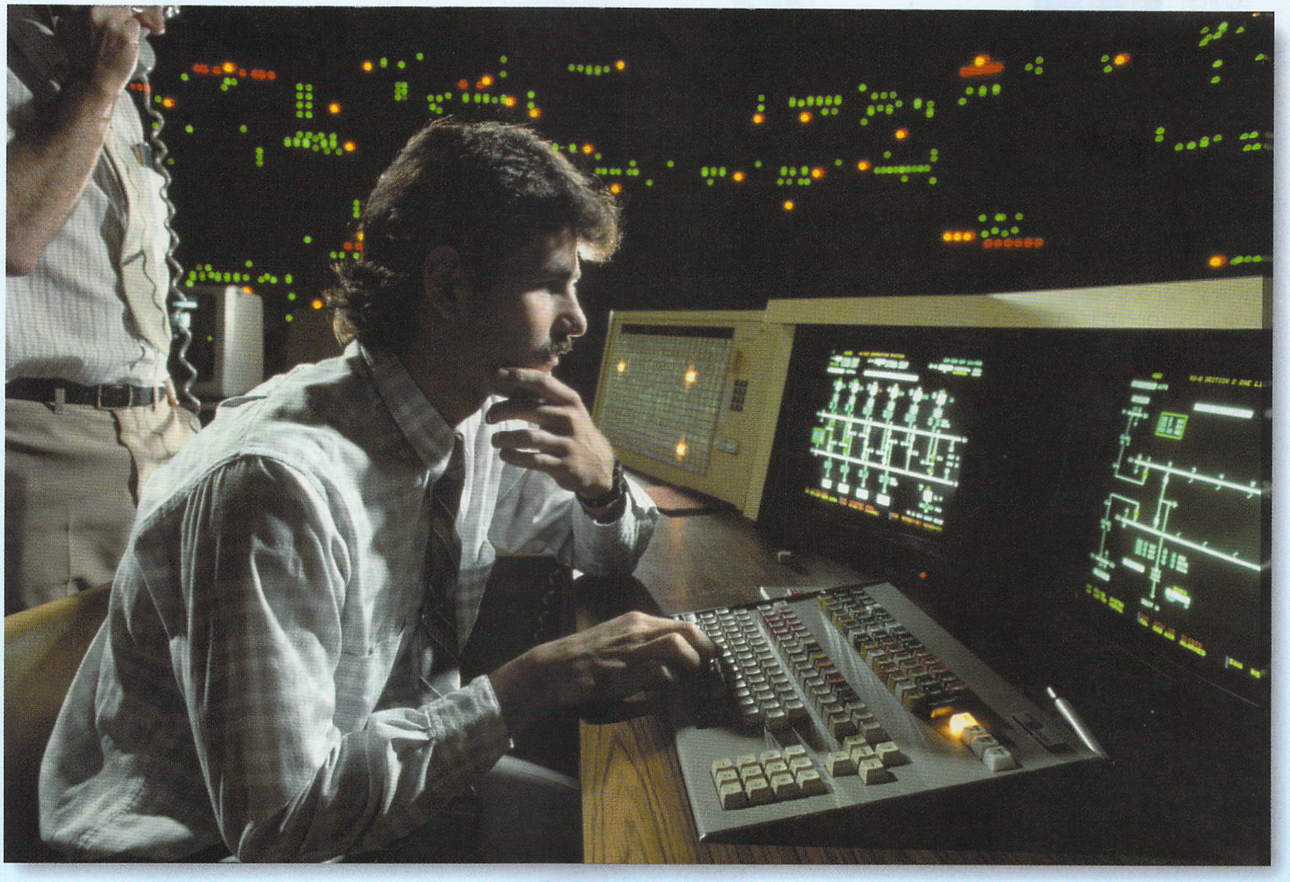
18 Electric Circuits

KEY IDEA

An electric circuit is a closed path through which electrons move to do work.



PHYSICS AROUND US . . . How Electricity Does Work

You press a button on your food processor and the machine springs into action, slicing up ingredients for supper. You flip a wall switch and the room is flooded with light. You click a button on your radio or TV and sit back to enjoy the programming. You get in your car and turn the ignition switch, and the engine surges into life, ready to take you to your destination.

All these experiences and countless more involve the movement of electric charges around a closed path—what we call an *electric circuit.* Although you probably never think about them, circuits are very much a part of your life. In fact, electric power is accessible in a large part of the world today, so people can use electric circuits in the home or at work. Circuits are essential for being able to use electric energy, which is the major form of energy in common use. In this chapter we look at the basic elements of circuits that make them such an important part of contemporary society.

BASIC ELEMENTS OF ELECTRIC CIRCUITS

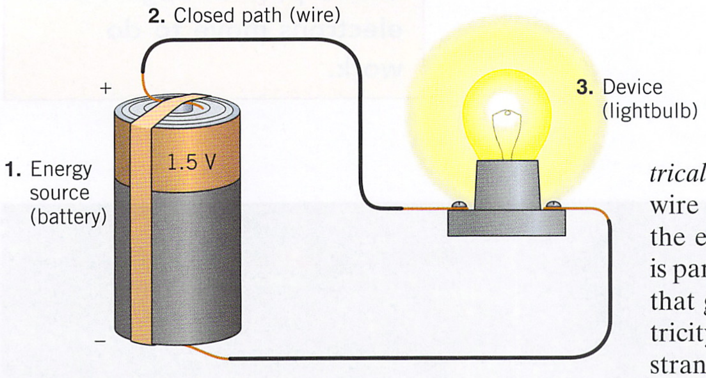


FIGURE 18-1. Every circuit consists of three parts: (1) a source of energy such as a battery; (2) a closed path, usually made of metal wire, through which the current can flow; and (3) a device such as a lightbulb that uses the electric energy.

Most people come into contact with electric phenomena through electric circuits in their homes and cars. In its most basic form, an **electric circuit** is an unbroken path of material that carries electricity; we call this material an *electrical conductor.* In most cases, the conductor is a metal wire or cable, typically made of copper. For example, the electric light that you are using to read this book is part of an electric circuit that begins at a power plant that generates electricity many miles away. That electricity continues through power lines (usually made of strands of aluminum) into your town and is distributed on overhead or underground wires until it finally arrives where you live. There, a circuit includes the light bulb and copper wires that run through the walls of your home.

Every circuit consists of three parts: a source of energy such as a battery; a closed path, usually made of metal wire, through which the current can flow; and a device such as a motor or a lightbulb that uses the electric energy (Figure 18-1). It is important to remember that a circuit must provide a path for current to go from the source to the operating device as well as a return path from the device back to the source. If any part of the circuit is incomplete (an *open circuit*), the device will not work.

Measuring Electric Currents

A good way to think about electric circuits is to draw an analogy between electrons flowing through a wire and water flowing through a pipe (Figure 18-2). In the case of water, we use two quantities to characterize the flow: the amount of

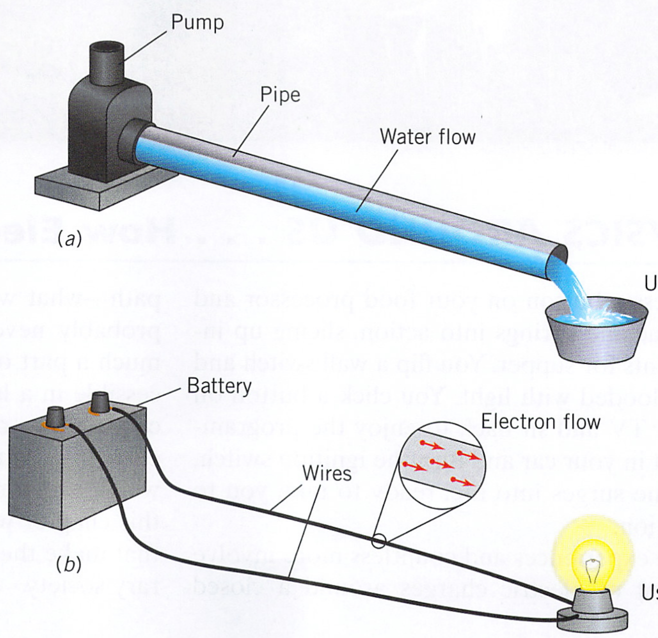
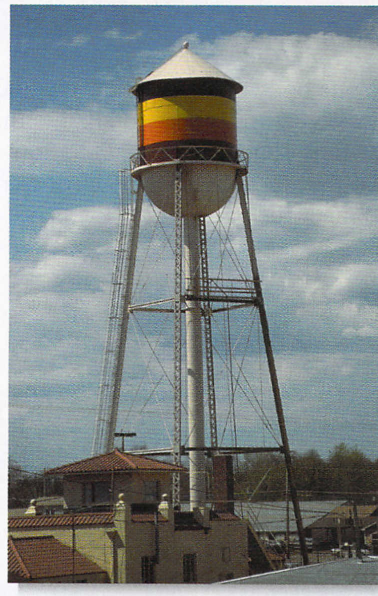


FIGURE 18-2. Electrons flowing through a wire are analogous to water flowing through a pipe. In the case of water (*a*), the flow is characterized by the amount of water that passes a point each second and the pressure difference that makes the water flow. In an electric circuit (*b*), the flow of electrons (current) is measured in amperes and the electric potential (voltage) is measured in volts.

water that passes a point each second and the pressure difference that makes the water move. For example, a city water system may send water through large pipes and push that water (i.e., generate pressure) with a large pump. In small towns, on the other hand, water is stored in a tall tower and the pull of gravity on the water is used to generate pressure—the taller the tower, the greater the pressure in the pipes.



A water tower uses gravitational potential energy to generate pressure; the taller the tower, the greater the pressure in the pipes.

The numbers we use to describe the flow of electrons in an electric circuit can be thought of in an analogous way. The quantity that is analogous to the volume of water flowing through the pipe is the number of electrons that flow through the wire, called the *electric current.* Current is measured in a unit called the **ampere** or **amp,** named after French physicist Andre-Marie Ampere (1775–1836). One amp corresponds to a flow of 1 coulomb (the unit of electric charge) per second past a point in the wire:

1 amp of current = 1 coulomb of charge per second

Alternatively, 1 amp of current corresponds to 6.25×10^{18} electrons moving past a point in the wire each second. Typical household appliances use anywhere from about 1 amp (a 100-watt bulb) to 40 amps (an electric range with all burners and the oven blazing away).

The quantity that is analogous to pressure is called the **electric potential.** (Note that the word "potential" does not denote an energy, as it does in Chapters 8 and 12.) You can think of the device that generates this potential—either a battery or an electric generator—as a kind of pump that supplies energy to the electrons that flow through the circuit. The electric potential of an energy source is measured in a unit called the **volt** (V), which was named after Alessandro Volta, the Italian scientist who invented the chemical battery. In ordinary use, we often refer to the electric potential as the **voltage** of the energy source in a circuit.

As we have said, you can think of voltage in circuits in much the same way you think of water pressure in your plumbing system. The power of the water pump or the height of the water tower produces water pressure. In an electric circuit, more volts mean more oomph to the current, just as more water pressure makes for a stronger flow of water. Typically, a new flashlight battery produces 1.5 volts, a fully charged car battery produces about 12 volts, and ordinary household circuits operate on either 120 or 240 volts. (See Looking at Voltage, page 376.)

Wires through which the electrons flow are analogous to pipes carrying water: the smaller the pipe, the harder it is to push water through it. Similarly, it is harder to push electrons through some wires than others. The quantity that measures how hard it is to push electrons through wires is called **electrical resistance,** and it is measured in a unit called the **ohm,** after the German physicist Georg Ohm (1789–1854).

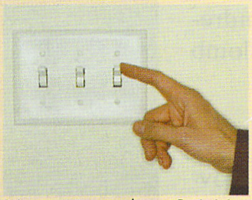
To understand the physical basis for resistance, think about electrons moving through a copper wire. Every so often, one of the moving electrons collides with a copper atom. In that collision, the electron, on average, loses energy and the atom gains energy. As a result of these collisions, some of the electrons' energy is converted into heat. The wire gets warmer, and the electric energy converted into heat has to be replaced by the power source in order to keep the electrons moving along the wire.

In real materials, such as copper, collisions happen so often, and the electrons change direction so often, that the actual speed of an electron in the wire (a quantity known as the *drift velocity*) is actually very low—often a fraction of a centimeter per second. However, even though the electrons themselves move

Looking at Voltage

Your body runs on electricity; nerve impulses are basically electrical in nature. However, the voltages involved are rather small, less than one-tenth the voltage of a standard flashlight battery. Our modern society runs on electrical energy that exceeds the body's voltage levels by over 1000 times. Really large voltages are generated in power plants and carried by transmission lines; these voltages can be very dangerous.

10^{-1} V

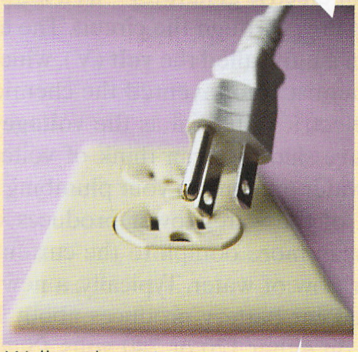


Nerve impulse, 0.1 V

10^{0} V

Flashlight battery, 1.5 V

10^{2} V

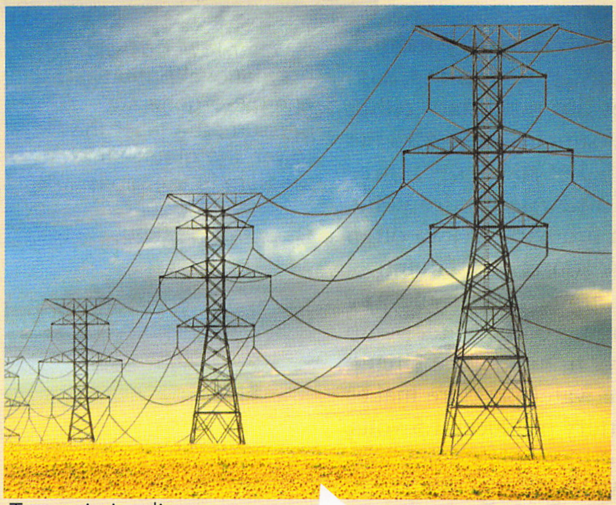


Wall outlet, 120 V

10^{4} V

Power plant, 25,000 V

10^{6} V



Transmission lines, 500,000 V

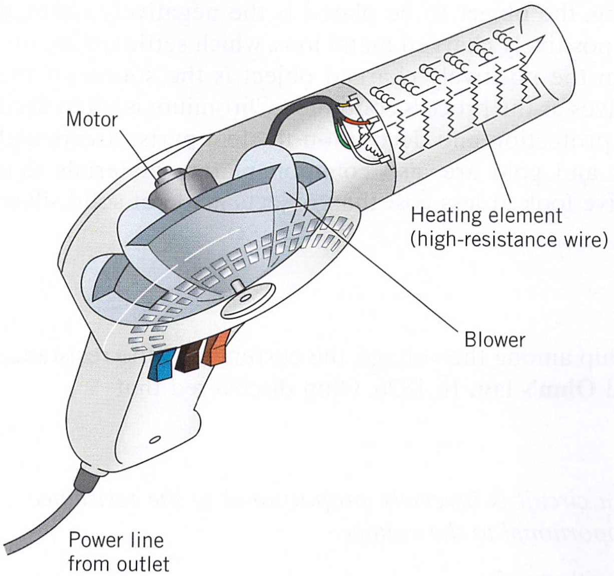


Figure 18-3. A hair dryer uses high-resistance wire to generate heat.

very slowly, electric signals travel through the wire at almost the speed of light. This situation is analogous to a wave on water, which can move quickly even though the water molecules do not.

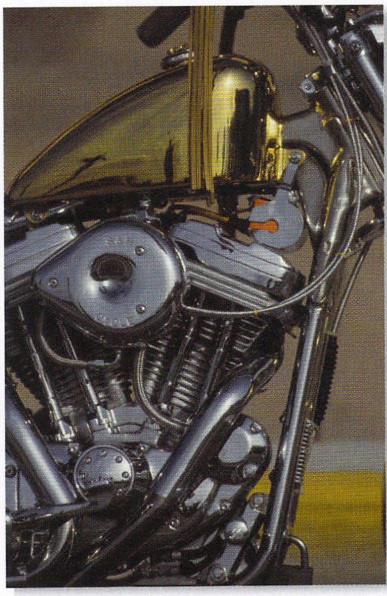
Greater electrical resistance in wires and other conducting materials means that more of the electrons' energy is converted into heat. For example, ordinary copper wire has a low resistance, which explains why we use it to carry electricity around our homes. On the other hand, toasters, space heaters, and hair dryers contain high-resistance wires so that they produce large amounts of heat when current flows through them (Figure 18-3). In transmission lines, it is important that as much energy as possible gets from one end of the line to the other; thus electric power companies use very thick low-resistance (high-efficiency) wires.

Connection

Electrolysis and Electroplating

Not all electric circuits involve electrons flowing along wires. For example, transistors and integrated circuit chips, which are part of all modern electronic equipment, use both positive and negative charge carriers moving along paths etched into thin layers of crystalline silicon. As another example, consider the large electroplating industry.

Electrolysis employs a reaction opposite to what takes place in batteries. A battery uses a chemical reaction to produce an electric current; electrolysis uses electric current to drive a chemical reaction that normally wouldn't occur. Michael Faraday first worked out the principles of electrolysis. The idea is that two objects are placed in a solution of ions and connected to a strong current supply. Electrons are stripped from one object, leaving that object with a positive charge, and are supplied to the second object, giving it a negative charge. The ions in the solution are attracted toward the two objects, with negative ions moving to the positively charged object and positive ions moving toward the negatively charged object. The moving ions complete a circuit, allowing current to flow through the entire apparatus.



Chrome electroplating is a technology based on electrolysis.

In electroplating, the object to be plated is the negatively charged object and attracts positively charged metal ions, which settle on the object's surface. Often the positively charged object is the source of the ions; it slowly dissolves as the process continues. Chromium is often used in this way to add protection and decoration to steel parts of cars and motorcycles. Silver and gold are also common plating materials that give a rich decorative look at less cost than objects made of solid silver or gold. ●

Ohm's Law

The close relationship among the voltage, the current, and the resistance of a circuit is called **Ohm's law.** In 1826, Ohm discovered that

1. In words:

The current in a circuit is inversely proportional to the resistance and directly proportional to the voltage.

2. In an equation with words:

Current (in amps) = Voltage (in volts) divided by Resistance (in ohms)

or Voltage = Current × Resistance

3. In an equation with symbols:

$$I = \frac{V}{R} \quad \text{or} \quad V = IR$$

where I is the standard symbol used to denote electric current.

Ohm's law tells us that, if we want to increase the amount of current flowing in a circuit, we can do one of two things: we can increase the voltage, or we can lower the resistance (Figure 18-4). If you think of our analogy with the flow of water in a pipe, this makes sense. You can increase the flow of water by increasing the pressure (for example, by using a more powerful pump) or by installing a

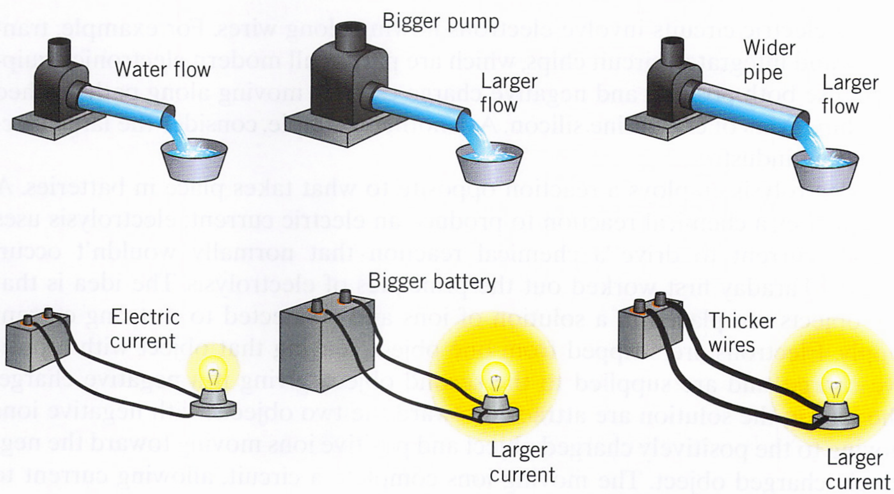


FIGURE 18-4. Ohm's law says that an increase in current can be accomplished by an increase in voltage or a decrease in resistance. This behavior is analogous to water flowing in a pipe; greater water flow results from either a bigger pump or a wider pipe.

larger-diameter pipe. In the same way, in an electric circuit you can increase current by increasing voltage (for example, by using a more powerful pump) or by lowering the resistance (for example, by using a larger-diameter copper wire).

Ohm's law does not apply to all materials, but it does apply to metals used in electrical wiring and to many other materials found in simple electric circuits. However, it does not work for the semiconductor materials we will discuss in Chapter 25.

You can understand the behavior of lightning in terms of electric circuits (Figure 18-5). In a thunderstorm, collisions between particles in the clouds produce a buildup of negative charge at the bottom of the cloud, which attracts a corresponding buildup of positive charge in objects on the ground underneath the cloud. This buildup creates a voltage between cloud and ground. The lightning stroke is the electric current that runs between the two when the voltage is high enough. Lightning normally strikes tall objects such as buildings and trees because they're closer to the thunderstorm and the positive charge on the ground tends to accumulate in these tall objects. When the potential difference between clouds and ground becomes large enough, the air becomes ionized and electricity passes through it. As we have mentioned earlier, the lightning rod invented by Benjamin Franklin uses this principle by allowing the lightning to flow through a low-resistance bar of metal instead of through the building.

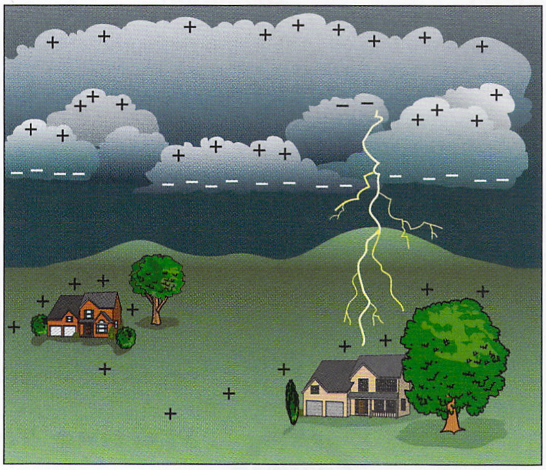


FIGURE 18-5. Lightning occurs when collisions between particles in a thundercloud produce a buildup of negative charge at the bottom of the cloud, which attracts a corresponding buildup of positive charge in objects on the ground underneath the cloud. The lightning stroke is the electric current that runs between the two when the voltage is high enough.

ELECTRIC POWER

In Chapter 8 we saw that power, measured in watts, is the rate at which work is done or, equivalently, the rate at which energy is expended. This concept is important in the design and application of electric circuits.

The *load* in any electric circuit is the "business end"—the place where useful work gets done. The filament of a lightbulb, the heating element in your hair dryer, and coils of wire in an electric motor are typical loads in household circuits. The power used by the load depends both on how much current flows through it and on the voltage. The greater the current or voltage, the more power is used. A simple equation allows us to calculate the amount of electric power used.

1. In words:

The power consumed by an electric appliance is equal to the product of the current flowing through it and the voltage across it.

2. In an equation with words:

Power (in watts) = Current (in amps) times Voltage (in volts)

3. In an equation with symbols:

$$P = I \times V$$

TABLE 18-1 Terms Related to Electric Circuits

Term	Definition	Unit	Plumbing Analog
Voltage	Electric pressure	volt	Water pressure
Resistance	Resistance to electron flow	ohm	Pipe diameter
Current	Flow rate of electrons	amp	Flow rate of water
Power	Current times voltage	watt	Rate of work done by moving water

This equation tells us that both the current and the voltage have to be large for a device to consume high levels of electric power. Table 18-1 summarizes some key terms about electric circuits.

EXAMPLE 18-1

Starting Your Car

When you turn on the ignition of your automobile, your 12-volt car battery must turn a 400-amp starter motor. How much power is required to start your car?

REASONING AND SOLUTION: In order to calculate electric power, we need to multiply current times voltage. We apply the equation for electric power:

$$\begin{aligned} \text{Power (watts)} &= \text{Current (amps)} \times \text{Voltage (volts)} \\ &= 400 \text{ amps} \times 12 \text{ volts} \\ &= 4800 \text{ watts} = 4.8 \text{ kilowatts} \end{aligned}$$

Most early automobiles were started by a hand crank, which might have required 100 watts of power, a reasonable amount for an adult to exert. Modern high-compression automobile engines require much more starting power than could be generated by one person. That's why your car has a powerful starting motor. ●

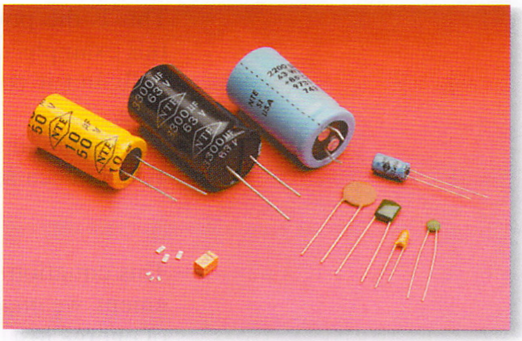
Connection

Capacitors

It often happens that you don't need much energy to keep an electric device running, but you do need an occasional jolt of energy for some particular function. For example, a light meter on a camera requires only a small amount of current from a battery, but if you want to use a flash attachment for taking pictures at night, you need a good-size burst of energy for the flash. The circuit device that enables you to store large amounts of electric energy and then use it when needed is called a *capacitor.*

In its simplest form, a capacitor consists of two parallel conducting plates kept a small distance apart. When placed in a circuit with a battery or other voltage source, one plate accumulates positive charge and the other plate accumulates negative charge. The charge stays on the plates; it can't cross the insulating gap between them. In this way you can build up a good deal of electric potential energy in the capacitor. When you want to tap this energy, you just close a switch on some other part of the circuit connected to the capacitor and the charge immediately leaves the plates as a current in this new part of the circuit.

Capacitors come in different sizes and can store different amounts of charge. The ratio of stored charge to voltage across the capacitor is called *capacitance* and is measured in units called "farads" (after Michael Faraday). Modern capacitors use a thin layer of insulating material, such as paper, wax, or plastic, between thin conducting sheets, such as metal foil. Then the whole device is wrapped up into a tight cylinder.



A variety of capacitors.

Capacitors are common circuit components for supplying energy in repeated bursts instead of a continuous stream. Think of windshield wipers set to an intermittent sweep. Capacitors are also used for equipment that needs more energy to start up than to continue operation, such as TV sets and automobiles. (The large capacitor in a car is often called a condenser because it "condenses" electric energy into a larger concentration than the battery can supply.) Capacitors are also used to shield delicate circuit components from large currents that might damage them; the large current runs up a charge in the capacitor instead. Surge protectors also use capacitors to protect electronic equipment from large bursts of current triggered by lightning or a power outage. ●

Resistive Loss

Ohm's law and the equation for electric power provide us with a very simple way of calculating the power dissipated in the resistance of an electric circuit. Consider, as in Figure 18-6, a resistance of R ohms (the bulb filament) in a circuit through which a current I is flowing. According to Ohm's law, the voltage drop across the resistor is

$$V = IR$$

But the power equation tells us that the power being dissipated in the resistor is

$$P = IV$$

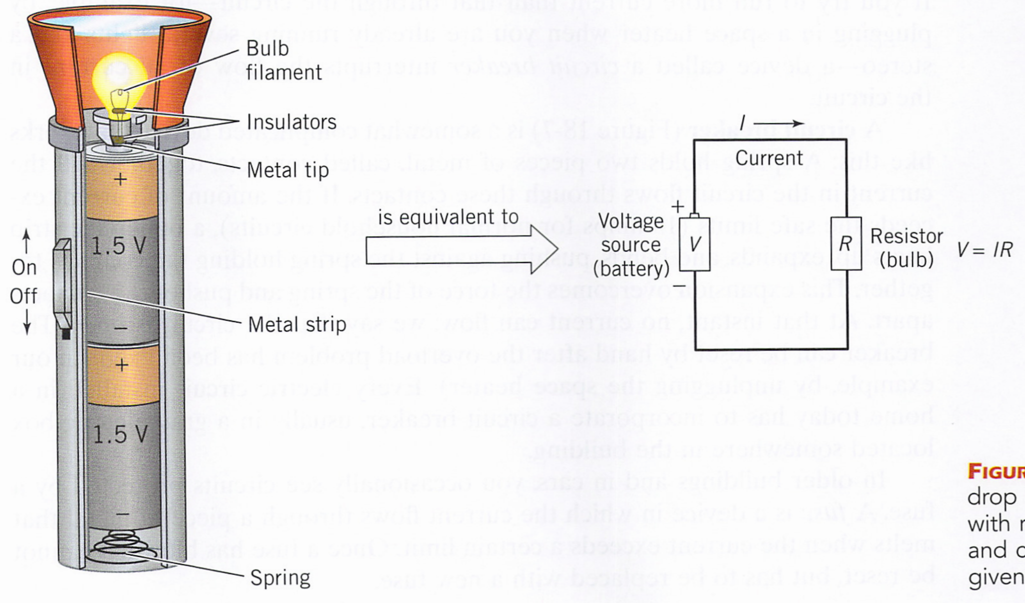


FIGURE 18-6. The voltage drop V (in volts) in a circuit with resistance of R (in ohms) and current I (in amps) is given by Ohm's law: $V = IR$.

This is the power that moving electrons transform into heat in the resistor. In this example, the resistor could be a useful appliance such as a toaster or a lightbulb, but it could also be another part of a circuit, such as a length of copper wire.

Combining these two equations, we find that the amount of energy dissipated as heat each second in a resistor in any electric circuit is

$$P = I^2R$$

This equation tells us that if we double the current through a wire or circuit element, we *quadruple* the amount of heat generated (or, equivalently, the amount of energy lost). This fact has important implications for the design of the nation's power grid, as we'll see in Example 4.

CIRCUIT SAFETY

Electric circuits are all around us. Because these circuits can release a great deal of electric energy, we have to be aware of the fact that they can be dangerous. Two different sorts of dangers are associated with electricity: the generation of fires, and electric shock. Each of these dangers is met in a different way in modern electric systems.

Overloading Circuits

Because current flowing through a wire generates heat, there is always the danger that a wire will overheat and ignite materials around it, causing a potentially lethal fire. Consequently, electric codes are written so that the size of the wire in every circuit in a building is set so that it can carry the maximum allowed current without overheating. This is why the wires that carry high currents (such as those that run to an electric stove) have to have a much larger diameter than the familiar cords that power ordinary electric lamps.

In general, most household circuits are designed to carry 15 amps of current. If you try to run more current than that through the circuit—for example, by plugging in a space heater when you are already running several lights and a stereo—a device called a *circuit breaker* interrupts the flow of all current in the circuit.

A **circuit breaker** (Figure 18-7) is a somewhat complicated device that works like this: A spring holds two pieces of metal, called contacts, together. All the current in the circuit flows through these contacts. If the amount of current exceeds the safe limits (15 amps for normal household circuits), a bimetallic strip heats up, expands, and bends, pushing against the spring holding the contacts together. This expansion overcomes the force of the spring and pushes the contacts apart. At that instant, no current can flow; we say that the circuit is *open*. The breaker can be reset by hand after the overload problem has been fixed (in our example, by unplugging the space heater). Every electric circuit installed in a home today has to incorporate a circuit breaker, usually in a gray electric box located somewhere in the building.

In older buildings and in cars, you occasionally see circuits protected by a fuse. A *fuse* is a device in which the current flows through a piece of metal that melts when the current exceeds a certain limit. Once a fuse has blown, it cannot be reset, but has to be replaced with a new fuse.

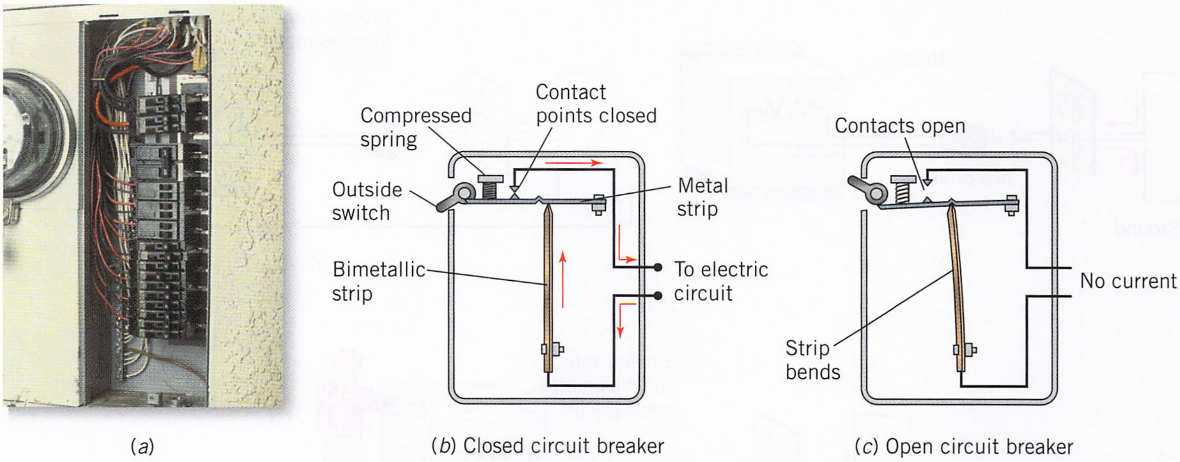


FIGURE 18-7. A circuit breaker opens when electric current exceeds a critical value. This safety feature prevents a circuit from overheating.

Develop Your Intuition: Tripping a Circuit Breaker

You have a 100-W lightbulb on in your room, along with your 360-W stereo receiver and a 1600-W electric heater, all plugged into the same 120-V outlet. The circuit is protected by a 20-amp circuit breaker. Suppose you decide to plug in your 650-W hair dryer to the same circuit; will you trip the circuit breaker when you turn on the hair dryer?

The question is, how much current does each appliance draw? The sum must be less than 20 amps for the circuit breaker to stay closed. The current for each appliance equals its power use divided by the voltage:

$$\text{Lightbulb} \quad \frac{100\ \text{W}}{120\ \text{V}} = 0.8\ \text{amp}$$

$$\text{Stereo} \quad \frac{360\ \text{W}}{120\ \text{V}} = 3.0\ \text{amp}$$

$$\text{Heater} \quad \frac{1600\ \text{W}}{120\ \text{V}} = 13.8\ \text{amp}$$

$$\text{Hair dryer} \quad \frac{650\ \text{W}}{120\ \text{V}} = 5.4\ \text{amp}$$

Without the hair dryer, the circuit is carrying a current of 17.6 amps, primarily because of the heater. Adding another heat-generating appliance such as a hair dryer will be too much; the total current of 23 amps will exceed the rating of the circuit breaker and it will open.

Electric Shock

Another danger involves situations in which human beings inadvertently make themselves part of an electric circuit. As outlined in the Connection: The Propagation of Nerve Signals on page 385, the human nervous system is electrical

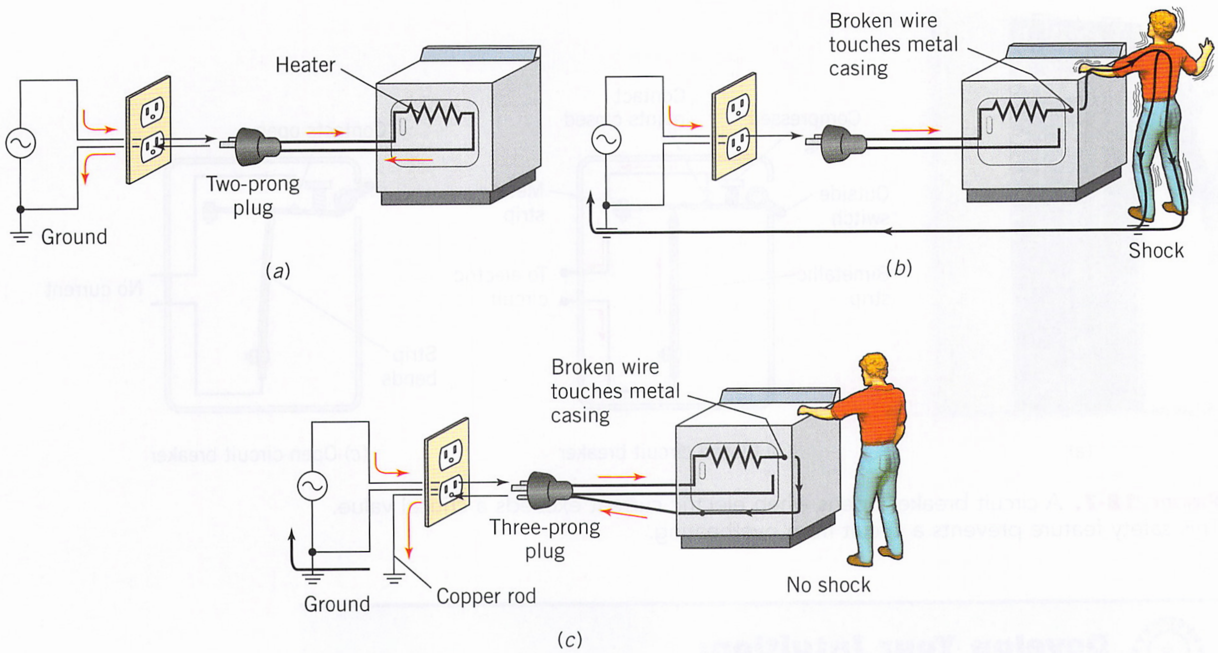


FIGURE 18-8. (*a*) Electric appliances that use a two-pronged plug may cause an electric shock. (*b*) If the insulation on wires inside a metal appliance rubs off and you touch the appliance casing, current will try to flow through your body into the ground. (*c*) A three-pronged plug alleviates this problem.

in nature and can be damaged and even destroyed by flows of current through the body.

A common situation is shown in Figure 18-8. The insulation on wires inside the metal casing of an appliance has, over time, been rubbed off, so that the metal frame is in electrical contact with the wire. This means that the entire metal casing is at 120 V. If you touch the casing (Figure 18-8*b*), current will try to flow through your body into the ground. As shown in the following examples, the amount of current (and the damage to you) depends on the resistance that your body offers to that current.

EXAMPLE 18-2

A Little Shock

If you are standing on a dry floor and your skin is dry when you touch the appliance frame that has damaged wires, the resistance of your body could be as high as 100,000 ohms. How much current can flow through your body?

REASONING AND SOLUTION: Ohm's law allows us to calculate the current when we know both the voltage (120 volts) and resistance (100,000 ohms). Solving for the current,

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

$$= \frac{120 \text{ volts}}{100{,}000 \text{ ohms}}$$

$$= 0.0012 \text{ amp}$$

This is a small current. You will probably feel a little tingle, but not much else.

EXAMPLE 18-3

A Big Shock

Now suppose you touch the appliance frame that has damaged wires when you are wet, perhaps when you are standing in a puddle of water or (much worse!) a bathtub. Water is a good conductor because of the ions it contains. In this case, your resistance could be quite low, perhaps only 1000 ohms. Now how much current flows?

SOLUTION:

$$I = \frac{V}{R} = \frac{120 \text{ volts}}{1000 \text{ ohms}} = 0.12 \text{ amp}$$

This large current is enough to kill you. In fact, muscle spasms may occur when about 0.015 amp flows through the body, and currents of 0.07 amp can stop the heart from beating if they last long enough.

The bottom line: ***Never*** touch electric devices when you are in contact with water! ●

Grounding

To counter the danger from electric shock around the home, modern electric circuits are grounded. Look at a wall receptacle and you'll note that there are usually three holes to accommodate an electric plug. The two flat prongs of a plug carry the normal current, but the third round prong carries an extra wire that connects the electric device to the ground (Figure 18-8*c*). If it happens that one of the "hot" wires touches the casing of the device, as in Examples 18-2 and 18-3 a very low-resistance path is opened up. Potentially dangerous current is carried from the high-voltage wires directly into the ground. When a low-resistance path such as this has opened up, we say that we have a **short circuit.**

As a result of the short circuit, large amounts of current begin to flow and the circuit breaker trips, preventing the current from flowing in the circuit until the problem is repaired. This process of **grounding** a circuit protects people by ensuring that the circuit is taken out of operation as soon as a potential for delivering electric shock develops (Figure 18-7*c*).

Connection

The Propagation of Nerve Signals

All of your body's movements, from the beating of your heart to the blinking of your eyes, are controlled by nerve impulses. Although nerve signals in the human body are electrical in nature, they bear little resemblance to the movement of electrons through a wire. Nerve cells of the type illustrated in Figure 18-9, called neurons, form the fundamental element of the nervous system. A neuron consists of a central body with a large number of radiating filaments at each end. These filaments connect one nerve cell to many others. The long filament that carries signals away from the central nerve body and delivers those signals to other cells is called the axon.

The membrane surrounding the axon is a complex structure, full of channels through which atoms and molecules can move. When the nerve cell is resting, positively charged molecules tend to remain outside the membrane, while

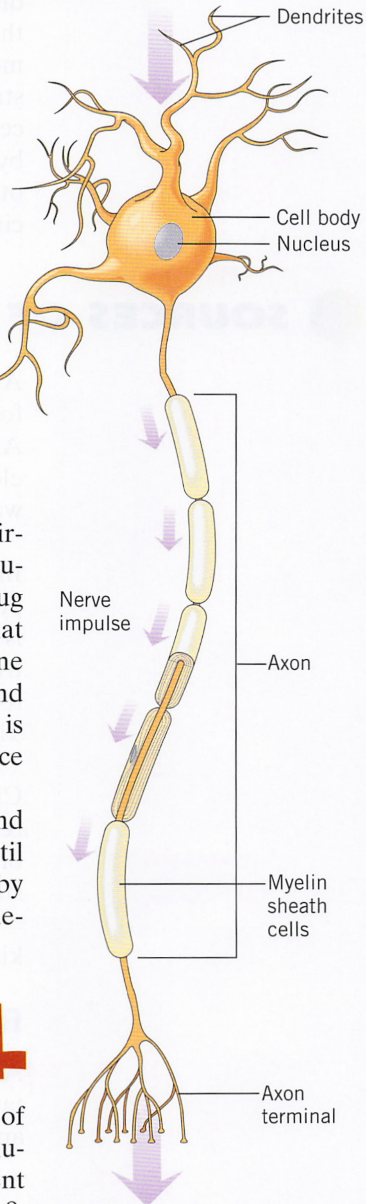


FIGURE 18-9. A nerve cell (neuron) consists of a central body and a number of filaments. The dendrites receive incoming signals and the axon conducts outgoing signals away from the cell body. The myelin sheath allows the nerve signal to move faster.

negatively charged molecules remain inside. However, when an electric signal triggers the axon, the membrane is distorted and, for a short time, positive charges (mainly sodium atoms) pour into the cell. When the inside becomes more positively charged the membrane changes again and positive charges (this time mainly potassium) move back outside to restore the original charge. This charge disturbance moves down the filament as a nerve signal. When the signal reaches the end of one of the filaments, it is transferred to the next cell by a group of molecules called *neurotransmitters* that are sprayed out from the end of the upstream cell, and received by special structures on the downstream cell. The reception of neurotransmitters initiates a complex and poorly understood process by which the nerve cell decides whether or not to send a signal down its axon to other cells. Thus, although the human nervous system is not an ordinary electric circuit, it does operate by electric signals. ●

SOURCES OF ELECTRIC ENERGY

As we have seen in Chapter 17, there are two primary ways of converting other forms of energy into electric energy. The oldest technology, first developed by Alessandro Volta, is the battery, which uses chemical potential energy to move electrons through a wire. The battery produces current in which the electrons always flow in the same direction, which we call *direct current* (DC).

The other device, associated with Michael Faraday, is the electric generator. In a power plant using a generator, stored energy in some form (gravitational potential energy of falling water, for example, or stored chemical energy in coal) is used to turn a shaft between large magnets, producing electric current by electromagnetic induction. Current produced by a generator flows in one direction for half of a rotation of the shaft and in the other direction for the other half. This we call *alternating current* (AC).

We use both kinds of current in our daily lives. When you turn on a portable CD player, boot up your laptop computer, or start your car, you use direct current generated by batteries. When you plug your stereo into a wall outlet or turn on an electric stove, you use alternating current generated at a distant power station.

This interplay between direct and alternating current in our lives makes two kinds of devices, called *rectifiers* and *transformers*, very important.

Rectifiers

A **rectifier** is an electric device that converts AC into DC. Rectifiers are important because many types of electronic equipment, including cell phones, stereos, and laptop computers, are built so that their internal circuits run on direct

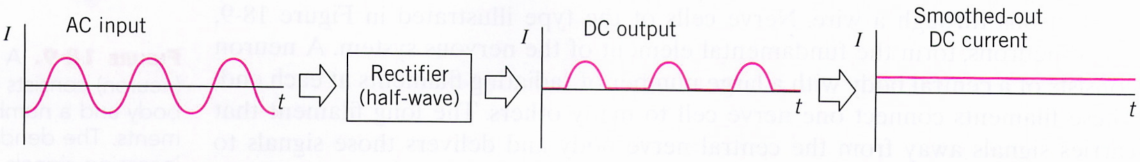


FIGURE 18-10. A simple rectifier acts as a one-way gate for electric current. Alternating current entering from the left is converted into a series of bumps, each of which flows in the same direction. Other electronic devices are used to smooth out the bumps and produce the steady DC current shown on the right.

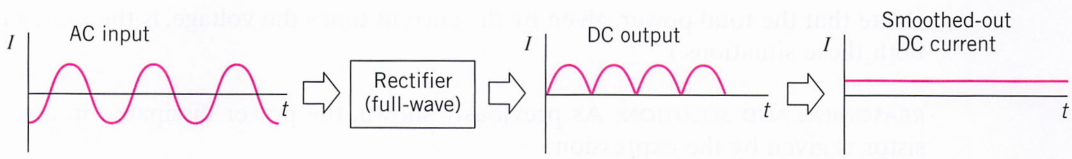


FIGURE 18-11. In a modern rectifier, special electronics flip the voltage on the current that is going the "wrong" way. The result is a system in which the incoming AC is converted into a series of contiguous pulses, all with current moving in the "right" direction, and then smoothed out.

current. However, when you plug them into the wall outlet or charge their batteries you bring in alternating current. The first thing you have to do to make the device operate is to convert AC to DC.

We discuss the details of how a common rectifier works at the atomic level in Chapter 25. For the moment, however, think of a rectifier as a one-way gate for electric current—a gate that opens when electrons move to the right, for example, but closes when they try to move back to the left. The effect of such a device is shown in Figure 18-10. The alternating current is shown by the graph on the left, in which the current is first negative, then positive, then negative, and so on. This corresponds to electrons in the circuit moving first one way, then the other way, then back to the first way, and so on. This current enters from the left (AC input) and is converted into a series of bumps (DC output). In each of these bumps the current is always flowing in the same direction. After this step, other electronic devices are used to smooth out the bumps and produce the steady DC current shown on the right.

Actually, in a real rectifier, we do not throw away half of the incoming electric energy, as in this simple example. Instead, by use of clever electronics, engineers flip the voltage on the current that is going the "wrong" way. The result is a system such as that shown in Figure 18-11, in which the incoming AC is converted into a series of contiguous pulses, all with current moving in the "right" direction, and then smoothed out.

Transformers

Engineers often need to change the voltage associated with AC current. For example, when electricity is generated at a power plant, it is usually sent through wires over long distances. As we see in Example 18-4, there is less loss due to resistance if a small current is sent at a high voltage than if a larger current is sent at a low voltage. For this reason, it is advantageous to increase or decrease the voltage of electric current flowing through a wire. The **transformer** is the device that carries out this task.

Transmitting Electric Power

EXAMPLE 18-4

Suppose you have a power source (such as a generator) that delivers 1 kilowatt of electric power. This power has to be sent over a long electric wire that has a resistance of 5 ohms. Calculate the energy dissipated as heat in the resistor if the power is sent in the form of

a. 10 amps at 100 volts
b. 0.1 amp at 10,000 volts

(Note that the total power, given by the current times the voltage, is the same in both these situations.)

REASONING AND SOLUTION: As previously shown, the power dissipated in a resistor is given by the expression

$$P = I^2R$$

All we have to do, then, is substitute the currents in the two cases:

a. Current = 10 amps, so

$$P = (10 \text{ amps})^2 \times 5 \text{ ohms}$$
$$= 500 \text{ watts}$$

b. Current = 0.1 amp, so

$$P = (0.1 \text{ amp})^2 \times 5 \text{ ohms}$$
$$= 0.05 \text{ watt}$$

In other words, in the first case almost half the power from the generator is lost in heating the wire, while in the second case almost none is lost. This result shows why electric power is always transmitted at very high voltages and low currents. ●

A simplified picture of a transformer is shown in Figure 18-12*a*. A loop of wire, called the "primary coil," is connected to an alternating-current power source. Situated on top of this wire loop is another loop, called the "secondary coil," which is connected to wires leading away from the device. When AC current flows through the primary coil, it creates a varying magnetic field. This oscillating field, in turn, causes a change in the magnetic field enclosed in the secondary coil. By electromagnetic induction, a voltage V is induced in the second coil. If the second coil is part of a circuit, the induced voltage causes current I_{out} to flow in the circuit. This result makes sense because, assuming no losses, the energy flowing into the transformer must be the same as the energy flowing out. Note that the secondary coil is not connected to a power source; it is linked to the primary coil only by the changing magnetic field. The only link between the two coils, in fact, is through the varying magnetic field.

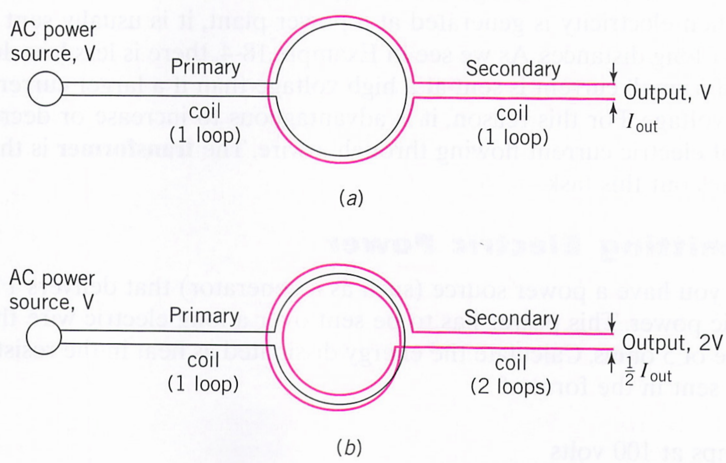


FIGURE 18-12. (*a*) A simplified picture of a transformer with one loop of wire in both the primary and secondary coils. (*b*) In a transformer in which the primary coil has one loop of wire and the secondary coil has two loops, half the current and twice the voltage flows in the secondary coil.

In this simple example, the current and voltage in the secondary coil are exactly the same as that in the primary coil (ignoring losses due to resistance in the wires). Suppose, however, that we have a situation like that shown in Figure 18-12*b*, with the secondary coil consisting of two loops of wire. In this case, voltage V is induced in each of the two loops in the secondary coil, producing a total voltage of $2V$. Here the energy flowing in (per unit of time) is $I_{in}V$, and this must be the same as the energy flowing out:

$$I_{in}V = I_{out}\,(2V)$$

$$I_{out} = \frac{I_{in}}{2}$$

Thus the output current is half of the original current.

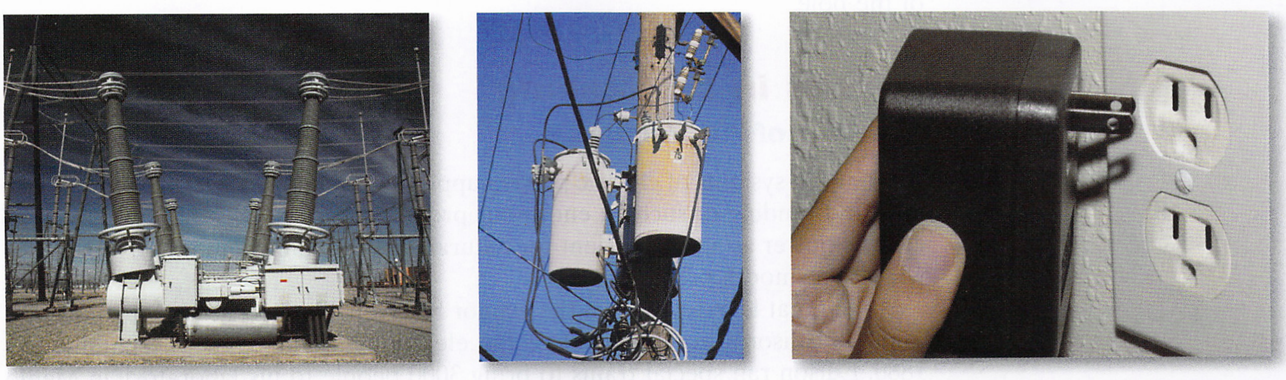
Adding more loops to the secondary coil of a transformer further increases the secondary voltage and decreases the secondary current. This kind of transformer, in which the secondary voltage is greater than the primary, is called a *step-up transformer.* You can apply the reasoning we've just used to a transformer that has more coils in the primary than in the secondary. In this case, the voltage in the secondary coil is less than that in the primary coil and the current is correspondingly higher—a situation known as a *step-down transformer.* Both kinds of transformers are used routinely in the electric industry. Step-up transformers at power stations provide high voltages for transmission lines, while step-down transformers in your local neighborhood reduce the voltages to manageable levels for delivery to homes (Figure 18-13).

In general, if the primary coil of a transformer has N_1 loops and the secondary coil has N_2 loops, then the relations between the primary and secondary currents and voltages are

$$I_{secondary} = \left(\frac{N_1}{N_2}\right) I_{primary}$$

and

$$V_{secondary} = \left(\frac{N_2}{N_1}\right) V_{primary}$$



(*a*) (*b*) (*c*)

FIGURE 18-13. (*a*) A step-up transformer converts current from power generators to high voltage for long-distance transmission. (*b*) A step-down transformer lowers voltage from power lines for home use. (*c*) A step-down transformer lowers voltage from home power outlets for use in delicate electronic devices.

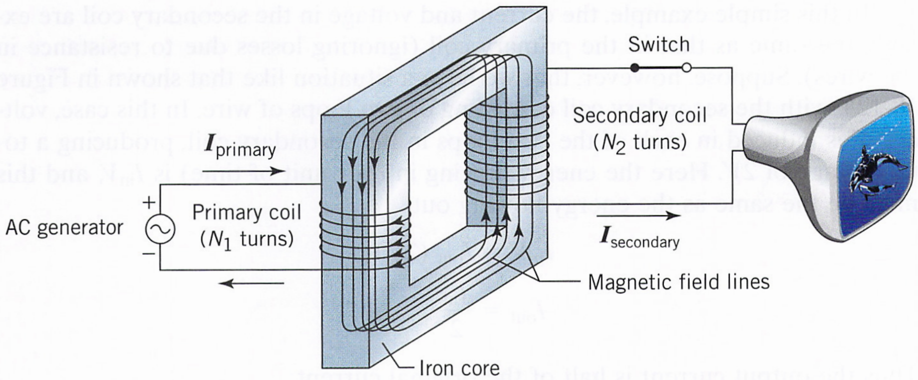


FIGURE 18-14. A typical transformer has both the primary and secondary coils wrapped around an iron core.

A typical transformer is shown in Figure 18-14. Both the primary and secondary coils are wrapped around an iron core, as shown. The core, in essence, traps the magnetic field produced by the primary and leads it around so that it all passes through the secondary coil. It is the presence of the iron that makes transformers heavy—a feature you may have noticed if you've ever picked one up.

The Power Grid

Transformers are routinely used to help bring electric power from distant generating plants to cities. First, in order to send the electricity over long distances with minimum loss, the output of a generator is stepped up to hundreds of thousands of volts. This high-voltage current provides the power that runs through the transmission lines that you see snaking across the open countryside near generating plants.

When this power comes into an urban area, the voltage is stepped down to 600 volts to be carried around the city on overhead lines. Finally, on a power pole near your home, another transformer steps the voltage down further, to the 240 volts that comes into your house. You can often see these final transformers on power poles in residential areas—they look like small garbage cans at the top of the pole.

Physics in the Making

The War of AC Versus DC

Nationwide systems of electric power supply cannot happen overnight. The planning and funding of such an enormous project takes years. The development of electric power as a replacement for natural gas and oil began in the 1880s, but it was not a smooth process.

The great leap forward in the clamor for available electric power came with Thomas Edison's improvement of the electric lightbulb, which he patented in 1880. Edison ran special trains to bring 3000 people to his laboratory in Menlo Park, New Jersey, to see his demonstration of hundreds of lamps in the streets and shops of the neighborhood, all run by a single central generator. News that Edison had solved the problem of electric lights caused stocks of gas companies to drop sharply worldwide.

Edison formed a company to build generators and offer electric power to businesses and neighborhoods in New York. He advocated direct current and claimed it was safe and easy to use. However, around 1890, competition arrived from the engineer and inventor George Westinghouse. Westinghouse had recognized the economic value of using transformers with alternating current to transmit power at low currents (high voltages) and had formed a partnership with the engineer Nikola Tesla to build practical power supplies of AC. Westinghouse Electric began offering power to businesses and factories at lower costs than Edison could match.

During most of the 1890s the war raged between AC and DC. Edison played up every fatal electric accident as due to high-voltage transmission. The state of New York introduced electrocution by alternating current as a means of capital punishment at that time, and Edison's friends tried to make AC a synonym for danger and death. In retaliation, Tesla invented an electric chair that worked on DC, a device still in use today.

Eventually, Westinghouse's financial arguments, as shown in Example 18-4, were too persuasive to ignore. Today he is considered the main figure in the worldwide use of AC for electric power. ●

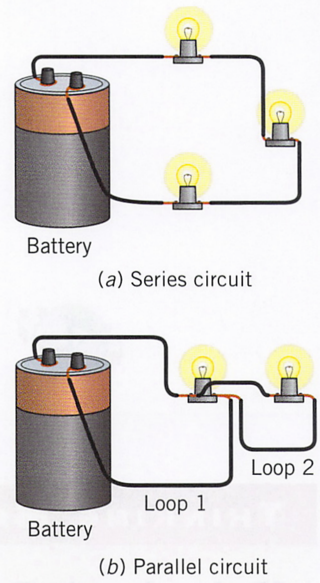


FIGURE 18-15. (*a*) In a series circuit, two or more loads are linked along a single loop of wire. (*b*) In a parallel circuit, different loads are situated on different wire loops.

PARALLEL AND SERIES CIRCUITS

Common household circuits come in two different types, depending on the arrangement of wires and loads. In **series circuits** (Figure 18-15*a*), two or more loads (a series of lightbulbs, for example) are linked along a single loop of wire. In **parallel circuits** (Figure 18-15*b*), by contrast, different loads are situated on different wire loops. Both types of circuits are used in every household (Figure 18-16).

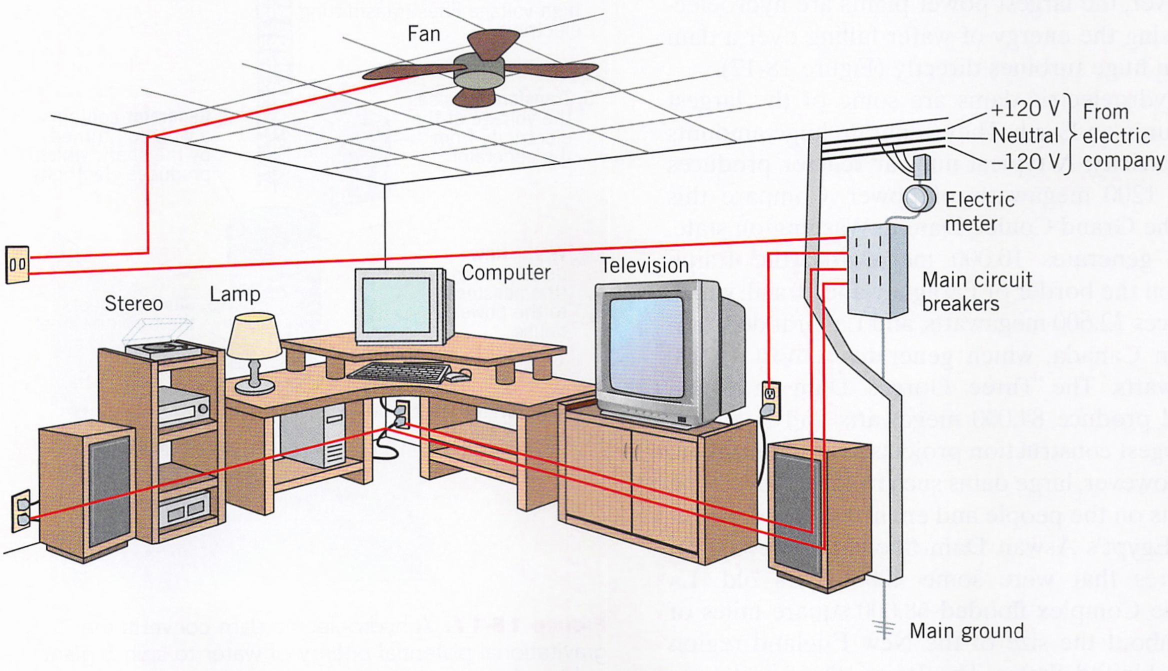


FIGURE 18-16. A typical household electric system has several parallel circuits, each with a number of lights and appliances or outlets in series. Each of these circuits has its own circuit breaker, which will trip if the circuit becomes overloaded.

The basic idea is that in a series circuit the same current flows through each circuit element. The voltage drop across each element, then, is given by Ohm's law and depends on the resistance of the element. In a parallel circuit, on the other hand, the voltage drop across each element is the same, and the amount of current flowing through each element can be different.

The differences between these two types of circuits can become obvious around Christmastime. Many older strands of Christmas lights are linked by a single series circuit. If any one light burns out, the entire strand goes dark because the electric circuit is broken. It can be a frustrating experience trying to find the one bad bulb. Most modern light strands, on the other hand, feature several parallel loops, each with just a few lights. So today, if one light burns out, only a few bulbs along the strand go dark.

THINKING MORE ABOUT

Hydroelectric Dams

Electric generating plants come in various types. Some run on fossil fuel, such as oil, coal, or natural gas. Others depend on nuclear reactors, geothermal vents, or the heat from solar energy. All of these power plants use heat to change water to steam, and the steam turns the turbines that rotate magnetic coils, inducing electric currents. However, the largest power plants are hydroelectric, using the energy of water falling over a dam to turn huge turbines directly (Figure 18-17).

Hydroelectric dams are some of the largest structures on Earth. They generate huge amounts of electricity. A typical nuclear reactor produces about 1200 megawatts of power. Compare this with the Grand Coulee Dam in Washington state, which generates 10,000 megawatts; the Itaipu Dam on the border of Paraguay and Brazil, which produces 12,600 megawatts, and La Grande Complex in Canada, which generates almost 16,000 megawatts. The Three Gorges Dam in China should produce 84,000 megawatts and is one of the largest construction projects ever undertaken.

However, large dams such as these have huge impacts on the people and environment of the region. Egypt's Aswan Dam flooded archeological treasures that were some 4000 years old. La Grande Complex flooded 68,000 square miles of land, about the size of the New England region of the United States. The Itaipu Dam cost over $18 billion and was partly responsible for Brazil's economic problems in the 1990s. The Three Gorges Dam has flooded one of the greatest scenic attractions in all of China and has forced the relocation of over 1 million people. Major dams such as these turn rivers into lakes in landscapes that are not designed for stable lakes.

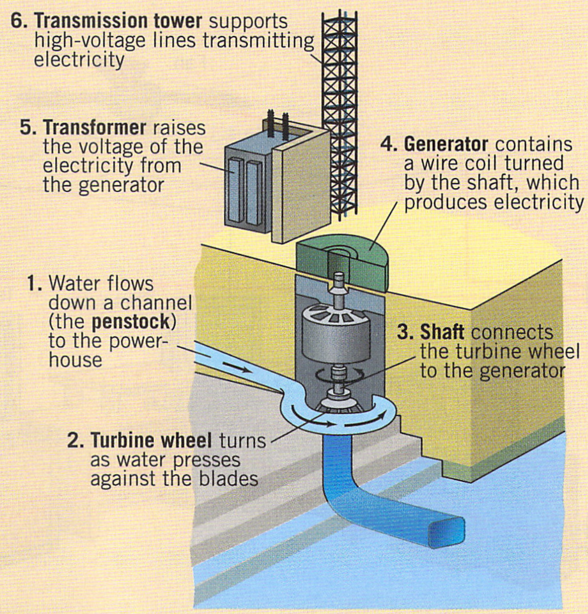


FIGURE 18-17. A hydroelectric dam converts the gravitational potential energy of water to spin a giant turbine that generates electric energy.

Is the availability of cheap electricity worth the cost of relocating people and wildlife? How can you determine the balance of benefits versus costs, both financial and otherwise? What would you think if plans were announced to build a hydroelectric plant near your home?

Summary

An **electric circuit** is an unbroken path of conducting material and contains a source, a closed conducting path, and a load. The quantity of charge flowing per second (the current) is measured in **amperes** or **amps,** the **electric potential** in **volts,** and the **electrical resistance** in **ohms.** When electrons flow through a wire, some of their energy is converted into heat. **Ohm's law** tells us that the **voltage** drop across any resistance is given by the product of the current times the resistance. The power dissipated in a circuit is given by the product of the voltage times the current.

Circuit breakers protect property by creating an open circuit when the current in a circuit exceeds a certain value. **Grounding** circuits protects people from electric shock. A **short circuit** is a low-resistance path from the positive to the negative side of a voltage source and may cause overheating of circuits.

A **rectifier** is a device that converts alternating current to direct current, and it is often used in modern electronic devices. A **transformer** is a device that changes the current and voltage of alternating current through the action of electromagnetic induction. Transformers play an important role in distributing electric power over long distances.

In a **parallel circuit,** all circuit branches have the same voltage. In a **series circuit,** the same current flows through all circuit elements.

Key Terms

ampere (amp) The physical unit used to define a quantity of electric current. (p. 375)

circuit breaker A device that prevents too much current from flowing through it by creating an open circuit. (p. 382)

electric circuit An unbroken path of material that carries electricity. (p. 374)

electric potential The quantity in electric circuits that is analogous to pressure in water flowing through pipes; it is the potential energy per unit charge across a region in a circuit. (p. 375)

electrical resistance (measured in **ohms**) The quantity that defines how hard it is to run electric current through an object. (p. 375)

grounding The process of connecting an element of a circuit to the ground to provide a safe path for the current in the case of an overload. (p. 385)

ohm The physical unit that defines the amount of electrical resistance. (p. 375)

Ohm's law The relationship among voltage, current, and resistance in a circuit. (p. 378)

parallel circuit A circuit, or part of a circuit, that consists of two or more loads linked together along different loops of wire. (p. 391)

rectifier An electric device that converts alternating current to direct current. (p. 386)

series circuit A circuit, or part of a circuit, that consists of two or more loads linked together along a single loop of wire. (p. 391)

short circuit A low-resistance path that causes potentially dangerous amounts of current in a circuit. (p. 385)

transformer A device that converts a high voltage to a low voltage (step-down transformer), or a low voltage to a high voltage (step-up transformer). (p. 387)

volt The physical unit used to quantify the amount of electric potential. (p. 375)

voltage (measured in **volts**) Synonymous with *electric potential*. (p. 375)

Key Equations

Power dissipated in a circuit element: $P = IV$

Voltage drop across a resistor (Ohm's law): $V = IR$

Power dissipated in a resistor: $P = I^2R$

Review

1. What is an electric circuit? What are its three key parts?
2. What are some of the similarities between electrons flowing through a wire and water flowing through a pipe? What are some of the differences?
3. What does an ampere measure? Where do you run into this term in your everyday experience?
4. What is electric potential?
5. What does the volt measure? Where do you run across this term in your everyday experience?
6. How is voltage like the pressure in a city water system? Explain.
7. What does the ohm measure? Where do you run across this term in your everyday experience?
8. What is the physical basis of resistance? Explain.
9. What is meant by the drift velocity of an electron? Is this a very fast velocity compared to the speed of the electric signal itself? Explain.
10. What is the relationship between the heat generated by electrons flowing in a wire and the resistance of the particular wire? How does this relationship affect the design of appliances such as toasters and space heaters?
11. What is the relationship between the voltage across a circuit, the current through it, and the resistance of the wire that composes the circuit?
12. What are two things that can be done to increase the flow of current in a circuit? How is this analogous to the water flow in a pipe?
13. How is lightning like an electric circuit? Explain.
14. What is the relationship between the power an appliance consumes, the voltage across it, and the current through it?
15. If we double the amount of wire through a wire or a circuit element, how much do we increase the heat generated? What equation demonstrates this?
16. What are two of the principal dangers of electric circuits?
17. Why do wires that carry large currents have much larger diameters than wires that carry power to ordinary electric lamps?
18. What is the purpose of a circuit breaker? How does it work?
19. What are the similarities and differences between a circuit breaker and a fuse?
20. Why should you *never* touch an electric device when you are in contact with water? Explain this in terms of Ohm's law.
21. What do you think are some of the more common causes of short circuits in household electric appliances? How might they be prevented?
22. What does grounding an electric circuit mean? How is this done?
23. What is a short circuit? How does grounding an electric device help decrease the danger of a short circuit?
24. What are some similarities and differences between the electric circuits in your home and the transmission of nerve impulses in your body?
25. What is direct current? Give an example of it.
26. What is alternating current? How does it differ from direct current?
27. What are the advantages and disadvantages of alternating current?
28. What is a rectifier? Name some ordinary devices that use a rectifier. Why is it needed and how does it work?
29. What is a transformer and why is it used? Give some examples of its use.
30. How does a transformer work? What is the purpose of the primary coil, and what is the purpose of the secondary coil?
31. Are the primary and secondary coils of a transformer directly linked? Explain.
32. Why is electric power transmitted at very high voltages?
33. What are the differences between a step-up and a step-down transformer? When is each used?
34. What is the relationship between the number of primary and secondary loops and the current going in and out of a transformer? What is the relationship between the voltages and the number of coils?
35. What do we mean by a series circuit? Give an example.
36. What is a parallel circuit? Give an example. In what ways does it differ from a series circuit?
37. What are some of the advantages of direct current? What are the disadvantages?
38. What are some common examples of series circuits? Parallel circuits? In what situations might one be preferable to the other?

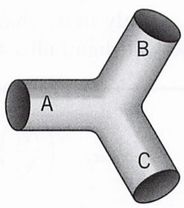
Questions

1. What is the difference between electric current and electric charge?
2. Suppose 100,000 electrons per second pass a particular point in a wire. Is this a large or small current compared to one ampere? Explain.
3. Why should you never seek the shelter of a tree if you are caught outside in a thunderstorm?
4. Suppose a very large number of ants are confined to the inside of a long cardboard tube. Half of the ants are red and half are black. The red ants have acquired a positive

charge by donating some of their electrons to the black ants. Thus, the black ants have acquired an equal and opposite amount of negative charge. Let the tube be aligned so that we can distinguish between the right and left ends of the tube. In which of the following situations is there an electric current? If there is an electric current, state its direction.

a. The black ants are moving to the right and the red ants are not moving.
b. The black and red ants are moving in the same direction at the same speed.
c. The black ants are moving to the left and the red ants are moving to the right.
d. None of the ants is moving.
e. The black ants are not moving, but half of the red ants are moving to the right and half are moving to the left.

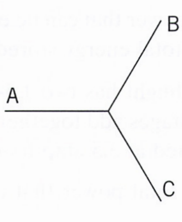
5. Consider the system of three water pipes connected at a junction, as shown in the figure. You measure 5 gallons per minute flow in pipe A toward the junction and 10 gallons per minute flow in pipe B toward the junction. What is the water flow in pipe C?



Questions 5, 6

6. Consider the system of three water pipes connected at a junction, as shown in the figure. You measure 5 gallons per minute flow in pipe A away from the junction and 10 gallons per minute flow in pipe B toward the junction. What is the water flow in pipe C?

7. Consider three wires connected at a junction, as shown in the figure. You measure 100 electrons per second flowing in wire A toward the junction and 200 electrons per second flowing in wire B toward the junction. What is the electron flow in wire C?



Questions 7, 8

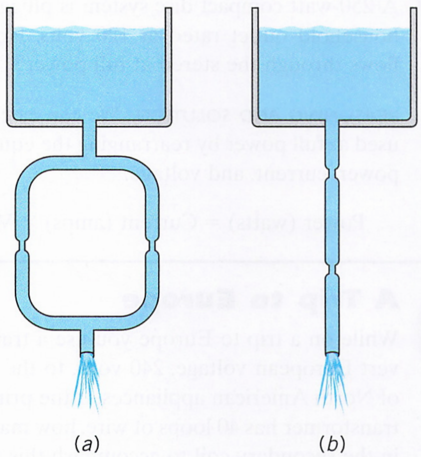
8. Consider three wires connected at a junction, as shown in the figure. You measure 200 electrons per second flowing in wire A toward the junction and 300 electrons per second flowing in wire B away from the junction. What is the electron flow in wire C?

9. Why do you think a thicker wire has less resistance than a thinner wire made of exactly the same material?

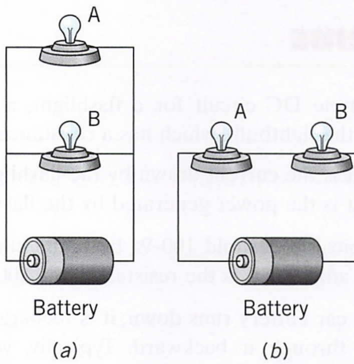
10. A copper wire carries 1 amp of electric current. Do the electrons flowing in the wire give it a negative charge? Explain.

11. How do the length, diameter, and temperature of a copper wire affect its resistance?

12. A water tank empties itself by draining water out of the bottom through a pipe network. The figure shows two possible configurations of pipes leading out of the bottom. In each case, the pipe has the same diameter and there are two identical constrictions in the pipe. (A constriction is simply a location where the pipe diameter is smaller.) In which case will the water tank drain in less time? Explain.



13. The figure represents two possible ways to connect two lightbulbs to a battery. All the bulbs are identical. In which case will the total current running through the battery be greater? Explain.



Questions 13, 14

14. The figure represents two possible ways to connect two lightbulbs to a battery. Bulbs A are identical and have less resistance than bulbs B, which are also identical. Which bulb has the most current running through it? Explain.

15. Does a transformer work with direct current? Why or why not?

16. How does a three-way lightbulb work?

17. Even though copper conducts electricity very well, it does have some resistance. How would the resistance of a 1-meter-long thick copper wire compare to the resistance of a 1-meter-long thin copper wire? Explain.

18. Why do you think strings of holiday or party lights are wired in parallel, not in series?

19. Which has more resistance: a 50-watt lightbulb or a 100-watt lightbulb? Explain.

20. Two lightbulbs are wired in series and connected to a 12-volt battery. What happens to the current through the battery if a third bulb is added in series? What happens to the power dissipated by the bulbs?

21. Two lightbulbs are wired in series and connected to a 12-volt battery. What happens to the current through the battery if a third bulb is wired in parallel with the other two bulbs? What happens to the power dissipated by the bulbs?

Problem-Solving Examples

The Power of Sound

EXAMPLE 18-5

A 250-watt compact disc system is plugged into a normal household outlet rated at 120 volts. How much current flows through the stereo at full power?

REASONING AND SOLUTION: We can calculate the current used at full power by rearranging the equation that relates power, current, and voltage:

$$\text{Power (watts)} = \text{Current (amps)} \times \text{Voltage (volts)}$$

We can manipulate this equation to find the current:

$$\text{Current} = \frac{\text{Power}}{\text{Voltage}} = \frac{250 \text{ watts}}{120 \text{ volts}} = 2.08 \text{ amps}$$

This current is slightly more than the current that flows through two 100-watt lightbulbs. ●

A Trip to Europe

EXAMPLE 18-6

While on a trip to Europe you use a transformer to convert European voltage, 240 volts, to the 120 volts typical of North American appliances. If the primary coil of your transformer has 40 loops of wire, how many loops must be in the secondary coil to accomplish this transformation?

REASONING AND SOLUTION: In this case we know the primary voltage (240 V), the secondary voltage (120 V), and N_1 (40). To determine N_2 we have to rearrange the transformer equation:

$$V_{\text{secondary}} = \left(\frac{N_1}{N_2}\right) V_{\text{primary}}$$

so

$$N_2 = N_1\left(\frac{V_{\text{primary}}}{V_{\text{secondary}}}\right) = 40\left(\frac{240}{120}\right) = 80 \text{ loops}$$ ●

Problems

1. In a simple DC circuit for a flashlight, a 1.5-V battery powers the lightbulb, which has a resistance of 2 ohms.

a. What is the current drawn by the flashlight?
b. What is the power generated by the flashlight?

2. In a typical household 100-W bulb, the current drawn is about 1 amp. What is the resistance of a 100-W lightbulb?

3. When a car battery runs down, it is recharged by running current through it backward. Typically, you might run 5 amps at 12 volts for 1 hour. How much energy does it take to recharge a battery?

4. A single electron has a charge of 1.60×10^{-19} C. How many electrons does it take to produce 1 ampere of current if they all pass a specific point in 1 second?

5. A typical 1.5-V alkaline D battery is rated at 3.5 amp-hours.

a. What is the power that can be expended by the battery?
b. What is the total energy stored by this battery?

6. A standard flashlight has two 1.5-V D batteries arranged so that their voltages add together, with a 2-W bulb. These batteries are rated at 3.5 amp-hours each.

a. What is the total power that can be expended by the batteries?
b. What is the total energy stored in the flashlight batteries?
c. How long can the flashlight keep the bulb lit at its rated power of 2 W?

7. Giselle and Anna decided to impress their physical science professor with a simple experiment investigating the resistance of a 100-W lightbulb. They used a VARIAC (which provides a variable voltage to a circuit) in a series circuit with one 100-W lightbulb. They measured the current and voltage, which are listed in the following table.

Voltage (volts)	Current (amps)
120	0.81
100	0.72
80	0.62
60	0.51
40	0.40
20	0.23

a. Calculate the resistance of the lightbulb for each voltage setting.
b. Does the resistance of the 100-W bulb increase or decrease with the voltage? With the current?
c. From your personal experience, can you predict whether the temperature of the filament of the lightbulb increases or decreases with the voltage?
d. Using this information, speculate on the reason(s) the resistance of the lightbulb changes.

8. Most household circuits have fuses or circuit breakers that open a switch when the current in the circuit exceeds 15 amps. Will the lights go off when you plug in an air conditioner (1 kilowatt), a TV (250 watts), and four 100-watt lightbulbs? Why?
9. Energy-efficient appliances are important in today's economy. Suppose that a lightbulb gives as much light as a 100-watt bulb, but consumes only 20 watts while costing $2.00 more. If electricity costs 8 cents per kilowatt-hour, how long will the bulb have to operate to make up the difference in price?
10. An energy-efficient air conditioner draws 7 amps in a standard 120-volt circuit. It costs $40 more than a standard air conditioner that draws 12 amps. If electricity costs 8 cents per kilowatt-hour, how long would you have to run the efficient air conditioner to recoup the difference in price?

Investigations

1. Explore the beginnings of the electric generation and transmission utility industry. How was the choice made to use alternating current over direct current to transmit power? Was there any disagreement over which to use and, if so, what were the arguments for and against each?
2. Make an inventory of all your electric appliances. How many watts does each use?
3. Most household circuits have fuses or circuit breakers that open a switch when the current in the circuit exceeds 15 amps. How many of the appliances that you listed in Investigation 2 could you run on the same circuit without overloading it?
4. Examine your most recent electric bill. How much power did you use? How much did it cost? Is there a discount for electricity used at off-peak hours? Examine your living place for all the locations where you use electricity. Plan a strategy for reducing your electric bill by 10% next month. You can reduce consumption by turning off lights and appliances when not in use, installing lower-wattage bulbs, or using electricity during low-rate times.
5. How many kilowatts of electric power does a typical commercial power plant generate? How much electricity does the United States use each year? Is this amount going up or down?
6. Identify the major electric circuit components in your automobile. Which require the greatest power?
7. What materials other than copper might be used as common wire for electricity? What are the advantages and disadvantages of other such materials?

WWW Resources

See the *Physics Matters* home page at **www.wiley.com/college/trefil** for valuable web links.

1. **http://www.physics.uoguelph.ca/tutorials/ohm/index.html** DC circuits tutorials from the University of Guelph, Canada.
2. **http://www.ee.umd.edu/~taylor/frame1.htm** A gallery of electromagnetic personalities, including Ampere, Ohm, Franklin, and Volta.
3. **http://jersey.uoregon.edu/Voltage/** An animated circuit simulator teaching Ohm's law from the University of Oregon.
4. **http://micro.magnet.fsu.edu/electromag/java/transformer/index.html** A simple Java applet demonstrating a simple two stage transformer from Florida State University.