volt "electric pressure" between your hand and the ground. The soles of your shoes normally provide a very large resistance between your feet and the ground, so the current would probably not be enough to do serious harm. But if you are standing barefoot in a wet bathtub connected through its plumbing to the ground, the resistance between you and the ground is very small. Your overall resistance is lowered so much that the 120-volt potential difference may produce a harmful current through your body.

Drops of water that collect around the on/off switches 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

FIGURE 34.7 ▲
Handling a wet hair dryer can be like sticking your fingers into a live socket.

FIGURE 34.8 ▲
The bird can stand harmlessly on one wire of high potential, but it better not grab a neighboring wire!

reduce the electric resistance. There is also 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 electric devices while taking a bath is extremely dangerous.

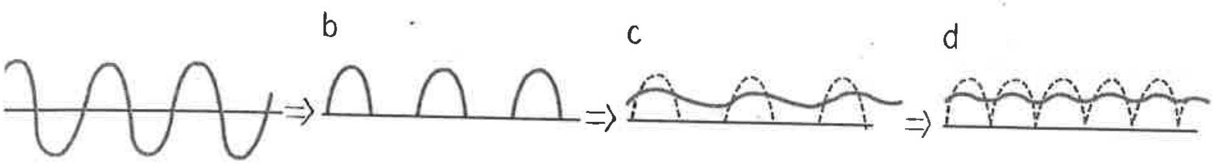
High-Voltage Wires You probably have seen birds perched on high-voltage wires like the one in Figure 34.8. Every part of the bird's body is at the same high potential as the wire, and it feels no ill effects. For the bird to receive a shock, there must be a *difference* in potential between one part of its body and another part. Most of the current will then pass along the path of least electric resistance connecting these two points.

Suppose you fall from a bridge and manage 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 thousands of 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 appreciable difference in electric potential between your hands. If, however, you reach over with one hand and grab onto a wire of different potential, ZAP!!

Ground Wires Mild shocks occur when the surfaces of appliances are at an electric potential different from that of the surfaces of other nearby devices. If you touch surfaces of different potentials, you become a pathway for current. To prevent this problem, the outsides of electric appliances are connected to a ground wire, which is connected to the round third prong of a three-wire electric plug, shown in 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. 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.

FIGURE 34.9 ▼
The third prong connects the body of the appliance directly to ground. Any charge that builds up on a appliance is therefore con ducted to the ground.

FIGURE 34.11 ▼
a. When input to a diode is AC, **b.** output is pulsating DC.
c. Charging and discharging of a capacitor provides continuous and smoother current. **d.** In practice, a pair of diodes are used so there are no gaps in current output.



34.8 Converting AC to DC

The current in your home is AC. The current in a battery-operated device, such as a laptop computer or cell phone, is DC. ✓ **With an AC–DC converter, you can operate a battery-run device on AC instead of batteries.** In addition to a transformer to lower the voltage (Chapter 37), the converter uses a **diode,** a tiny electronic device that acts as a one-way valve to allow electron flow in only one direction. Since alternating current vibrates in two directions, only half of each cycle will pass through a diode (Figures 34.11a and 34.11b). The output is a rough DC, off half the time. To maintain continuous current while smoothing the bumps, a capacitor is used (Figure 34.11c).

Recall from the previous chapter that a capacitor acts as a storage reservoir for charge. Just as it takes time to raise or lower the water level in a reservoir, it takes time to add or remove electrons from the plates of a capacitor. A capacitor therefore produces a retarding effect on changes in current flow. It smooths the pulsed output.

familiar diode is the
ght-emitting diode
ED) seen on clocks
nd instrument panels.
solar cell is an LED
reverse—it absorbs
ght and produces
ectricity.

CONCEPT CHECK How can you operate a battery-run device on AC?

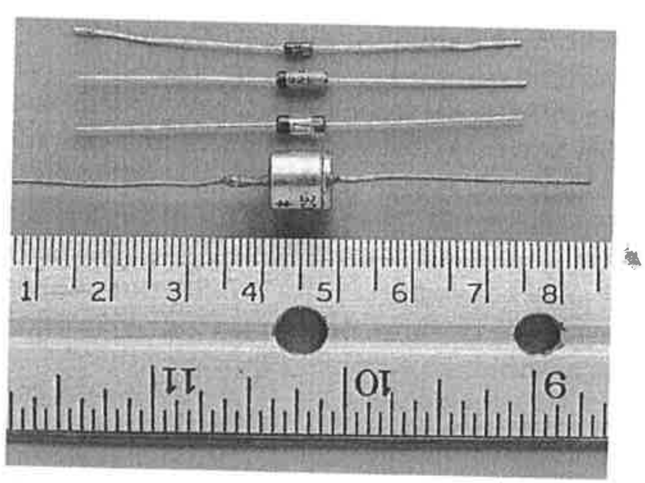


FIGURE 34.12 ▶
Diodes are tiny devices that allow electrons to flow in only one direction.

34.9

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34.9 The Speed of Electrons in a Circuit

When you flip on the light switch on your wall and the circuit is completed, the lightbulb appears to glow immediately. Energy is transported through the connecting wires at nearly the speed of light. The electrons that make up the current, however, do not move at this high speed.

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 net flow in any one direction. But when a battery or generator is connected, an electric field is established inside the wire. It is a pulsating electric field that can travel through a circuit at nearly the speed of light. The electrons continue their random motions in all directions while simultaneously being nudged along the wire by the electric field.

The conducting wire acts as a guide or "pipe" for electric field lines, as you can see in Figure 34.13. In the space outside the wire, the electric field has a pattern determined by the location of electric charges, including charges in the wire. Inside the wire, the electric field is directed along the wire. If the voltage source is DC, like the battery shown in Figure 34.13, the electric field lines are maintained in one direction in the conductor.

Caution: Don't short out the terminals of a battery as shown in Figure 34.13. If you touch both terminals with a metal wrench, for instance, you can create a spark that can ignite hydrogen gas in the battery and send pieces of battery and acid flying.

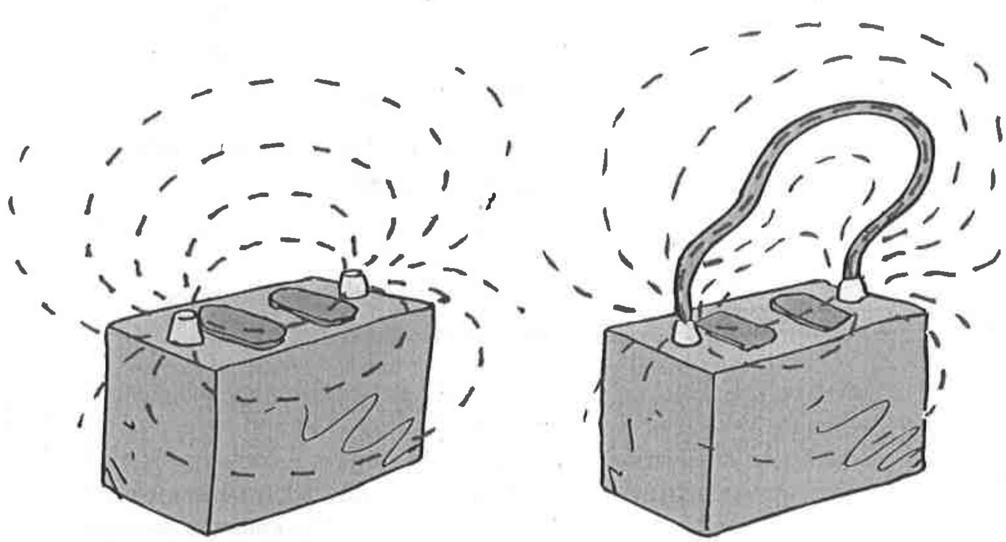
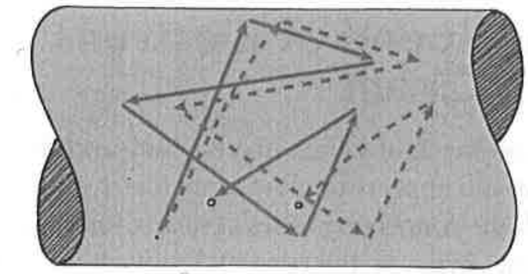


FIGURE 34.13 ▲
The electric field lines between the terminals of a battery are directed through a conductor, which joins the terminals.

FIGURE 34.14 ▶
The solid lines depict a random path of an electron bouncing off atoms in a conductor. The dashed lines show an exaggerated view of how this path changes when an electric field is applied. The electron drifts toward the right with an average speed less than a snail's pace.



Conduction electrons are accelerated by the field. Before the electrons gain appreciable speed, they "bump into" the anchored metallic ions in their paths and transfer some of their kinetic energy to them. This is why current-carrying wires become hot. ✓ **In a current-carrying wire, 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 electric 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 about three hours for an electron to travel through 1 meter of wire.

In an AC circuit, the conduction electrons don't make any net progress in any direction. In a single cycle they drift a tiny fraction of a centimeter in one direction, and then the same tiny distance in the opposite direction. Hence they oscillate rhythmically to and fro about relatively fixed positions. When you talk to your friend on a conventional 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. (In a cell phone, as you'll see in Chapter 37, the electrons dance to the rhythmic pattern of electromagnetic waves in the air.)

CONCEPT CHECK: Why is the drift speed of electrons in a current-carrying wire extremely low?

Link to ELECTROCHEMISTRY

Electrolysis Electrochemistry is about electrical energy and chemical change. Molecules in a liquid can be broken apart and separated by the action of electric current. This is *electrolysis*. A common example is passing an electric current through water, separating water molecules into their hydrogen and oxygen components. This common process is also at work when a car battery is recharged. Electrolysis is also used to produce metals from ores. Aluminum is a familiar metal produced by electrolysis. Aluminum is common today, but before the advent of its production by electrolysis in 1886, aluminum was much more expensive than silver or gold!

34.10 The Source of Electrons in a Circuit

In a hardware store you can buy a water hose that is empty of water. But you can't buy a piece of wire, an "electron pipe," that is empty of electrons. **The source of electrons in a circuit is the conducting circuit material itself.** Some people think that the electric 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 appreciable distances through a wire in an AC circuit. Instead, they vibrate to and fro about relatively fixed positions.

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

Thus, when you are jolted by an AC 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.

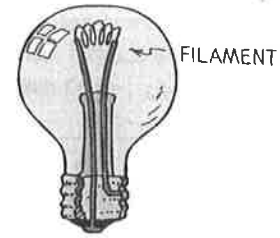


FIGURE 34.15 ▲
The conduction electrons that surge to and fro in the filament of the lamp do not come from the voltage source. They are in the filament to begin with. The voltage source simply provides them with surges of energy.

CONCEPT CHECK What is the source of electrons in a circuit?

34.11 Electric Power

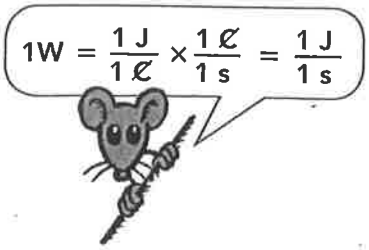
Unless it is in a superconductor, a charge moving in a circuit expends energy. This may result in heating the circuit or in turning a motor. **Electric power** is the rate at which electrical energy is converted into another form such as mechanical energy, heat, or light. **Electric power is equal to the product of current and voltage.**[34.11.1]

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

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

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

Solid-state lighting may soon make conventional lightbulbs obsolete. Watch for the progression of LEDs from flashlights to automobile headlights.



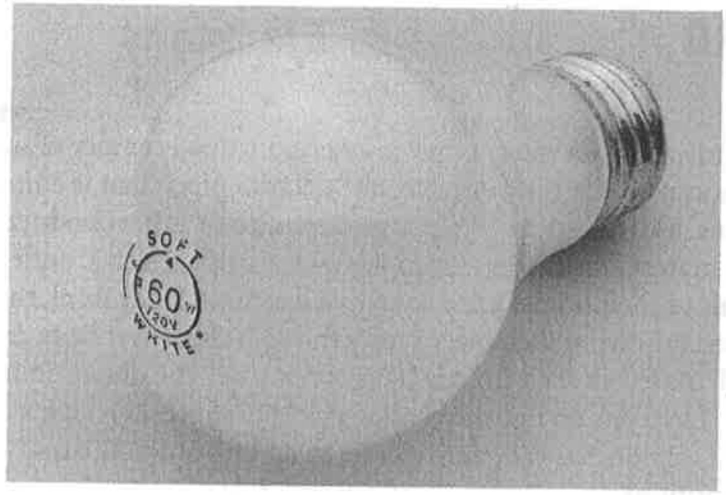


FIGURE 34.16 ▲
The power and voltage on the lightbulb read "60 W, 120 V." You can calculate the current that would flow through the bulb as follows: $I = P/V = (60\text{ W})/(120\text{ V}) = 0.5\text{ A}$.

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.[34.11.2] Therefore, in a locality where electrical energy costs 10 cents per kilowatt-hour, a 100-watt electric lightbulb can be run for 10 hours at a cost of 10 cents, or a 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.

CONCEPT CHECK: How can you express electric power in terms of current and voltage?

think!

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?
Answer: 34.11.1

Will a 1200-watt hair dryer operate on a 120-volt line if the current is limited to 15 amperes by a safety fuse? Can two hair dryers operate on this line?
Answer: 34.11.2