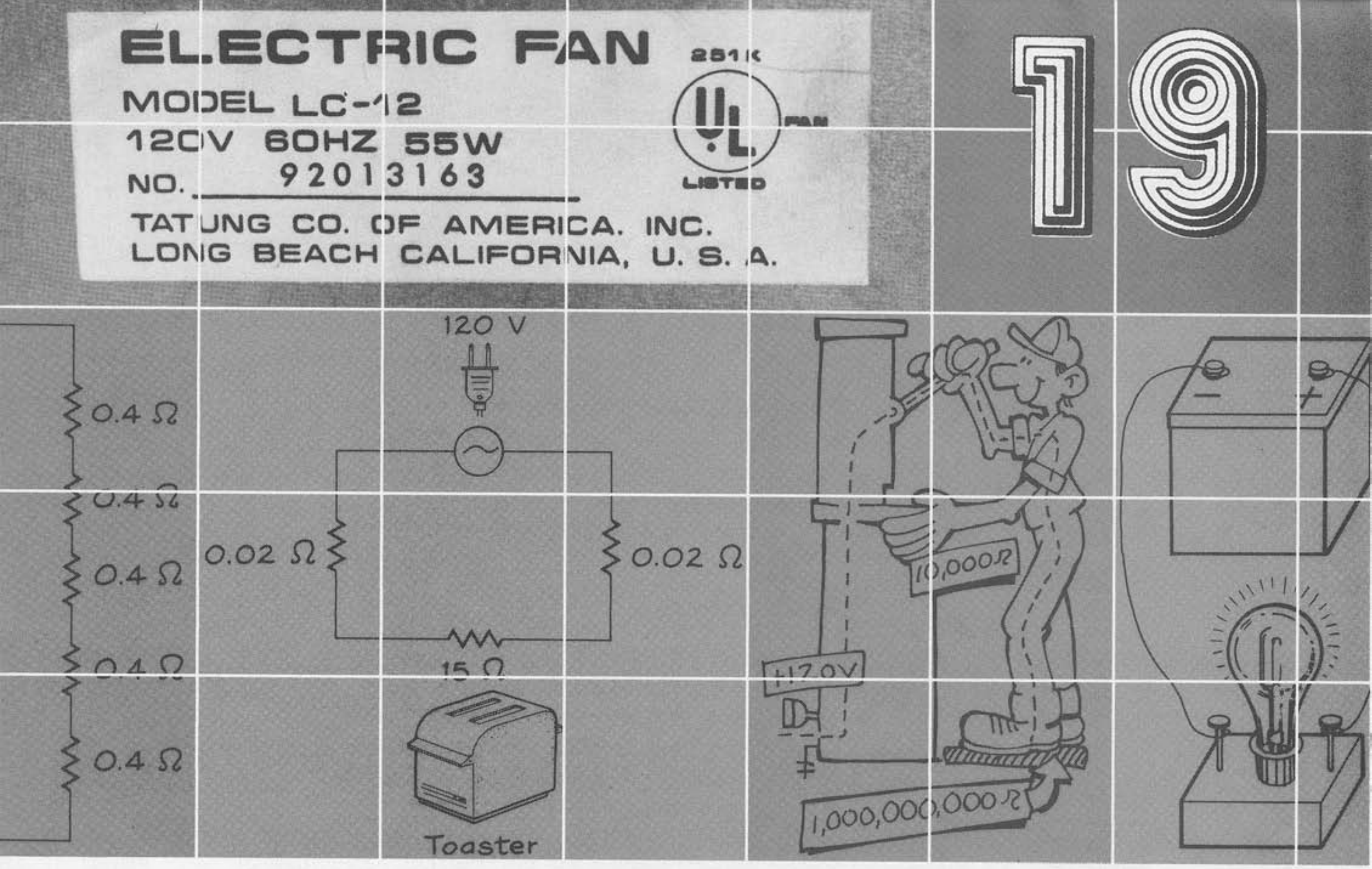

Turning on the Lights

"Live better electrically" was an advertising slogan of the electrical industry during the 1950s. The advantages were clear. Electrical energy could be transmitted over hundreds of kilometers through relatively small wires, was instantly available, and was controlled at the flip of a switch. Automatic devices ranging from washing machines to garage door openers offered more freedom and less drudgery to the average American family. As we used more and more electrically operated gadgets, we required larger amounts of electrical energy. By the mid-1970s our needs began to outstrip our supplies. Living better electrically began to threaten limited energy resources.

In this chapter we examine the process by which electrical energy is transferred from an energy source to an energy receiver. Lightning and sparks are uncontrolled transfers of energy, while *electric circuits* provide a means of controlling the transfer. The *voltage* and *current* in the circuit describe the rate of energy transfer. The *resistance* of any energy receiver states how that receiver resists or retards the motion of the current. Given two of the three circuit variables—voltage, current, and resistance—*Ohm's law* allows us to determine the third. Circuits that involve two energy receivers can be either *series circuits* or *parallel circuits*. We discuss the way in which each configuration affects the total power and current delivered by the energy source. Electrical energy is delivered to receivers by electrons that move through the components in the circuits. The motion of these electrons depends on the type of circuit, the voltage of the source, and the resistance of the receiver.

SPARKS AND LIGHTNING

The electrical interaction, one of the four fundamental interactions, has proven useful in explaining the structure of the atom and is one of the most common ways by which we transport energy from one place to another. As we have seen, electrical charges come in two varieties, positive and negative. In matter, the positive charges are carried by the protons in the nucleus of the atom, while the much less massive electrons carry the negative charge. The attraction between opposite charges and repulsion between like charges can be controlled to move energy about.

Before people learned to control the movement of electrical energy, they observed the uncontrolled transfer of electrical energy by sparks and lightning. These two phenomena are variations on the same general theme. In each, some type of motion or rubbing pulls electrons away from their atoms, building up concentrations of electrical charge. When the electrical forces become very great, the charges jump toward a place of opposite charge. This sudden motion of the electrical charges is what we call a spark or lightning.

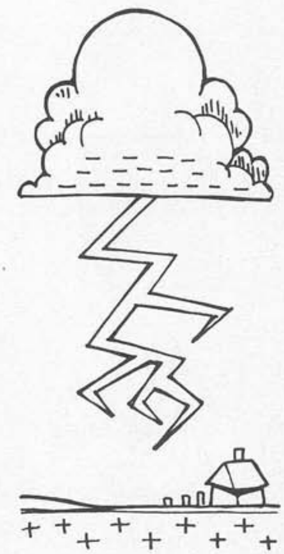

Figure 19-1
When the concentration of negative charges gets large enough, a bolt of lightning transfers electric charge (with energy!) to the ground below.

During a thunderstorm, molecules and atoms move about rapidly in the clouds. As this motion occurs, electrons are stripped from the atoms. One result is a separation of charges within the clouds (Figure 19-1). Electrons with their negative charges tend to collect at the bottom of the cloud, leaving positive charges at the top. The electrical interaction at a distance creates a strong attraction between the negative cloud bottom and the ground. If the force becomes great enough, it causes a sudden motion of the charges and a transfer of electrical energy between the cloud and the earth.

Approximately a century after Benjamin Franklin first showed that lightning was the uncontrolled transfer of electrical energy (Figure 19-2), we began to control electricity. Electrical forces can be used to explain our present methods. However, quantities that can be derived from the concept of electrical force—voltage and current—offer us a more convenient way of describing electricity. We turn now to a study of these quantities.

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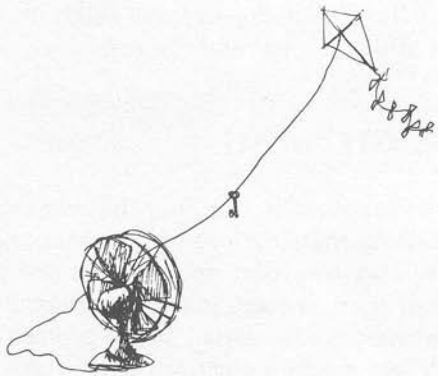
Figure 19-2
Benjamin Franklin demonstrated that lightning was the uncontrolled transfer of electrical energy.



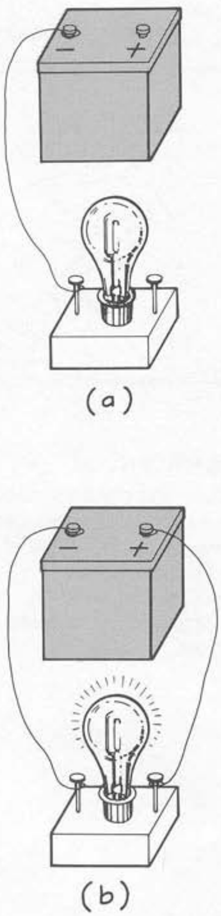


Figure 19-3

Energy can be transferred from the source to the receiver only in a closed circuit. **(a)** No conducting wire leads to the other side of the battery. **(b)** Conducting wires offer a complete path from source to receiver and back to source.

ELECTRICAL CIRCUITS

Walk into a dark room and flip the switch. Energy in the form of light floods the room. Turn on the electric stove to cook supper. Thermal energy cooks the food. Turn on the television to catch the evening news. Energy—sound and light—gets the message across. Need to saw a board? Flip a switch; kinetic energy is instantly available. The dentist's office is on the fourth floor. Push the elevator button; your gravitational potential energy changes as you move upward. Countless devices convert electrical energy into other forms—light, heat, sound, kinetic energy, and gravitational potential energy.

We can describe the process that supplies these devices with energy in terms of our energy-source-energy-receiver model. A source, typically a battery or a wall socket connected to the local power plant, supplies the energy. Wires transfer this energy from the source to the receiver, like the television, which converts the energy into some other form. The energy source, the energy receiver, and the wires are collectively called an **electric circuit.** Let's examine the role of each component in delivering the energy we so readily consume.

Energy Sources: Voltages

Hook a flashlight bulb to a 1.5-volt (V) battery, and the light glows. Connect the same bulb to a 3-V battery, and it glows more brightly. Whatever voltage is, we see its effect in the brightness of the bulb. When connected to the same receiver, a 3-V battery delivers more energy than a 1.5-V battery.

A battery's voltage is related to its electrical potential energy. To understand how this energy arises, let's look at an analogy from gravitation. A hammer lies on the ground because gravitational forces draw it and the earth together. When we lift the hammer, we do work to overcome the forces of attraction between the hammer and the earth. The amount of work we do describes the amount of gravitational potential energy gained by the hammer. Much the same model can be applied to electrical charges. Positive and negative charges attract one another. Batteries and electrical generators pull negative charges away from positive ones, doing work to overcome the electrical forces of attraction. The amount of work done depends on the number of charges and the distance they are separated. This work describes the electrical potential energy gained by the negative charges (electrons). Thus, work done by the battery or generator becomes available to the electric circuit as electrical potential energy.

When a battery separates two pairs of charges, it does twice as much work as when it separates one pair. However, the work done on each charge is the same in both cases and so is the change in the potential energy of each charge. Because each charge carries potential energy, the energy of each one is a convenient measure of the ability of the source to supply electrical energy.

The electrical potential energy which an energy source provides to each unit of charge is called the **voltage,** or **potential difference,** of the source. Thus

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

Voltage

Potential energy

$$V = \frac{PE}{q}$$

Electric charge

The units of voltage and potential difference are **volts** (V). A 1-V energy source supplies 1 joule (J) of energy to 1 coulomb (C) of charge.

As with other forms of potential energy, voltages are relative quantities. To state a voltage we must first choose a reference, then measure the voltage (potential difference) between the source and the reference. For many sources the reference is chosen to be the electrical potential energy of the charges on the surface of the earth, commonly called the *ground.* Most electrical power companies deliver a voltage of 120 V to your outlets. This statement means that the potential difference (voltage) between one of the prongs and the ground is 120 V. (The other prong is held at the same potential energy per charge as the ground. It is said to be *grounded.*) In some cases the reference is not the ground. For a battery either of its terminals is chosen as a reference, and the voltage of the other terminal is measured relative to it. To say your battery has a voltage of 1.5 V is shorthand for stating that the difference in voltage between the two terminals is 1.5 V.

Energy Transmission: Current

Attach a wire from a terminal on a battery to one side of a light socket (Figure 19-3(a)). Nothing happens. Add a second wire from the other side of the socket to the other terminal on the battery (Figure 19-3(b)). The light bulb glows. For electrical energy to move from the battery to the light bulb, a complete path must be available from one side of the battery to the other.

Lightning jumps from a cloud to the ground; current travels from one terminal to the other. In both cases, electrical energy moves from the point of higher voltage to that of lower voltage. You will recall that thermal energy always moves from regions of higher temperature to regions of lower temperature. In an analogous fashion, electrical energy always moves from a higher voltage to a lower voltage. When the voltage difference is enormous (as in a thunderstorm) and no established transmission path exists, the energy may be moved suddenly in the form of a spark or lightning. To be of any use,

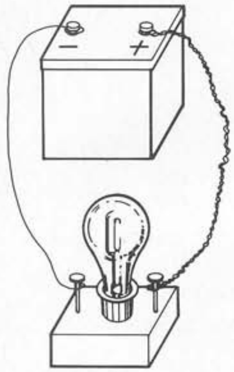


Figure 19-4
Metal wires work; strings do not.

however, the transfer of energy must proceed in a controlled fashion along an established path.

If you connect a wire between two places with different voltages, electrical energy moves from one to the other only until the voltages are equal. When lightning strikes, the voltages in the cloud and on the earth become the same for a brief moment. A similar result occurs when you connect a single wire to a light bulb. A tiny amount of charge moves from the battery to the lamp before the two attain the same voltage. However, this process occurs so quickly that you see no light. By connecting the bulb to the second terminal of the battery—completing the circuit—you create an entirely different situation. The battery maintains a constant voltage difference between its two terminals. Current continues to move from one terminal to the other until the battery runs down. An essential requirement for a current is a transmission path with its ends maintained at different voltages.

Consider an experiment in which one of the wires connecting the bulb and the battery is replaced with a string (Figure 19-4). The light goes off. Not just any material can provide a transmission path for current. Metal wires work; strings do not. Materials that allow the easy movement of charge are called **conductors,** while those that do not allow such easy motion are called **insulators.** Air is a good insulator—as you can see—because energy does not move from one terminal of a battery to the other through the air. Only tremendous voltages, such as those in a storm, can cause the transmission of electrical energy through air. Metals, on the other hand, are excellent conductors. Metal wires are the most commonly used transmission routes for electrical energy.

We can use these concepts to describe the two types of circuits shown in Figures 19-3 and 19-4. A **closed circuit** has a complete path of conductors from the one terminal of the source, through the energy receiver, and back to the other side of the source. Electrical energy will flow through these circuits, of which the circuit in Figure 19-3(b) is an example. Circuits through which electrical energy does not move are called **open circuits.** Figures 19-3(a) and 19-4 are examples. While a complete path may be present in Figure 19-4, at least part of the path includes an insulator. Thus no complete path of conductors is available to carry the energy. The controlled transfer of electrical energy can occur only in closed circuits.

The most common way to open and close a circuit is by using switches. In the off position (Figure 19-5(a)) the metal parts of a switch do not touch. The circuit is open. When the switch is turned to the on position, the metal parts touch (Figure 19-5(b)) and create a closed circuit. This opening and closing of circuits provides us some control over the transfer of electrical energy.

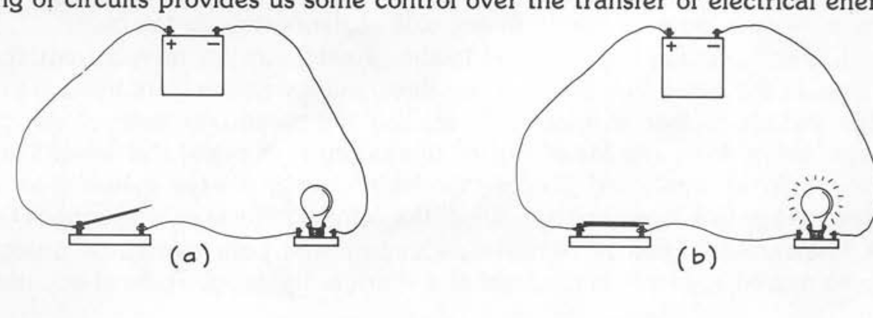
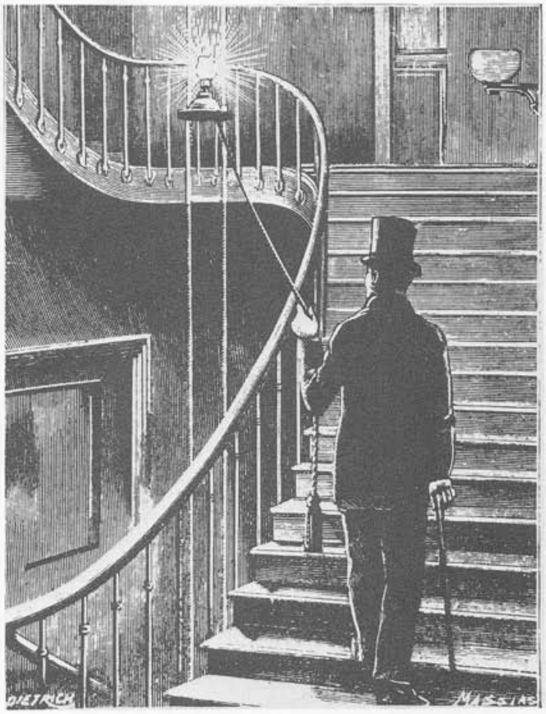


Figure 19-5
A switch can be used to **(a)** open and **(b)** close an electrical circuit.



TAKING THE LIGHT WITH YOU

When you walk up the spiral staircase of your Victorian mansion, how can you be certain that the way is lighted and still minimize the cost of electricity? This question was on the mind of Armand Murat in 1895 when he invented the traveling stairway lamp. The lamp rides on two cables (a) and (b), which are electrical conductors. Thus when a switch (not shown) is closed, the conductors and the lamp (c) make a closed circuit. Because the conducting cables go from the ground floor to the top of the house, the circuit is closed at any point at which the lamp makes a connection between the two conductors. You will have light by which to see all along the stairs as you push the lamp with your cane (d). Just make sure that your cane is constructed from an insulator!

Once the circuit is closed, charges move from the energy source to the receiver. This motion of charges is an **electrical current,** defined as the amount of charge that moves past a point in a circuit divided by the time interval in which the measurement of charge is made:

$$\text{Electric current} = \frac{\text{amount of charge moving past a point}}{\text{time interval}}$$

Electrical current

Electrical charge that flows past a point

$$I = \frac{q}{t}$$

Time interval

When electric charge is measured in coulombs and time in seconds, the current is measured in **amperes** (A), often just called amps. One ampere is equal to 1 C of charge passing a point each second. **Ammeters** are used to measure current in a circuit.

SELF-CHECK 19A

An electron has a charge of 1.6×10^{-19} C. What is the current when one electron passes a point per second? When 10^{19} pass in 1 second?

Energy Receivers: Resistance

Thousands of different energy receivers are used in electric circuits. All play the same role—converting the electrical energy supplied by the energy receiver into some other useful form of energy—heat, light, sound, kinetic energy, and so on. Yet each of the receivers affects the circuits in which they are placed differently. We can investigate these differences by measuring the current present when different energy receivers are connected to the same energy source.

Suppose you reach into a drawer full of old light bulbs and pull out three of them. Their markings are gone, but each seems a little different from the others. To see if they are really different, you hook each bulb into a circuit with an ammeter and connect each to an identical source. Although the voltage across each circuit is the same, each bulb burns with a different brightness, and the current in each circuit is different. The circuit containing the brightest bulb has the most current; that containing the dimmest bulb has the least current.

The characteristic of the energy receiver that determines the size of the current when the energy sources are identical is electrical resistance. As its name implies, **electrical resistance** describes how well a circuit component resists, or retards, the passage of electric current. The brightest bulb has the lowest resistance of the three and, therefore, allows the movement of the most current through it. Resistance is a characteristic of the entire circuit, but since the resistance of the transmitting wires is generally very small, we are usually concerned only with the resistance of the energy receiver.

Numerically, **electrical resistance** is defined as the ratio of the voltage of the energy source to the current moving through the energy receiver.

Electrical resistance

Voltage

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

Current

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

When voltage is measured in volts and current in amperes, resistance is determined in **ohms,** often represented by the symbol Ω. For a light bulb connected to a 120 V energy source in a circuit carrying a current of 1.4 A, the resistance is $(120\text{V})/(1.4\text{ A}) = 85.7\ \Omega$. If a different light bulb is placed in the same circuit, a current of 0.5 A moves through it. Then the resistance of this second light bulb is $(120\text{ V})/(0.5\text{ A}) = 240\ \Omega$. As the resistance of an energy receiver increases, the current decreases.

Electrical resistance is a property of the material from which a device is made. If we compare the resistance of a piece of copper with an identically shaped piece of rubber (Table 19-1), we see the difference between electrical conductors and insulators. Copper, with its extremely low resistance, is used to make connecting wires in electrical circuits. Rubber, a substance with very high resistance, is used in a variety of electrical insulators. Between the extremes of insulators and conductors lie materials with resistances that range from a few ohms to a few million ohms.

Table 19-1 Electrical Resistance of Some Energy Receivers (in ohms)

Copper wire*	1.7×10^{-8}	Light bulbs	100-3000
Aluminum wire*	2.7×10^{-8}	Distilled water*	5000
Salt water*	0.02	Glass*	10^{12}
Toaster	16	Rubber*	10^{15}
Vacuum sweeper	20		

*These resistances are for a cube of one meter on the side.

Ohm's Law

The equation defining resistance is often called **Ohm's law.** It describes the relationship between current, voltage, and resistance in an electrical circuit. The definition of resistance given above is one form of Ohm's law. When we know the voltage and the current, we can use it to calculate the resistance of an energy receiver. However, Ohm's law can be used to determine any one of the three variables if we know the other two. Ohm's law can be written as

$$\text{Voltage} = \text{current} \times \text{resistance}$$

$V = IR$

and as

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

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

Together with the definition of resistance, these equations provide a way of calculating any one of the variables, given measurements of the other two.

Ohm's law tells us that we can control a current going to an energy receiver by changing either the voltage of the source or the resistance of the receiver. In many applications the voltage of the source is fixed, so we vary the resistance of the receiver. For example, a common three-way light bulb has resistances of 96 Ω, 144 Ω, and 288 Ω. With each change of the switch, we connect a different one of these resistances to the circuit and thus change the brightness of the light bulb.

SELF-CHECK 19B

Use Ohm's law to determine the current in the three-way lamp that has resistances of 96 Ω, 144 Ω, and 288 Ω. The lamp is connected to a 120-V energy source.

Circuits, Resistance, and Safety

Normally we do not think of the human body as part of an electrical circuit. However, any time we come into contact with an electrical energy source, we become part of a circuit whether we realize it or not. Knowledge of electrical resistance has played a large role in helping us protect ourselves in today's electrical world.

The damage done to the human body by an electrical shock is either tissue damage due to the conversion of electrical energy to heat or nerve damage due to disruption of normal nerve functions. Nerve impulses involve rather small currents. Consequently, it does not take much to disrupt the human body. However, the path of the current also determines its effect. Currents are most dangerous when they pass through the heart because they disrupt the normal electrical nerve pulses that pace the heart. Currents that would destroy the heart's operation can pass safely through one finger and out the next with little tissue damage. Table 19-2 describes the effects of different sizes of electrical currents on the human body.

Since currents in ordinary household circuits range up to several amperes, electrical circuits in the home pose a potential hazard. Fortunately, large currents frequently travel through two points close to one another on the body. For example, if you touch two adjacent fingers to bare wires, most of the current will go in one finger and out the other and probably cause little damage to the rest of the body. The most vulnerable organ, the heart, is somewhat protected. Additionally, your layer of skin provides a resistance of some 10,000 Ω to 100,000 Ω. If you accidentally come into contact with a 120-V outlet, the current moving through you would be (120 V)/(10,000 Ω) = 0.012 A to (120 V)/(100,000 Ω) = 0.0012 A. Even if it passes through your heart, you will probably survive, although you would certainly notice the effect.

The rather large resistance of your body helps assure that currents through your body remain low. However, we use other resistances to increase the total resistance and, thus, decrease

Table 19-2 Effect of Various Electric Currents on the Body

Current (A)	Effect
0.001	Can feel it
0.005	Painful
0.010	Involuntary muscle contractions (spasms)
0.015	Lose control of muscles (cannot let go)
0.070	If this current passes through the heart, serious disruption occurs. If a current of this size lasts for more than 1 s, it can be fatal.

the current between the user and the electrical device. A variety of common practices add this additional protection. Ordinary conducting wire is surrounded by plastic or rubber insulation that provides a resistance of millions of ohms. Electrical devices are covered by insulated cases that separate the user from the currents inside. Each practice increases the total resistance the system offers to the electric current, consequently decreasing the size of the current that might accidentally be established.

In spite of these safeguards, people are electrocuted accidentally while using ordinary household devices. The majority of these accidents occur because the devices are handled around water. Two effects occur when a hair dryer, for example, is used while taking a bath. Water has a fairly low resistance when it has anything, such as small amounts of salt, dissolved in it. Drops of water that collect around the on-off switch of a hair dryer can conduct current to the user. Touching it becomes similar to sticking your finger in a socket. Further, water on the surface of the skin dissolves the salt that is normally left from perspiration, leaving a layer of salt water, which lowers the skin's resistance to a few hundred ohms or less. If, while wet, you handle a hair dryer with a wet switch, substantial current can move through your body. Most electrical accidents that involve normal household voltages occur near water.

Other accidents occur because of voltage differences between the surfaces of two electrical appliances or between one appliance and the ground. In the kitchen, for example, the surface of a refrigerator may be at a different voltage than that of a stove. If an energy receiver, such as the cook, touches both simultaneously, current moves from one appliance to the other. While the current may flow for a very short time, it can deposit sufficient energy in the cook to do significant damage.

The difference in potential between two objects can occur in some older devices because of the way they were designed. Charges build up on their surfaces. In most modern appliances, such a voltage is most likely to occur because of a failure in the insulation around a wire. A bare or wet wire comes in contact with the metal exterior. Thus the exterior reaches the same voltage as the wall socket.

To prevent these kinds of problems, appliances have a built-in alternative to completing the circuit from the surface through the user. This alternate path, called the ground wire, is the round third prong of a three-wire electrical plug. The outside of each appliance is connected by a conductor to the ground plug. Then, all ground wires in all plugs are connected together through the house's wiring system. Finally, these connections are all attached to a long metal rod placed in the ground. (Hence, the name *ground wire*.) Because conducting paths always exist among the surfaces of appliances and between the appliances and the ground, no voltage differences can build up. Ground wires allow us to prevent unwanted currents, especially when we are likely to be the energy receivers.

The concepts of resistance and complete circuits tells us how to avoid shocks and more serious electrical hazards when using everyday voltages. Do not use electrical devices while wet or around water so you do not lower your resistance, and make sure all appliances are grounded so they cannot build up voltages.

ENERGY TRANSFER IN CIRCUITS

Ouch! The electric bill hit $60 this month and it is not even winter yet. How can I be using so much energy? Let's see—lights, hair dryer, toaster, oven (no, it's gas), stereo, dishwasher, microwave, clock, washer, and dryer. Hmm . . . wonder what uses so much electricity?

As energy costs soar, we have all had to reconsider the amount of electrical energy we consume. Some devices use little energy; others use lots. Some devices are used daily; others are used only a few times a month. Some jobs must be done electrically; others could be done by hand. Before we can list our priorities, we need to be able to describe the energy produced and consumed in electrical circuits.

Electrical Energy and Power

A light bulb converts electrical energy into light and, as we learn when we touch one, heat. How brightly the light bulb shines and how warm it gets provides us with a rough idea of how much electrical energy it has consumed. A light bulb burns more brightly when attached to a 3-V battery than when attached to a 1.5-V battery. Further, a light bulb burns more brightly in a circuit that has a large current than in one with a small current. Certainly, the longer the bulb stays on, the more energy it transforms into heat and light. Voltage, current, and time affect the amount of electrical energy transformed by the light bulb.

From these types of observations, we can conclude that voltage, current, and time each affect the amount of energy delivered to energy receivers such as light bulbs. The definitions of voltage and current are consistent with these observations. Voltage describes the amount of energy supplied to each unit of charge, while current describes the number of charges that pass through the receiver during each second. The product of voltage and current describes the rate (amount per second) at which energy is transferred to the receiver.

Electrical power

Current

$P = IV$

Voltage

We use the concept of power to describe the rate of energy transfer. In a circuit the **electrical power** is the product of the voltage and the current.

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

When voltage is measured in volts and current is measured in amperes, the electrical power is given in watts. One **watt** (W) is equivalent to a rate of energy transfer of 1 joule per second (J/s).

Electrical energy

Current

$EE = IVt$

Time

Voltage

The total energy transferred is the product of the power and the time. For a circuit the **electrical energy** becomes

$$\text{Electrical energy} = \text{current} \times \text{voltage} \times \text{time}$$

Voltage is measured in volts; current, in amperes; time, in seconds; thus, electrical energy is given in **joules.**

SELF-CHECK 19C

Use the current that you calculated in Self-Check 19B to determine the power of the three-way light bulb for each of the resistances.

Consuming Electrical Energy

All electrical appliances and tools carry information about the electrical power they consume. If you look on the bottom of an appliance, you will see information such as that shown in Figure 19-6. Suppose we have a toaster that uses electrical energy at a rate of 900 W and operates at a voltage of 120 V. The bottom of our vacuum sweeper shows similar information. This sweeper operates with a current of 6 A when connected to a 120-V circuit.

Which of the two devices, sweeper or toaster, costs more to operate? Comparing these costs involves two factors: the power required by each and the time during which each operates. We were told the power used by the toaster—900 W. We can calculate the power consumption of the vacuum sweeper from the voltage and current given on the tag. The sweeper uses (120 V) × (6 A) = 720 W. While the toaster consumes more power, we generally use it for shorter times than the vacuum sweeper. Suppose we spend 2 minutes per day toasting bread, for a total of 14 minutes per week. A fair estimate of a thorough vacuuming job might be 30 minutes per week. The total electrical energy consumed in 1 week would be:

$$\text{Electrical energy} = \text{voltage} \times \text{current} \times \text{time}$$

$$\text{Toaster} = (900\ \text{W}) \times (840\ \text{s}) = 756{,}000\ \text{J} \qquad \text{Sweeper} = (720\ \text{W}) \times (1800\ \text{s}) = 1{,}296{,}000\ \text{J}$$

Figure 19-6
Electrical devices carry information about the electrical power they consume.

The weekly cost of vacuuming exceeds that of toasting two slices of bread each morning.

We can analyze a variety of electrical devices in this manner. While the cost of electrical energy supplied by the power company depends on other factors, such as the time of day in which you are consuming and the total monthly consumption, a simple analysis like this one can enable you to get an idea of how much your electrical devices cost to operate. Such information is enormously valuable to consumers in selecting and operating electrical devices.

SELF-CHECK 19D

Before the late 1970s electric hair dryers required 750 W of power. The average person needed to use the dryers for 7 minutes (420 s) to have dry hair. A modern 1200-W hair dryer completes the same job in 3 minutes (180 s). Which dryer is less costly to operate?

MORE THAN ONE RECEIVER

Most circuits have more than one energy receiver. A string of Christmas tree lights may have 20 to 30 light bulbs. The circuit in your kitchen allows you to use the toaster, the blender, and the electric grill simultaneously. A car's electrical circuit includes the spark plugs, the ignition system, the starter motor, lights, radio, windshield wipers, and who knows what else. Using the shorthand notation provided by the circuit symbols listed in Figure 19-7, we can investigate ways in which additional energy receivers can be placed into a simple circuit.

If we construct a circuit with one energy source and two energy receivers, the two distinct configurations shown in Figure 19-8 are possible. These configurations, called series and parallel circuits, differ in terms of the routes that the electric current can take. In a **series circuit** the current must follow one route. It leaves the energy source, passes through both energy receivers, and then returns to the energy source. In a **parallel circuit** the current has more than one route available to it. The current leaves the energy source and separates into two routes at point *A*. Then, part of the current passes through each of the energy receivers. Finally, the two parts of the current recombine at point *B* and return to the energy source. We now examine each of these configurations and their effects on the electrical energy transferred in circuits.

Series Circuits

To examine what happens when energy receivers with identical resistances are added one at a time into a series circuit, consider the situation in Figure

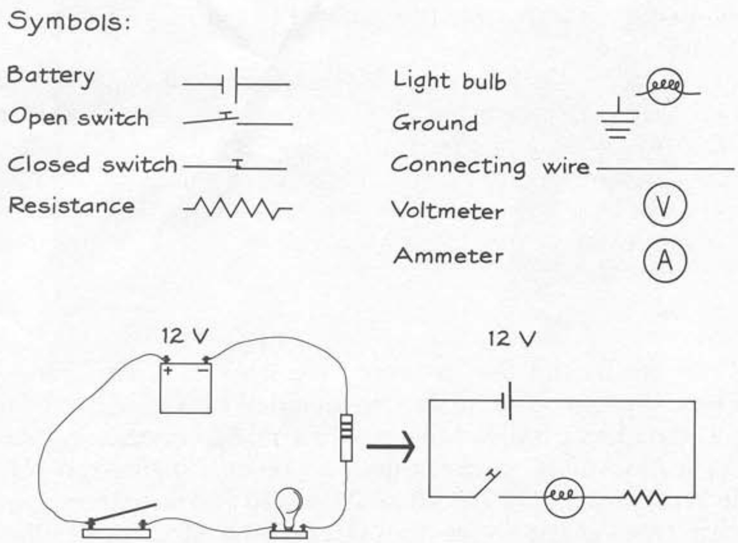


Figure 19-7
Symbols are generally used to provide simpler pictures of electrical circuits.

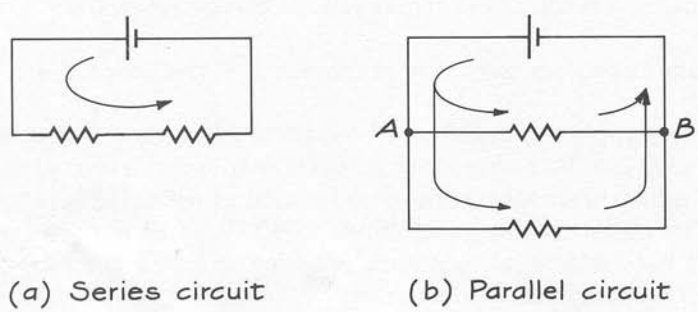


Figure 19-8
Two energy receivers can be placed in series or in parallel with one another. **(a)** In a series circuit, the current has only one route available to it. **(b)** In a parallel circuit, the current separates at point *A* and follows two separate routes before recombining at *B*.

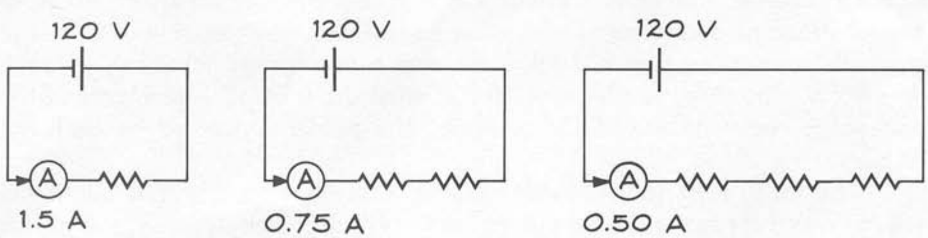


Figure 19-9
Adding energy receivers in series decreases the current in the circuit.

19-9. One resistance, then two, and finally three identical resistances are placed in series with one another. While the voltage provided by the source remains constant, the current in the circuit drops as the resistances are added. The current drops from 1.5 A with one resistance to one-half that value, 0.75 A, when a second identical resistance is added. A third identical resistance decreases the current to 0.5 A, one-third of the current in the original circuit. Adding energy receivers in series decreases the current in the circuit.

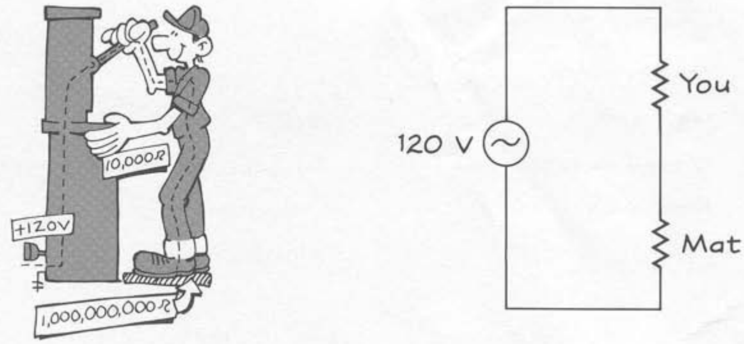


Figure 19-10
A rubber mat adds a second energy receiver in series with the machine operator. The two resistances add, decreasing any accidental currents to a safe level.

We can understand the decrease in current as energy receivers are added in series by looking at the way the electrical resistances of the receivers combine. Using Ohm's law, we find that the total resistance in circuit (a) is (120 V)/(1.5 A) = 80 Ω. In circuit (b) it is (120 V)/(0.75 A) = 160 Ω. The resistance in circuit (c) is (120 V)/(0.50 A) = 240 Ω. The pattern seems clear. Each energy receiver has an identical resistance of 80 Ω. If we place two of them in a series circuit, their resistances add to give us 160 Ω. Placing three of them in series gives us a resistance of 240 Ω. The total resistance in series is the sum of the resistances of the individual energy receivers.

Total resistance (series)

Resistance of element 2

$$R_s = R_1 + R_2 + \cdots$$

Add any other resistances that might be present

Resistance of element 1

$$\text{Total resistance (series)} = \text{resistance } 1 + \text{resistance } 2 + \cdots$$

We can apply the definition of electrical power to the circuits in Figure 19-9 and examine the way in which power is distributed as energy receivers are added in series. In circuit (a) the energy source provides (120 V) × (1.5 A) = 180 W. For circuit (b) the power drops to 90 W, while in circuit (c) it is only 60 W. As each additional resistance is added in series, the total power supplied by the energy source decreases.

Adding receivers in series also decreases the electrical power available to each receiver. Placed in a circuit by itself, each resistance uses 180 W of power. When placed in series with other resistances, each must now share the available energy. In Figure 19-9(b) the two receivers are identical, so each gets 45 W. The three receivers in 19-9(c) must share 60 W—each gets 20 W. As energy receivers are added in series, the power consumed by each decreases.

The most important characteristic of a series circuit is that additional energy receivers decrease the current in the circuit. Consequently, the power delivered to the whole circuit and to each individual receiver decreases. Depending on the situation, this decrease in current and power can be either beneficial or harmful.

Tackling the benefits first, we turn to electrical safety. People who routinely work with devices that operate at high voltages stand on rubber mats. We can understand the usefulness of this practice in terms of energy receivers connected in series. Suppose that a break in the insulation of a wire exposes a machine operator to 120 V. With an average body resistance of 10,000 Ω, the operator experiences a current of (120 V)/(10,000 Ω) = 0.012 A. As shown in Figure 19-10, a rubber mat adds a second energy receiver with a resistance of 1,000,000,000 Ω to the circuit. Because the mat and the person

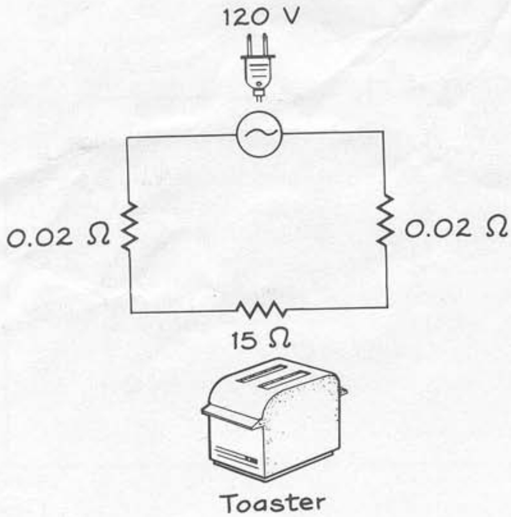


Figure 19-11
A one-meter-long extension cord adds two 0.02 ohm resistances in series with the toaster. The current in the circuit will drop slightly.

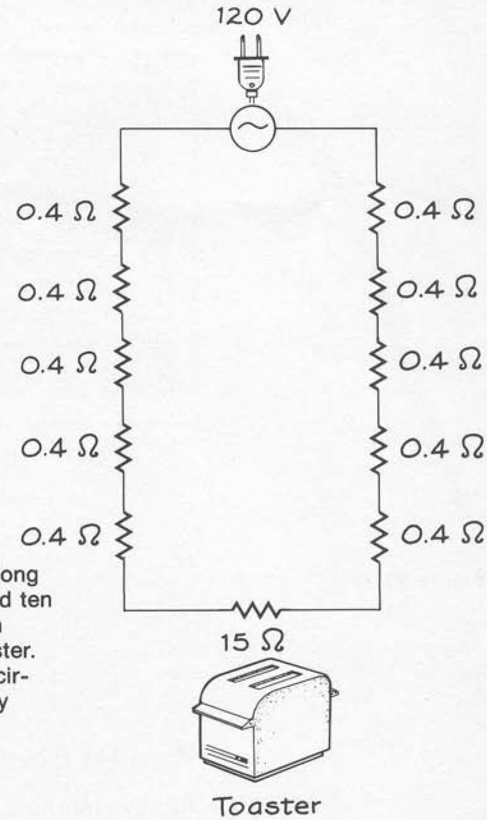


Figure 19-12
Five twenty-meter-long extension cords add ten 0.4 Ω resistances in series with the toaster. The current in the circuit drops by nearly 20%.

are in series, their resistances add. The current moving through each of them is (120 V)/(1,000,010,000 Ω), less than 1.2×10^{-7} A—not enough to cause any damage. Adding an energy receiver in series with a person can save a life!

The disadvantage of resistors in series is that this configuration places some limitations on the design of electrical circuits. A metal conductor, such as copper connecting wire, has such a small resistance that its effect on most electrical circuits is ignored. Nonetheless, each connecting wire does have a small resistance, which adds to the resistance of the circuit. For example, the resistance of a heavy-duty copper extension cord is about 0.02 ohms per meter (Ω/m). If we connect a toaster to a one-meter-long extension cord, we obtain the circuit in Figure 19-11. (The cord contains two 1-meter wires, one leading to the receiver and a second going back to the source.) The total resistance increases from 15 Ω for the toaster by itself to 15.04 Ω for the cord-toaster combination. When plugged into a 120-V outlet, the current drops from 8.0 A to 7.98 A.

For a toaster that operates at 8 A this may seem like no big deal. But suppose you were to decide to eat breakfast in your rose garden, 100 m from your house. You collect five 20-m extension cords, make sure the ground is dry, and string them together. The resistance of each single strand of a 20-m wire is (0.02 Ω/m) × (20 m) = 0.4 Ω. The new toaster-cord circuit, shown in Figure 19-12, has a resistance of 19 Ω. The current has been reduced to 6.3 A, and the power delivered to the toaster is nearly 20% less than when the toaster was sitting on the kitchen shelf. You will have to wait a lot longer for your toast!

SELF-CHECK 19E

One way to construct a circuit that allows you to dim a lamp is to use a variable resistance in series with the lamp. This circuit is shown in Figure 19-13, where the resistance of the lamp is 140 Ω and the arrow indicates that the resistance of the resistor can be changed. Suppose that the variable resistor (VR) has a value of 0 Ω. What are the total resistance, the current, and the power of the circuit? Calculate the same quantities when VR has a value of 60 Ω, and of 120 Ω. Which of these values will give the brightest light? The dimmest light?

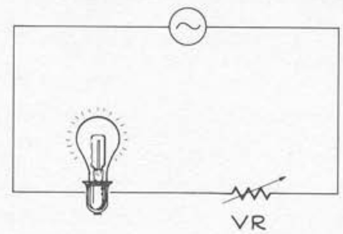


Figure 19-13

Parallel Circuits

Series circuits are useful in situations in which we would like to control the electric current supplied to an energy receiver—either for safety or for convenience. However, such arrangements would be very inconvenient in your home. If household devices were connected in series, the current supplied to each receiver would vary with the number of devices that were being used. If your brother dried his hair, your reading light would dim. Fortunately, there is an alternative.

Examine what happens to a circuit when identical bulbs are added one at a time in parallel. Figure 19-14 shows parallel circuits with (a) one light

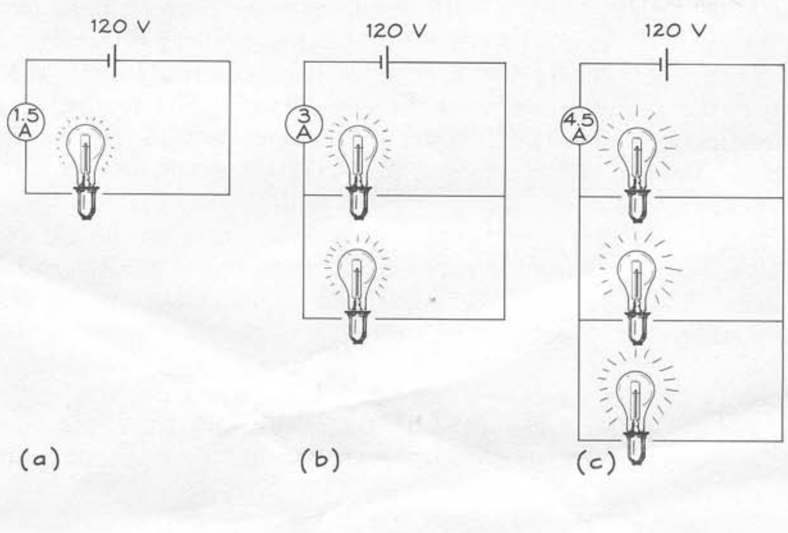


Figure 19-14
Adding light bulbs in parallel increases the current in the circuit.

Why Do My Christmas Tree Lights Burn Out So Fast?

On the boxes in which many Christmas tree lights are packaged is the admonition: Replace burned-out bulbs immediately to avoid additional burnouts. Strings to which this statement applies are connected in series, so to understand the warning we must learn a little more about series circuits.

A series circuit requires fewer wires than a parallel one, so manufacturers frequently use series Christmas light strings to lower the cost of their product. However, a series circuit of lights has a rather annoying property. When one bulb burns out, all the bulbs turn off. Several years ago, someone came up with a solution to this problem. Rather than becoming an open circuit, the burned-out bulb becomes a direct connection—its resistance becomes zero. This type of bulb allows current to move through it, so the rest of the lights stay on.

Even though the line of lights stays on, the package tells us that the other bulbs will burn out if we do not replace the one burned-out light. To see why, consider the whole circuit. In a series circuit every charge moves through every receiver. Thus the current is the same everywhere in the circuit. The voltage, however, is applied across the entire string, so each light gets only part of the total voltage. We can calculate the voltage across each lamp by using Ohm's law. Suppose you have a string of 20 lights, each of which has a resistance of 5 Ω. The total resistance of the circuit is 100 Ω. When connected to a 120-V source, the current is $(120\ \text{V})/(100\ \Omega) = 1.2\ \text{A}$. This current moves through every light. Putting this value into Ohm's law, we can find the voltage across each individual light as voltage = $(1.2\ \text{A}) \times (5\ \Omega) = 6\ \text{V}$. We can also determine the power of each light as power = voltage × current = $(6\ \text{V}) \times (1.2\ \text{A}) = 7.2\ \text{W}$. Repeated use of Ohm's law gives us the voltage across each light and the rate at which it transforms energy into heat and light.

Now, let us see what happens when one of these Christmas lights burns out. The resistance of that light is now zero, while the other 19 lights still have a resistance of 5 Ω each. The total resistance of the circuit becomes $19 \times 5\ \Omega = 95\ \Omega$, and the current through the lights is $(120\ \text{V})/(95\ \Omega) = 1.26\ \text{A}$. So, the voltage across each lamp increases to $(1.26\ \text{A}) \times 5\ \Omega = 6.30\ \text{V}$, and the new power is $(6.3\ \text{V}) \times (1.2\ \text{A}) = 7.94\ \text{W}$. Each light has increased the rate of energy transformation from 7.2 J/s to 7.94 J/s. This change does not seem like much, but it does cause the lights to heat up a little more. The heat will increase the probability of another burnout. When another light burns out, the power increases even more (to 8.89 W). Rather soon, you have a few bulbs burning very brightly . . . but not for long.

bulb, (b) two light bulbs, and (c) three light bulbs. As lamps are added, the voltage provided by the energy source remains constant. The current in the circuit, however, increases. The current in circuit (a) is 1.5 A. Adding a second light bulb increases the current to twice that—3 A—while the addition of the third light bulb increases the current to 4.5 A, three times the initial value. Adding energy receivers in parallel increases the current supplied by the energy source even though the voltage remains unchanged.

We can understand the increase in current as energy receivers are added in parallel by looking at the connections between the energy source and each of the receivers. For the circuit in Figure 19-14(c) we can trace a wire from each side of each light bulb to one side of the energy source. In effect, each light bulb is connected directly to the energy source. We conclude that, when connected in parallel, energy receivers act independently of one another. Each acts as if it were the only energy receiver in the circuit. Thus, in any parallel circuit the current through a receiver is the same as it would be when the receiver is the only device in the circuit.

The total current supplied by the energy source must be the sum of the currents required by each energy receiver. In Figure 19-14 each light bulb needs 1.5 A. Two light bulbs connected in parallel require 1.5 A + 1.5 A = 3 A. Three identical light bulbs require 1.5 A + 1.5 A + 1.5 A = 4.5 A. The total current supplied by the energy source must equal the sum of the currents in each branch of the parallel circuit.

Total current (parallel)

Current in branch 1

$$I_p = I_1 + I_2 + \cdots$$

Current in other branches

Current in branch 2

$$\text{Total current (parallel)} = \text{current 1} + \text{current 2} + \cdots$$

As energy receivers are added in parallel, the total current supplied by the energy source must increase. If we compare the total resistances of the three circuits in Figure 19-14, this increase in current reflects a decrease in the total resistance of the circuit. Applying Ohm's law, we can calculate the total resistance of any circuit by dividing the energy-source voltage by the total current coming from the energy source. In the circuit of Figure 19-14(a), the total resistance is (120 V)/(1.5 A) = 80 Ω—the resistance of one light bulb. In the circuit in (b), the total resistance is (120 V)/(3.0 A) = 40 Ω—half the resistance of either one of the energy receivers. In the circuit of (c), the total resistance is (120 V)/(4.5 A) = 26.7 Ω—one-third the resistance of any one of the light bulbs. Adding energy receivers in parallel decreases the total resistance of the circuit.

If we apply the definition of electrical power to each circuit in Figure 19-14, we see that adding receivers in parallel increases the total power supplied by the energy source. The energy source supplies 180 W in the circuit in (a); twice that (360 W) in the circuit in (b); and three times (540 W) in the circuit in (c).

Adding energy receivers in parallel does not alter the electrical power available to each receiver. Placed in a circuit by itself, each light bulb would consume 180 W of electrical power. When two are placed in parallel, the energy source provides each one with 180 W. The light bulbs remain as bright in parallel with each other as they had been in a circuit by themselves.

SELF-CHECK 19F

A 10-Ω resistor and a 12-Ω resistor are connected in parallel to a 12-V energy source.
(a) What is the current through each resistor?
(b) What is the total current in the circuit?
(c) What is the total resistance of the circuit?
(d) Determine the electrical power of each resistor.
(e) Determine the total electrical power supplied by the energy source.

A STEP FURTHER—MATH

CALCULATING RESISTANCE IN PARALLEL CIRCUITS

To calculate the resistance in a parallel circuit, we may follow the steps described in Self-Check 19F. First, treat each energy receiver as if it were in the circuit by itself and use Ohm's law to calculate the current passing through it. Then, add all the currents to obtain the total current in the circuit. Finally, put the total current and the voltage in Ohm's law to determine the total resistance.

As an example, consider three receivers with individual resistances of 5 Ω, 10 Ω, and 20 Ω connected in parallel to a 60-V energy source. The current through the 5-Ω resistance will be (60 V)/(5 Ω) = 12 A; through the 10-Ω resistance, the current is (60 V)/(10 Ω) = 6 A; and through the 20-Ω resistance it is (60 V)/(20 Ω) = 3 A. Then, the total current in the circuit is 12 A + 6 A + 3 A = 21 A. Placing this value in Ohm's law we find a total resistance of (60 V)/(21 A) = 2.9 Ω.

A general equation for the total resistance of any number of devices in parallel with each other can be derived using the ideas described above. The equation is:

$$\frac{1}{\text{Total resistance}} = \frac{1}{\text{resistance 1}} + \frac{1}{\text{resistance 2}} + \cdots$$

So, for the 5-Ω, 10-Ω, and 20-Ω resistances, we have

$$\frac{1}{\text{Total resistance}} = \frac{1}{5\ \Omega} + \frac{1}{10\ \Omega} + \frac{1}{20\ \Omega} = \frac{7}{20\ \Omega}$$

$$\text{Total resistance} = \frac{20}{7}\ \Omega = 2.9\ \Omega$$

You can calculate the total resistance of a parallel circuit either by using this equation or by working through the three-step process described above. Both methods are equally valid and give the same answer.

Plus the resistances of other circuit elements

$$\frac{1}{R_p} = \frac{1}{R_1} + \frac{1}{R_2} + \cdots$$

Total resistance (parallel circuit)

Resistance of Element 1

Resistance of Element 2

Fuses, Brownouts, and Blackouts

Parallel circuits are useful in situations in which we would like to maintain the voltage supplied to each energy receiver at a constant value. Household wall sockets are wired in parallel with one another so that the current delivered to your study lamp does not change when your brother turns on his hair dryer. Groups of homes are wired in parallel so that the current delivered to your dishwasher will not change when your neighbor turns on a vacuum sweeper. The convenience provided by parallel circuits has a cost, however. Fuses blow, brownouts must be ordered, and, occasionally, blackouts occur.

Each household appliance that is plugged into a wall socket increases the total current moving through the wires. However, the current in these wires cannot grow without any bound. Electrical wires are rated in terms of the amount of electrical current they can carry before they begin to heat up appreciably. Overheating caused by excessive currents, frequently called **overloading the circuit,** can cause fires in the walls and insulation surrounding the wires. To prevent the homeowner from accidently overloading the circuit, fuses or circuit breakers are placed in series with the energy source. (A fuse is a wire that melts—or blows—when the current exceeds the value printed on it. A circuit breaker is an automatic switch that turns off—or trips—when the current exceeds its stated value.) When the current in the circuit begins to exceed the wire's current rating, the fuse blows or the circuit breaker trips, creating an open circuit.

For example, suppose that your household wiring is rated at 20 A. Twenty-ampere fuses have been placed in series with the wires entering your home. You get up in the morning and turn on the television. With a resistance of 60 Ω, your television has $(120\ \mathrm{V})/(60\ \Omega) = 2$ A moving through it. A 15-Ω toaster adds more current—8 A. While watching television and waiting for the toast, you plug in a 12-Ω hair dryer. That is another 10 A. You are at the maximum allowed for the circuit—20 A. When you turn on the lamp . . . ZAP! There goes the fuse. The blown fuse is a signal that you have overloaded the circuit.

Power plants, like household circuits, can be overloaded. They are rated according to the maximum electrical power they can deliver. A 50-megawatt (MW; mega = million) power plant can deliver 50,000,000 W of electrical power. Any combination of energy receivers that requires more than this maximum available power will damage the electrical generators. Consequently, circuit breakers are used to open the circuit when the power required exceeds this maximum.

Most power plants have at least two options in responding to demand overloads. The plants are usually designed in networks so that excessive demands in one area can be supplied with extra power available in other areas. Power plants in northern cities often supply power to southern locations during periods of extreme hot weather. The second option is for the local power plant to reduce the voltage at which the electrical energy is supplied to consumers. Called a *brownout,* this procedure decreases the power consumed by each energy receiver without removing any energy receivers from the circuit.

Occasionally, accidents occur during periods of peak demands. Then, we learn how fragile our energy system is. In 1965 most of the northeastern section of the United States was blacked out when circuit breakers removed virtually all power plants from the energy distribution network. On a hot summer evening 12 years later, New York City experienced a blackout when lightning removed one major energy source at the same time that a second one had been shut down for repairs. Once the demand exceeds the power rating available from the plant, the circuit opens and we can be left in the dark.

CHAPTER SUMMARY

The process by which electrical energy is supplied to electrical devices can be analyzed in terms of our energy-source–energy-receiver model. An electrical energy source, like a battery, supplies electrical potential energy to a receiver, which converts the energy into another form such as light. The source, the receiver, and the transmission path are called an *electric circuit.*

We measure the energy of the source in terms of its *voltage,* the energy supplied per unit of electric charge. Energy can be transmitted from the source to the receiver only along paths (conductors) in which electrical charges can move from regions of higher voltage to lower voltage. *Electric current* describes the rate at which electric charge moves in a circuit. *Electrical resistance* is the characteristic of the energy receivers that determines the size of the current for an energy source of fixed voltage. It is defined as the ratio of the voltage to the current: resistance = voltage/current. This relationship allows us to determine one of the variables when we know the other two. *Ohm's law* can also be written as voltage = current × resistance and as current = voltage/resistance.

Voltage, current, and time affect the amount of energy delivered to the energy receiver. The product of voltage and current describes the rate at which electrical energy is transferred in the circuit; this rate is called the *electrical power.* The product of the electrical power and the time is the total *electrical energy* delivered to the energy receivers during some interval of time. These two concepts, electrical energy and electrical power, allow us to compare the energy consumed by common household devices.

Electrical circuits that have more than one energy receiver can be either series circuits or parallel circuits. In a *series circuit,* the electrical current has only one route available to it. Resistances add, so that the current in the circuit decreases as more energy receivers are added in series. Both the electrical power supplied to the circuit and the electrical power supplied to each individual receiver decrease as receivers are added in series. In a *parallel circuit* the electrical current has more than one route available to it. As energy receivers are added in parallel, the current in the circuit increases. Each receiver acts independently of the others, receiving the same current as though it were the only receiver in the circuit. As energy receivers are added in parallel, the electrical power supplied by the circuit increases, but the electrical power supplied to each individual receiver remains unchanged.

ANSWERS TO SELF-CHECKS

19A. Current = charge/time.

For one electron per second:

$$\text{Current} = \frac{(1.6 \times 10^{-19}\ \text{C})}{(1\ \text{s})} = 1.6 \times 10^{-19}\ \text{A};$$

For 10^{19} electrons per second:

$$\text{Current} = \frac{(1.6 \times 10^{-19}\ \text{C} \times 10^{19})}{(1\ \text{s})} = 1.6\ \text{A}$$

19B. Current = voltage/resistance.

$$\text{For } 96\ \Omega\text{: } I = \frac{(120\ \text{V})}{(96\ \Omega)} = 1.25\ \text{A}$$

$$\text{For } 144\ \Omega\text{: } I = \frac{(120\ \text{V})}{(144\ \Omega)} = 0.83\ \text{A}$$

$$\text{For } 288\ \Omega\text{: } I = \frac{(120\ \text{V})}{(288\ \Omega)} = 0.42\ \text{A}$$

19C. Power = current × voltage.

For 96 Ω: $P = (1.25\ \text{A}) \times (120\ \text{V}) = 150\ \text{W}$

For 144 Ω: $P = (0.83\ \text{A}) \times (120\ \text{V}) = 100\ \text{W}$

For 288 Ω: $P = (0.42\ \text{A}) \times (120\ \text{V}) = 50\ \text{W}$

19D. Energy = power × time.

Old hair dryer: $EE = (750\ \text{W}) \times (420\ \text{s}) = 315{,}000\ \text{J}$

New hair dryer: $EE = (1200\ \text{W}) \times (180\ \text{s}) = 216{,}000\ \text{J}$

The new hair dryer uses less energy than the old one.

19E. The total power to the circuit decreases as the resistance of the variable resistance increases. When the variable resistance is zero, the total resistance is 140 Ω; the current is (120 V)/(140 Ω) = 0.86 A; and the power is voltage × current = (120 V) × (0.86 A) = 103 W.

When the variable resistance has a resistance of 60 Ω, the total resistance is 60 Ω + 140 Ω = 200 Ω. The current in the circuit is (120 V)/ (200 Ω) = 0.6 A; the power is (120 V) × (0.6 A) = 72 W.

With a variable resistance of 120 Ω, the total resistance becomes 120 Ω + 140 Ω = 260 Ω. The current is (120 V)/(260 Ω) = 0.46 A, and the power is (120 V) × (0.46 A) = 55 W.

The brightest light occurs when the power is the greatest (VR = 0 Ω). The dimmest light occurs when the power is the least (VR = 120 Ω).

19F. a. Each resistor acts as if it is in the circuit by itself, so the current through it is the same as if it were alone in the circuit. For the 10-Ω resistance, the current is (12 V)/(10 Ω) = 1.2 A. For the 12-Ω resistance, the current is (12 V)/(12 Ω) = 1 A.

b. The total current is 1.2 A + 1 A = 2.2 A.

c. The total resistance of the circuit is the voltage divided by the total current: total resistance = voltage/current = (12 V)/(2.2 A) = 5.4 Ω.

d. power = voltage × current. For 10 Ω: $P = (12\ \text{V}) \times (1.2\ \text{A}) =$ 14.4 W; for 2 Ω: $P = (12\ \text{V}) \times (1\ \text{A}) = 12$ W.

e. The total power is the sum of the individual powers: 14.4 W + 12 W = 26.4 W.

PROBLEMS AND QUESTIONS

A. Review of Chapter Material

A1. Define the following terms:

Conductor	Open circuit
Insulator	Closed circuit
Voltage	Electrical power
Resistance	Ampere
Electric circuit	Volt
Series circuit	Ohm
Parallel circuit	

A2. Describe the process that causes lightning.

A3. Which term—resistance or voltage—is used to describe electrical energy sources? Which describes electrical energy receivers?

A4. Two lamps are connected to identical batteries. One is much brighter than the other. Which has a greater resistance?

A5. State Ohm's law. How is it useful?

A6. Describe how resistance is related to electrical safety.

A7. How are electrical power and energy related to current and voltage?

A8. As energy receivers are added in series, what happens to the total current? To the power delivered by the energy source? To the power received by each receiver?

A9. How does the resistance of a circuit change as energy receivers are added in series? In parallel?

A10. State the rule for calculating the total resistance of a series circuit.

A11. As energy receivers are added in parallel, what happens to the total current of the circuit? To the power delivered by the energy source? To the power received by each receiver?

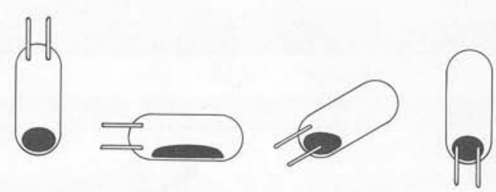
A12. How would you determine the total resistance of a parallel circuit?

A13. Describe the process that causes a fuse to blow.

A14. Why can brownouts decrease electrical energy use?

B. Using the Chapter Material

B1. The mercury switch is used in thermostat and noiseless wall switches. It consists of two wires and a small amount of liquid mercury (a metal) in a glass capsule. Which of the positions shown below represents a closed mercury switch?



(a) (b) (c) (d)

B2. Thirteen coulombs of charge pass a point in 26 s. What is the current at that point?

B3. A generator does 12 J of work on 2 C of electric charge. What voltage does it supply?

B4. A calculator operates on 8 V and 0.1 A. What is the power used by the calculator? How much energy does the calculator use in 200 s?

B5. What is the resistance of the calculator in problem B4? If the calculator were connected to 120 V, how much current would move through it? (High currents destroy electronic devices.)

B6. Some people determine if a 9-V transistor battery is functioning by placing its terminals against their wet lips. Why would you feel current in this situation and not when holding the terminals in your dry hands?

B7. How much current moves through your fingers (resistance = 1500 Ω) when you hold them against the terminals of a 1.5-V battery?

B8. Why can a wet electrical wire be a safety hazard even if it is covered with insulation?

B9. Three energy receivers with resistances of 5 Ω, 10 Ω, and 15 Ω are connected in series to a 60-V energy source. What is the total resistance of the circuit? What is the total current in the circuit?

B10. Automobiles have either two or four headlights. Are these headlights connected in series or parallel with each other? Explain how you obtained your answer.

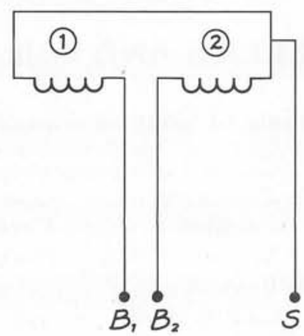
B11. Three energy receivers with resistances of 3 Ω, 4 Ω, and 6 Ω are connected in parallel to a 12-V energy source. What is the current in each resistor? What is the total current in the circuit? What is the total power?

C. Extensions to New Situations

C1. The rear-window defrosters on automobiles consist of several strips of heater wire connected in parallel. Each wire typically has a resistance of 6 Ω. The car battery's voltage is 12 V.
   a. What is the total current through a defroster consisting of five wires connected in parallel?
   b. What is the total resistance of the five-wire defroster?
   c. What is the power consumed by the defroster?
   d. How much energy is consumed in 500 s?
   e. How much energy is needed to melt 0.1 kg of ice from the back window? (Refer to Chapter 10.)
   f. Can the defroster melt 0.1 kg of ice in 500 s?

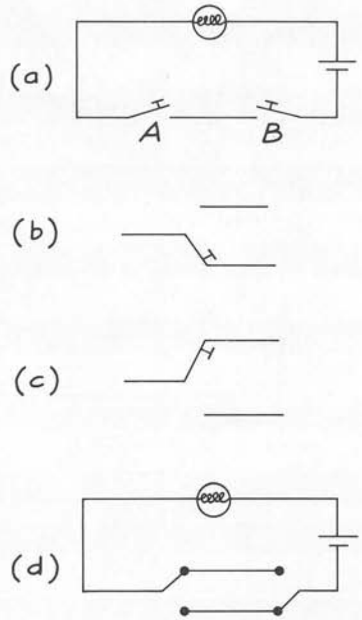
C2. In normal household wiring, one side of the outlet is connected to the ground. This wire is said to be grounded. The other side, called the live wire, is connected to 120 V.
   a. Why does a health hazard exist for a person who holds only the live wire?
   b. Is a similar hazard present if the person holds only the grounded wire? Why or why not?
   c. If you were working on a live wire while standing on a ladder, would you prefer a wooden ladder or an aluminum one? Why?

C3. A three-way light can be constructed as shown below. The bulb has two separate connections, $B1$ and $B2$, at its base and one connection, S, on the side of the light bulb.



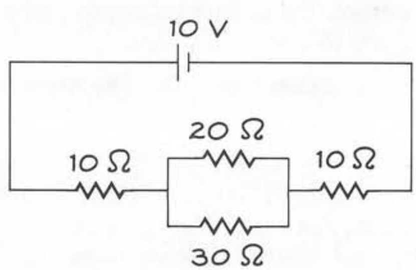
   a. To what points should the energy source be connected so that resistance 1 comes on by itself? So that resistance 2 comes on by itself? So that both resistances come on in parallel?
   b. When resistance 1 is 24 Ω and resistance 2 is 48 Ω, what is the current through each resistance when it is in the circuit alone? When both are in the circuit in parallel?
   c. What are the three different electrical powers this bulb can emit?

C4. For convenience we frequently desire switches at more than one location to control a single light. For example, rather than using the traveling stairway lamp described in the chapter, we may wish to turn on a light at the bottom of the stairs and turn it off at the top. To see how this works, we begin with two ordinary switches connected to a light, as shown on page 463.
   a. What happens to the light when either switch A or B is open?
   b. Using this circuit would you have complete control over the light at either switch? Why or why not?
   c. Now consider the switch shown in (b)



and (c). This switch is always connected to a wire; in (b) the lower wire is connected, while in (c) the upper wire is connected. As shown in (d), these switches can be placed in a lamp circuit. Using the idea of a closed circuit, show that you have complete control of the lamp at either switch.

C5. Some circuits can be combinations of series and parallel circuits. To learn one way to determine the total resistance of such a circuit, consider the circuit below.



a. Identify the parallel part of this circuit. Draw a circuit consisting of the parallel part and a 10-V battery. Calculate the total resistance of this parallel circuit.
b. What single resistor could be used to replace the parallel resistor in part (a) and still have the same total current from the battery?
c. Replace the parallel resistors in the circuit drawing with the resistor from part (b). What is the total resistance of this circuit? (This is the total resistance for the combination circuit.)

C6. To see how brownouts can decrease power requirements, consider a home that has a television (resistance = 60 Ω), toaster (12 Ω), hair dryer (10 Ω), and lamp (120 Ω). All are connected in parallel.
a. What is the current through each component when they are connected to 120 V? What is the total current?
b. How much total power is used when all components are on?
c. The electric company decreases the voltage to 100 V. What are the new individual and total currents?
d. What is the new total power for all components?
e. Describe in words how the voltage decrease changes the power used.

C7. Here is a somewhat simplified version of a blackout. Suppose the energy sources are connected so that their energies add in the total circuit. Source A has a maximum power output of 5 kilowatts (kW); source B, 6 kW; and source C, 7 kW. If the power required by the receivers exceeds these values, a circuit breaker shuts off the source. The sources are connected to three homes. Each home has an air conditioner (2 kW) and a large freezer (1 kW).
a. What is the total power supplied by the sources?
b. What is the total power needed by all three homes?
c. Now, suppose a person in each home turns on a coffee pot (1 kW) and a microwave oven (1 kW). What is the total power requirement? Why should the electric company become concerned?
d. How would a brownout help alleviate the problem in part (c)?
e. Suppose that lightning destroys source A. What will happen to sources B and C? Why?

D. Activities

D1. Look inside a flashlight. Describe how the conductors change to open and close the circuit.