# More for Less

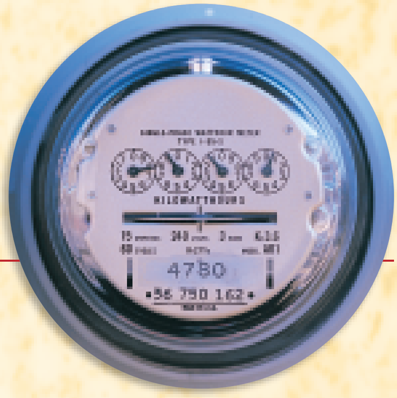
**High-voltage power transmission lines criss-cross our country. It would seem to be easier to simply transmit electrical energy at the lower voltages used in homes. Why is this not done?**

*Look at the text on page 523 for the answer.*

Picture not available on CD

CHAPTER

# 22 Current Electricity



Electricity is such a common tool that we often take it for granted. Its importance is never truly considered until it is missing. When the power is out, your electric alarm clock doesn't wake you in time for school. The furnace doesn't turn on, leaving your bedroom cold. You stumble in the dark because the lights are out. Then you find you can't make toast or even zap your favorite breakfast food in the microwave. You fear the day will go downhill from here.

Electric energy is indispensable in our daily lives because it can easily be changed into other forms of energy—sound, thermal energy, light, and motion. Look around and see just how many ways you depend on electric energy's ability to change form.

Electric energy can be transported, or transferred, efficiently over long distances. You can readily understand that the large amounts of natural potential and kinetic energy available by resources such as Niagara Falls are of little use to a manufacturing complex 100 km away, unless that energy can be captured and transported efficiently. Electric energy provides the means to transfer large quantities of energy great distances with little loss. This transfer is usually done at high potential differences through power lines such as the ones shown in the photo at the left.

In this chapter, you will learn about the relationship among potential differences, resistance, and current. You will also learn about electric power and energy transfer.

## WHAT YOU'LL LEARN

- You will explain energy transfer in circuits.
- You will solve problems involving current, potential difference, and resistance.
- You will diagram simple electric circuits.
- You will solve problems involving the use and cost of electric energy.

## WHY IT'S IMPORTANT

- The electric tools and appliances you use are based upon the ability of electric circuits to transfer energy by potential difference and thus perform work.

**PHYSICS Online**

To find out more about current electricity, visit the Glencoe Science Web site at **science.glencoe.com**

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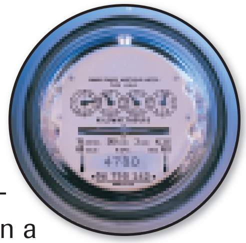
# 22.1 Current and Circuits



You have had many experiences with electric circuits. Every time you turn on a light, radio, or television, or turn the ignition key to start a car or turn on a flashlight, you complete an electric circuit. Electric charges flow and energy is transferred. In this chapter you will learn how electric circuits work.

## OBJECTIVES

- **Define** an electric current and the ampere.
- **Describe** conditions that create current in an electric circuit.
- **Draw** circuits and **recognize** that they are closed loops.
- **Define** power in electric circuits.
- **Define** *resistance* and **describe** Ohm's law.

## Producing Electric Current

In Chapter 21 you learned that when two conducting spheres touch, charges flow from the sphere at a higher potential difference to the one at a lower potential difference. The flow continues until the potential differences of both spheres are equal.

A flow of charged particles is an **electric current.** In **Figure 22–1a,** two conductors, A and B, are connected by a wire conductor, C. Charges flow from the higher potential difference of B to A through C. This flow of positive charge is called **conventional current.** The flow stops when the potential differences of A, B, and C are equal. How could you keep the flow going? You would have to maintain a potential difference between B and A. This could be done by pumping charged particles from conductor A back to conductor B. The electric potential energy of the charges would have to be increased by this pump, so it would require external energy to run. The electric energy could come from one of several other forms of energy. One familiar source of electric energy, a voltaic or galvanic cell (a common dry cell), converts chemical energy to electric energy. Several of these cells connected together are called a **battery.** A second source of electric energy, the **photovoltaic cell,** or solar cell, changes light energy into electric energy. Yet another source of electric energy is a generator. A generator can be driven by moving water, rushing steam, or wind and converts kinetic energy into electric energy. One source of electric energy is pictured in **Figure 22–2.**

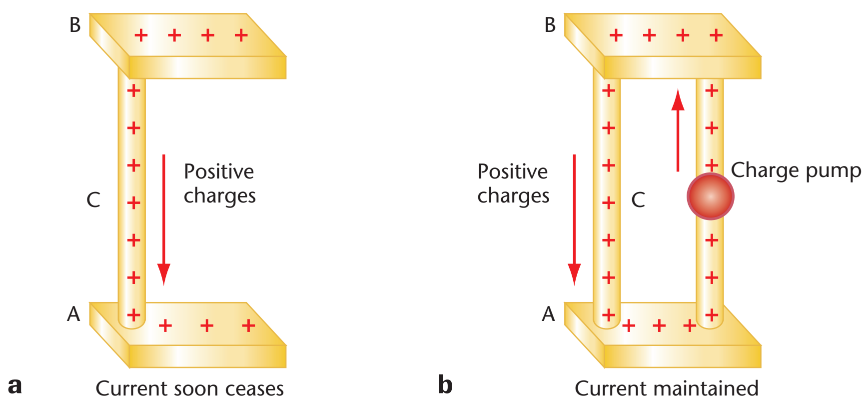



**FIGURE 22–1** Conventional current is defined as positive charges flowing from the positive plate to the negative plate **(a).** A generator pumps the positive charges back to the positive plate, creating the current **(b).** In most metals, negatively-charged electrons actually flow from the negative to the positive plate. When the electrons move, they create positive charges which appear to move in the opposite direction from the positive plate to the negative plate.

## Electric Circuits

The charges in **Figure 22–1b** move around a closed loop from the pump through B to A through C, and back to the pump. Such a closed loop is called an **electric circuit.** A circuit includes a charge pump, which increases the potential energy of the charges moving from A to B, and is connected to a device that reduces the potential energy of the charges moving from B to A. The potential energy lost by the charges, $qV$, in moving through the device is usually converted into some other form of energy. For example, a motor converts electric energy to kinetic energy, a lamp changes electric energy into light, and a heater converts electric energy into thermal energy. Note that the $\Delta$ is dropped from the $V$ for potential difference. This is a historical convention rather than an appropriate one. For convenience and uniformity, this text will also use $V$ rather than $\Delta V$.

The charge pump creates the flow of charged particles, or current. Consider a generator driven by a waterwheel, such as the one pictured in **Figure 22–3a.** The water falls and rotates the waterwheel and generator. Thus, the kinetic energy of the water is converted to electric energy by the generator. The generator increases the electric potential difference, $V$, between B and A as it removes charges from wire B and adds them to wire A. Energy in the amount $qV$ is needed to increase the potential difference of the charges. This energy comes from the change in energy of the water. No generator, however, is 100 percent efficient. Only 98 percent of the kinetic energy put into most generators is converted into electric energy. The remainder becomes thermal energy. The temperature of the generator increases, as shown in **Figure 22–3b.**

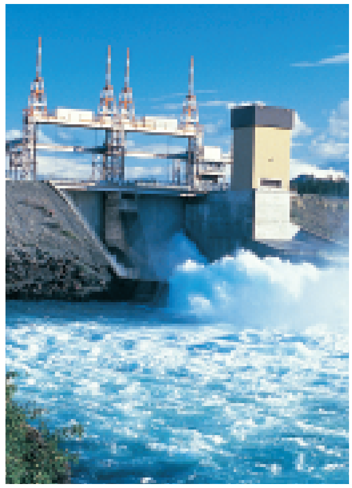


**FIGURE 22–2** Sources of electric energy include chemical, solar, hydrodynamic, wind, and nuclear energies.

### Charge and Field Conventions

- Positive charges are **red.**
- Negative charges are **blue.**
- Electric field lines are **indigo.**

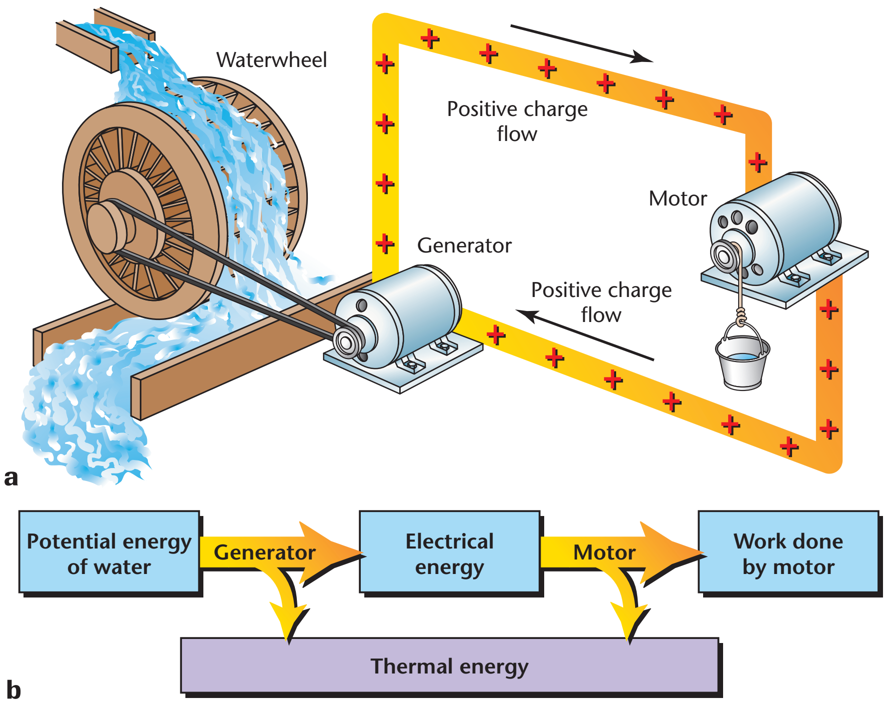



**FIGURE 22–3** The potential energy of the waterfall is eventually converted into work done raising the bucket **(a).** The production and use of electric current is not 100 percent efficient. Some thermal energy is produced by the splashing water, friction, and electrical resistance **(b).**

HELP WANTED

**WELDER**

Your technical knowledge of welding equipment and processes is important. A vocational/technical school education or military training, or extensive apprenticeship will be considered equally for this position with a major industrial employer. Excellent physical fitness, hand-eye coordination, and safety orientation are also important. Additional skills such as laser or inertial welding techniques will be useful in this diverse construction environment. For information contact:

American Welding Society
550 NW LeJeune Road
Miami, FL 33126

If wires are connected to a motor, the charges in the wire flow into the motor. The flow continues through the circuit back to the generator. The motor converts electric energy to kinetic energy. Like generators, motors are not 100 percent efficient. Typically, only 90 percent of the electric energy converted by a motor is changed into kinetic energy.

You know that charges can't be created or destroyed, only separated. Thus, the total amount of charge (number of negative electrons and positive ions) in the circuit does not change. If one coulomb flows through the generator in one second, then one coulomb also will flow through the motor in one second. Thus, charge is a conserved quantity. Energy is also conserved. The change in electric energy, $E$, equals $qV$. Because $q$ is conserved, the net change in potential energy of the charges going completely around the circuit must be zero. The potential difference increase produced by the generator equals the potential difference decrease across the motor.

If the potential difference between the two wires is 120 V, the generator must do 120 J of work on each coulomb of positive charge that it transfers from the more negative wire to the more positive wire. Every coulomb of positive charge that moves from the more positive wire through the motor and back to the more negative wire delivers 120 J of energy to the motor. Thus, electric energy serves as a way to transfer the energy of falling water to the kinetic energy of a turning motor.

## Rates of Charge Flow and Energy Transfer

Power measures the rate at which energy is transferred. If a generator transfers one joule of kinetic energy to electric energy each second, it is transferring energy at the rate of one joule per second, or one watt. The energy carried by an electric current depends on the charge transferred and the potential difference across which it moves, $E = qV$. Recall from Chapter 20 that the unit used for quantity of electric charge is the coulomb. Thus, the rate of flow of electric charge, or electric current, $I$, is measured in coulombs per second. A flow of one coulomb per second is called an **ampere,** A, and is represented by 1 C/s = 1 A. A device that measures current is called an ammeter.

Suppose that the current through the motor shown in **Figure 22–3** is 3.0 C/s (3.0 A). Because the potential difference is 120V, each coulomb of charge supplies the motor with 120 J of energy. The power of an electric device is found by multiplying the potential difference, $V$, by the current, $I$.

The power, or energy delivered to the motor per second, is represented by the following equation.

**Power** $P = IV$

$$P = (3.0\ \text{C/s})(120\ \text{J/C}) = 360\ \text{J/s} = 360\ \text{W}$$

Recall from Chapter 10 that power is defined in watts, W; thus, the power delivered by this motor is 360 watts.

## Example Problem

### Electric Power

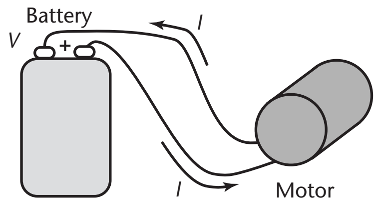
A 6.0-V battery delivers a 0.50-A current to an electric motor that is connected across its terminals.

**a.** What power is consumed by the motor?

**b.** If the motor runs for 5.0 minutes, how much electric energy is delivered?

#### Sketch the Problem

- Draw a circuit showing the positive terminal of a battery connected to a motor and the return wire from the motor connected to the negative terminal of the battery.
- Show the conventional current.




#### Calculate Your Answer

**Known:**

$V = 6.0$ V

$I = 0.50$ A

$t = 5.0$ min

**Unknown:**

$P = ?$

$E = ?$

**Strategy:**

**a.** Use $P = IV$ to find the power.

**b.** From Chapter 10 you learned that $P = E/t$, so use $E = Pt$ to find the energy.

**Calculations:**

**a.** $P = IV = (0.50\text{ A})(6.0\text{ V})$
$= 3.0\text{ W}$

**b.** $E = Pt = (3.0\text{ W})(5.0\text{ min})(60\text{ s}/1\text{ min})$
$= 9.0 \times 10^2\text{ J}$

#### Check Your Answer

- Are the units correct? Power is measured in watts and energy is measured in joules.
- Is the magnitude realistic? Small batteries deliver only a few watts of power.

## Practice Problems

1. The current through a lightbulb connected across the terminals of a 120-V outlet is 0.50 A. At what rate does the bulb convert electric energy to light?
2. A car battery causes a current of 2.0 A through a lamp while 12 V is across it. What is the power used by the lamp?
3. What is the current through a 75-W lightbulb connected to a 120-V outlet?
4. The current through the starter motor of a car is 210 A. If the battery keeps 12 V across the motor, what electric energy is delivered to the starter in 10.0 s?

## Pocket Lab

### Lighting Up

Use a D cell and a 10-cm length of wire to light a miniature lamp. Make a sketch of two circuits that work and two circuits that do not work.

**Analyze and Conclude** Can you light the lamp without having two connecting points on the lamp? Does a lamp connected in your house have two connecting points? Suggest a reason why two are needed.

# Resistance and Ohm's Law

Suppose that two conductors have a potential difference between them. If you connect them with a copper rod, you will create a large current. If, on the other hand, you put a glass rod between them, there will be almost no current. The property that determines how much current will flow is called the **resistance.** Resistance is measured by placing a potential difference across two points on a conductor and measuring the current. The resistance, *R*, is defined to be the ratio of the potential difference, *V*, to the current, *I*.

$$\textbf{Resistance} \quad R = \frac{V}{I}$$

The electric current, *I*, is in amperes. The potential difference, *V*, is in volts. The resistance of the conductor, *R*, is measured in ohms. One ohm (1 Ω) is the resistance that permits a current of 1 A to flow when a potential difference of 1 V is applied across the resistance. A simple circuit relating resistance, current, and voltage is shown in **Figure 22–4.** A 9-V battery is connected to a 3-Ω resistance lightbulb. The circuit is completed by connection to an ammeter. The current measures 3 A.

German scientist Georg Simon Ohm found that the ratio of the potential difference to the current is always a constant for a given conductor. Therefore, the resistance for most conductors does not vary as the magnitude or the direction of the potential applied to it changes. A device that has a constant resistance that is independent of the potential difference is said to obey Ohm's law.

Most metallic conductors obey Ohm's law, at least over a limited range of voltages. Many important devices, however, do not. A transistor radio or pocket calculator contains many devices, such as transistors and diodes, that do not obey Ohm's law. Even a lightbulb has a resistance that depends on the voltage and does not obey Ohm's law.

Wires used to connect electric devices have small resistance. One meter of a typical wire used in physics labs has a resistance of about 0.03 Ω. Wires used in house wiring offer as little as 0.004-Ω resistance for each meter of length. Because wires have so little resistance, there is almost no potential drop across them. To produce potential differences, you need large resistance concentrated into a small volume. **Resistors** are devices designed to have a specific resistance. They may be made of long, thin wires; graphite; or semiconductors.

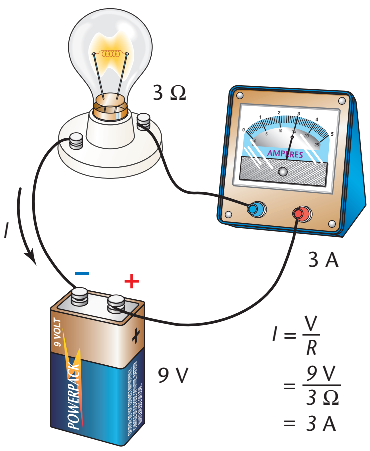



**FIGURE 22–4** In a circuit having a 3-Ω resistance and a 9-V battery, there is a 3-A current.

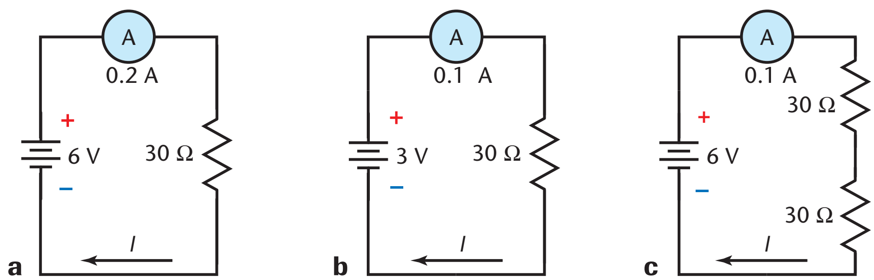



**FIGURE 22–5** The current through a simple circuit **(a)** can be regulated by removing some of the dry cells **(b)** or increasing the resistance of the circuit **(c).**



CONTENTS

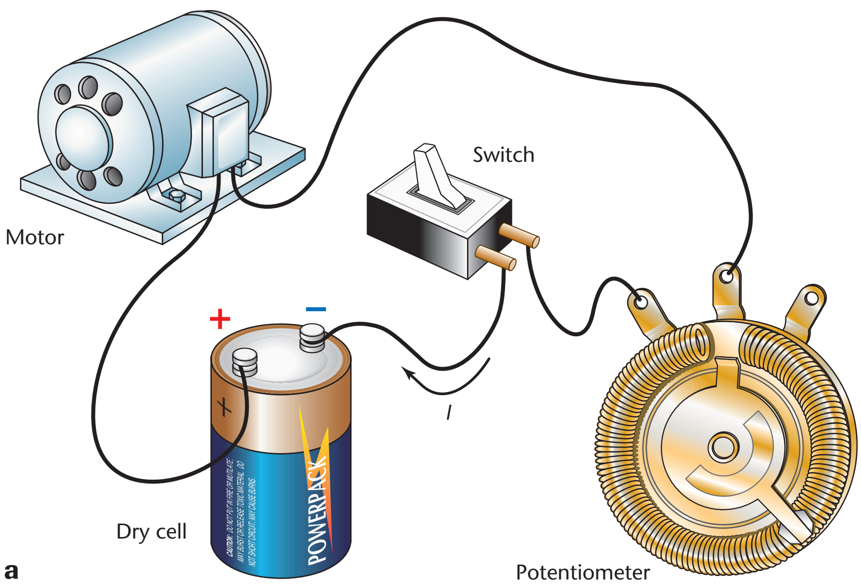
Superconductors are materials that have zero resistance. There is no restriction of current in these materials, and so there is no potential difference, $V$, across a superconductor. Because the power dissipated in a conductor is given by the product $IV$, a superconductor can conduct electricity without loss of energy. The development of superconductors that can be cooled by relatively inexpensive liquid nitrogen may lead to more efficient transfer of electric energy.

There are two ways to control the current in a circuit. Because $I = V/R$, $I$ can be changed by varying either $V$ or $R$, or both. **Figure 22–5a** shows a simple circuit. When $V$ is 6 V and $R$ is 30 Ω, the current is 0.2 A. How could the current be reduced to 0.1 A?

The larger the potential difference, or voltage, placed across a resistor, the larger the current that passes through it. If the current through a resistor is to be cut in half, the potential difference will be cut in half. In **Figure 22–5b,** the voltage applied across the resistor has been reduced from 6 V to 3 V to reduce the current to 0.1 A. A second way to reduce the current to 0.1 A is to increase the resistance to 60 Ω by adding a 30-Ω resistor to the circuit, as shown in **Figure 22–5c,** or by replacing the 30-Ω resistor with a 60-Ω resistor. Both of these methods will reduce the current to 0.1 A. Resistors are often used to control the current in circuits or parts of circuits. Sometimes a smooth, continuous variation of the current is desired. A lamp dimmer switch allows continuous rather than step-by-step changes in light intensity. To achieve this kind of control, a variable resistor, called a rheostat, or **potentiometer,** is used. A circuit containing a potentiometer is shown in **Figure 22–6.** A variable resistor consists of a coil of resistance wire and a sliding contact point. By moving the contact point to various positions along the coil, the amount of wire added to the circuit is varied. As more wire is placed in the circuit, the resistance of the circuit increases; thus, the current

# F.Y.I.

$V = IR$ is often taken as a statement of Ohm's law, but this is not true. The equation simply defines resistance and applies to all resistances whether or not they obey Ohm's law.



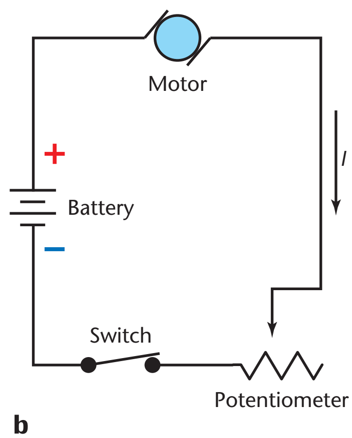




**FIGURE 22–6** A potentiometer can be used to change current in an electric circuit.

**FIGURE 22–7** An inside view of a potentiometer shows the coils and the sliding contact wire.

changes in accordance with the equation $I = V/R$. In this way, the light output of a lamp can be adjusted from bright with little wire in the circuit to dim with a lot of wire in the circuit. This type of device controls the speed of electric fans, electric mixers, and other appliances. To save space, the coil of wire is often bent into a circular shape and a sliding contact is moved by a knob, as shown in **Figure 22–7.**

Your body is a moderately good electrical conductor. Some physiological responses are documented in **Table 22–1.** If enough current is present through your body, your breathing or heart can stop. In addition, the energy transferred can burn you. If your skin is dry, its resistance is high enough to keep currents produced by small and moderate voltages low. If your skin becomes wet, however, its resistance is lower, and the currents can rise to dangerous levels, of tens of milliamps.

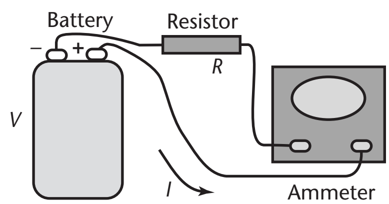
**TABLE 22–1**
**The Damage Caused by Electric Shock**

| Current | Possible Effects |
|---|---|
| 1 mA | mild shock can be felt |
| 5 mA | shock is painful |
| 15 mA | muscle control is lost |
| 100 mA | death can occur |

## Example Problem

### Current Through a Resistor

A 30.0-V battery is connected to a 10.0 Ω resistor. What is the current in the circuit?




#### Sketch the Problem

- Draw a circuit containing a battery, an ammeter, and a resistor.
- Show the conventional current.

#### Calculate Your Answer

**Known:**

$V = 30.0$ V

$R = 10.0\ \Omega$

**Unknown:**

$I = ?$

**Strategy:**

Use $I = V/R$ to determine the current.

**Calculations:**

$$I = \frac{V}{R} = \frac{30.0\ \text{V}}{10.\ 0\ \Omega} = 3.00\ \text{A}$$

#### Check Your Answer

- Are the units correct? Current is measured in amperes.
- Is the magnitude realistic? Batteries deliver a few amperes.

## Practice Problems

*For all problems, you should assume that the battery voltage is constant, no matter what current is present.*

**5.** An automobile headlight with a resistance of 30 Ω is placed across a 12-V battery. What is the current through the circuit?

**6.** A motor with an operating resistance of 32 Ω is connected to a voltage source. The current in the circuit is 3.8 A. What is the voltage of the source?

**7.** A transistor radio uses $2.0 \times 10^{-4}$ A of current when it is operated by a 3.0-V battery. What is the resistance of the radio circuit?

**8.** A lamp draws a current of 0.50 A when it is connected to a 120-V source.
   **a.** What is the resistance of the lamp?
   **b.** What is the power consumption of the lamp?

**9.** A 75-W lamp is connected to 120 V.
   **a.** What is the current through the lamp?
   **b.** What is the resistance of the lamp?

**10.** A resistor is added in series with the lamp in problem 9 to reduce the current to half its original value.
   **a.** What is the potential difference across the lamp? Assume that the lamp resistance is constant.
   **b.** How much resistance was added to the circuit?
   **c.** How much power is now dissipated in the lamp?

### BIOLOGY CONNECTION

**Body Resistance** The resistance of the human body when the skin is dry is about $10^5$ Ω. It drops to about 1500 Ω for wet hands. Therefore, the current through the body from 120 V is about 1.2 mA for dry skin and 80 mA for wet skin. A person will feel a tingle at about 1 mA, at 10 to 20 mA there will be muscular effects, and by 20 mA a person will not be able to let go of a conducting wire. Respiratory paralysis occurs between 20 and 100 mA, and currents above 100 mA can be fatal.

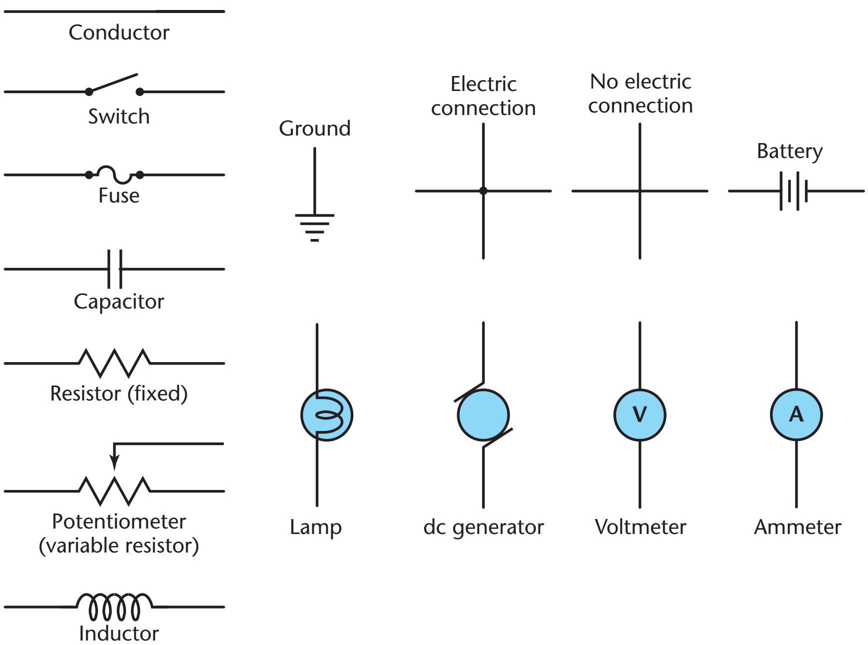



**FIGURE 22–8** Symbols that are commonly used to design electric circuits are presented.

## Pocket Lab

### Running Out

Use the proper symbols and design a drawing that shows a power supply in a continuous circuit with two miniature lamps. Next, draw the circuit with an ammeter included to measure the electrical flow between the power supply and the bulbs. Make a third drawing to show the ammeter at a position to measure the electrical flow between the bulbs.

**Test Your Prediction** Would you predict the current between the lamps to be more or less than the current before the lamps? Why? Build the circuits to find out. Record your results.

# Diagramming Circuits

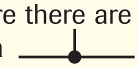
A simple circuit can be described in words. It can also be depicted by photographs or artist's drawings of the parts. Most frequently, however, a diagram of an electric circuit is drawn using standard symbols for the circuit elements. Such a diagram is called a circuit **schematic.** Some of the symbols used in schematics are shown in **Figure 22–8.**

Both an artist's drawing and a schematic of the same circuit are shown in **Figure 22–9** and **Figure 22–10.** Notice that in both the artist's drawing and the schematic, current is shown out of the positive terminal of the battery. You learned earlier in this chapter that this is called the conventional current. To draw schematic diagrams, use the following strategy and always set up a conventional current.

## PROBLEM SOLVING STRATEGIES

### Drawing Schematic Diagrams

**Follow these steps when drawing schematic diagrams.**

1. Draw the symbol for the battery or other source of electric energy (such as a generator) at the left side of the page. Put the positive terminal on top.
2. Draw a wire coming out of the positive terminal. When you reach a resistor or other device, draw the symbol for it.
3. If you reach a point where there are two current paths, such as at a voltmeter, draw a  in the diagram. Follow one path until the two current paths join again. Then draw the second path.
4. Follow the current path until you reach the negative terminal of the battery.
5. Check your work to make sure that you have included all parts and that there are complete paths for current to follow.

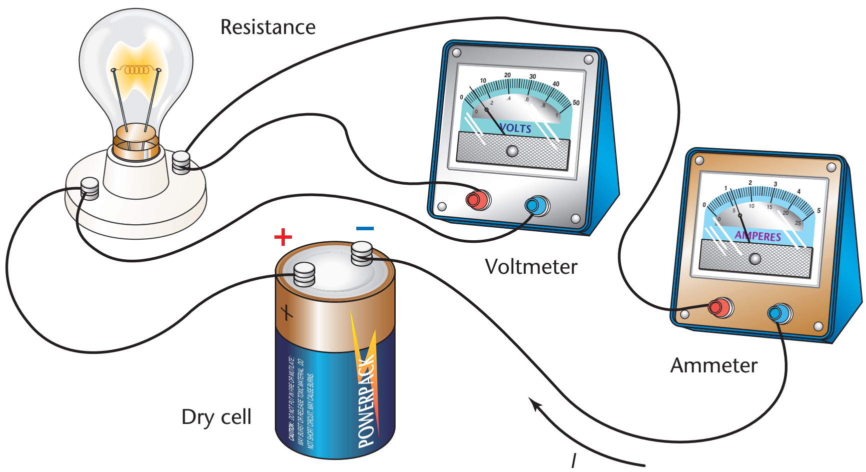



**FIGURE 22–9** A simple electric circuit is represented pictorially.

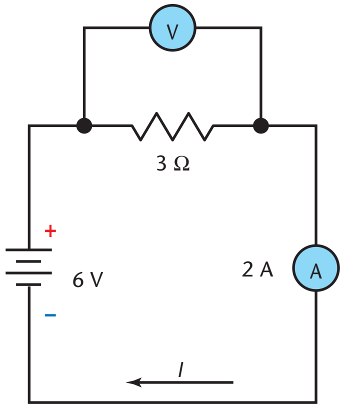



**FIGURE 22–10** A simple electric circuit is represented schematically.

You have learned that an ammeter measures current and that a voltmeter measures potential differences. Each instrument has two terminals, usually labeled + and −. When it is in use, the voltmeter measures the potential difference across any component of a circuit. When connecting the voltmeter in a circuit, always connect the + terminal to the end of the circuit component closer to the positive terminal of the battery and connect the other terminal to the other side of the component. This kind of connection is called a **parallel connection** because the circuit component and the voltmeter are aligned parallel to each other in the circuit, as diagrammed in **Figure 22–9.** The potential difference across the voltmeter is equal to that across the circuit element. Always associate the two words *voltage across.*

The ammeter measures the current through a circuit component. The same current that goes through the component must go through the ammeter, so there can be only one current path. This connection is called a **series connection.** To add an ammeter to a circuit, you must remove the wire connected to the circuit component and connect it to the ammeter instead. Then connect another wire from the second terminal of the ammeter to the circuit component. Always associate the two words *current through.*

# F.Y.I.

A fundamental rule of electric circuits states that electrical signals travel no faster than the speed of light, or one foot in one nanosecond. This is one of the fundamental limitations on the possible speed of a computer. Signals in an electric circuit cannot move any faster.

## Practice Problems

**11.** Draw a circuit diagram to include a 60.0-V battery, an ammeter, and a resistance of 12.5 Ω in series. Indicate the ammeter reading and the direction of current.

**12.** Draw a series-circuit diagram showing a 4.5-V battery, a resistor, and an ammeter reading 90 mA. Label the size of the resistor. Choose a direction for the conventional current and indicate the positive terminal of the battery.

**13.** Add a voltmeter that measures the potential difference across the resistors in problems 11 and 12 and repeat problems.

# Mystery Cans

## Problem

An electric device is inside each film can. How can you design and build a circuit to determine whether the resistance is constant for different voltages?

## Materials

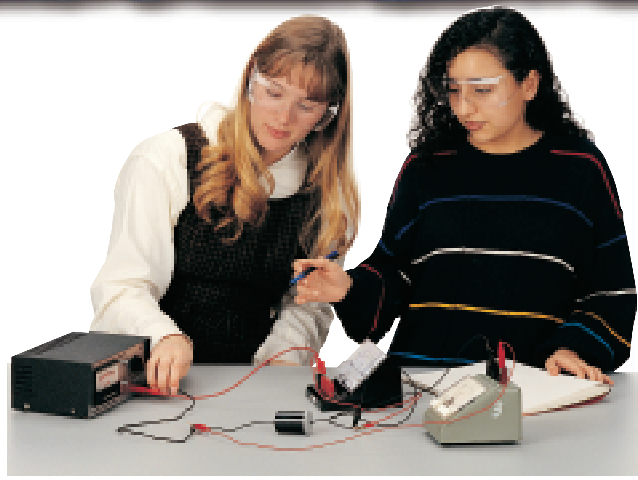
power supply with variable voltage
wires with clips
multimeter
ammeter
3 film cans for each group

## Procedure

1. Identify the variables to be measured.
2. Design your circuit and label each component. Use the proper symbols to make your drawing of the set-up. Show your teacher your plan before proceeding further.
3. Build the circuit of your design and slowly increase the voltage on your power supply to make sure that your meters are working properly. Do not exceed one amp or the current limitation set by your teacher. Reverse connections as needed.
4. Make at least three measurements of voltage and current for each can.
5. When you have completed the lab, put away materials that can be reused. Dispose of or recycle materials as appropriate.

## Data and Observations

1. Make a data table with at least three places for measurements on each can.



## Analyze and Conclude

1. **Calculating Results** Calculate $R$ for each test.
2. **Graphing Data** Graph $V$ versus $I$ for all of your data. If possible, use a graphing calculator or computer plotting program. Draw a separate line for each can. Identify the relationship between variables.
3. **Interpreting Graphs** Determine the slope for each of your lines.
4. **Comparing Values** Open each can to see the marked values of the resistors. Compare your predicted values to the actual values.

## Apply

1. Most incandescent lamps burn out when they are switched on rather than when they have been on for a while. Predict what happens to the resistance and the current when a cold lamp is switched on. Make a graph of $R$ versus $t$ and also $I$ versus $t$ for the first few seconds. Calculate the resistance of an operating 60-W lamp at 120 V. Now use a multimeter as an ohmmeter to measure the resistance of a cold 60-W lamp. Describe your results.

# Physics & Technology

## Digital Systems

Digital systems transmit information using a string of signals in binary code—*0*s and *1*s. A signal, which can be light, sound, color, electric current, or some other quantity, is on when the code is *1* and off when the code is *0*. Unlike analog signals, which vary continuously in wave form, digital signals arrive almost exactly as they were sent. In other words, with analog technology, time is continuous; with digital technology, time is measured at discrete moments.

Digital technology has made its way into many businesses and homes worldwide. Most computers, for example, are digital. Such machines receive and process software much more easily than their analog counterparts. Digital photography, while still in its infancy, allows photographers to take pictures, instantly view the results, and save those that they want to keep. Some disadvantages of this filmless photography, however, include the lack of detail and some-what fuzzy pictures.

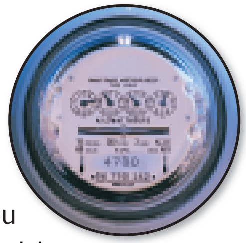
Digital X rays allow dentists to better diagnose dental problems while exposing their patients to up to 90 percent less radiation than that used by conventional X-ray techniques. Compact discs employ digital technology to preserve your favorite tunes and computer games. Most telephone systems now use digital technology to transmit voices. High-definition television, or HDTV, uses digital technology to enhance your viewing pleasure by improving both the picture resolution and the sound quality.

**Thinking Critically** You've probably experienced surround sound at your local movie theater. Why do you think this use of digital technology seems to really draw you into the movie?

## 22.1 Section Review

1. Draw a schematic diagram of a circuit, containing a battery and a bulb, that will make the bulb light.
2. Joe argues that because $R = V/I$, if he increases the voltage, the resistance will increase. Is Joe correct? Explain.
3. You are asked to measure the resistance of a long piece of wire. Show how you would construct a circuit containing a battery, voltmeter, ammeter, and the wire to be tested to make the measurement. Specify what you would measure and how you would compute the resistance.
4. **Critical Thinking** We say that power is "dissipated" in a resistor. To *dissipate* is to use, or to waste, or to squander. What is "used" when charge flows through a resistor?

# 22.2 Using Electric Energy



## OBJECTIVES

- **Explain** how electric energy is converted into thermal energy.
- **Determine** why high-voltage transmission lines are used to carry electric energy over long distances.
- **Define** *kilowatt-hour*.

**F.Y.I.**

Electricity is produced in hydroelectric power plants by the conversion of mechanical energy into electric energy.

Among the electrical appliances in your home, you probably have a hair dryer, several lamps, a television set, a stereo, a microwave oven, a refrigerator, and a stove. Each converts electrical energy into another form: light, kinetic, sound, or thermal energy. How much is converted, and at what rate?

## Energy Transfer in Electric Circuits

Energy supplied to a circuit can be used in many different ways. A motor converts electric energy to mechanical energy. An electric lamp changes electric energy into light. Unfortunately, not all of the energy delivered to a motor or a light ends up in a useful form. Lights, especially incandescent bulbs, get hot. Motors are often too hot to touch. In each case, some energy is converted into thermal energy. Let's examine some devices designed to convert as much energy as possible into thermal energy.

## Heating a Resistor

A space heater, a hot plate, and the heating element in a hair dryer are designed to convert almost all the electric energy into thermal energy. Household appliances, such as those pictured in **Figure 22–11,** act like resistors when these devices are in a circuit. When charge, $q$, moves through a resistor, its potential difference is reduced by an amount $V$. As you have learned, the energy change is represented by $qV$. In practical use, it is the rate at which energy is changed, that is, the power, $P = E/t$, that is important. You learned earlier that current is the rate at which charge flows, $I = q/t$, and that power dissipated in a resistor is represented by $P = IV$. For a resistor, $V = IR$. Substituting this expression into the equation for electric power, you obtain the following.

**Power** $P = I^2R$

**FIGURE 22–11** Which of these appliances are designed specifically to change electrical energy into thermal energy?

The power dissipated in a resistor is thus proportional to the square of the current that passes through it and to the resistance. The power is the rate at which energy is converted from one form to another. Energy is changed from electric to thermal energy, and the temperature of the resistor rises. That is, the resistor gets hot. If the resistor is an immersion heater or burner on an electric stove top for example, heat flows into cold water fast enough to bring the water to the boiling point in a few minutes.

If the power continues to be dissipated at this rate, then after a time, $t$, the energy converted to thermal energy, will be $E = Pt$. Because $P = I^2R$ the total energy that will be converted to thermal energy can be written in the following way.

$$E = Pt = I^2Rt$$

## Pocket Lab

### Appliances

Look closely at three electric appliances in your home. Record the power (watts) or the current (amps) of each appliance. Assume that each appliance operates at 120 V. Determine the resistance of each appliance.

**Analyze and Conclude** Relate the power used in an appliance to its resistance.

## Example Problem

### Thermal Energy Produced by an Electric Current

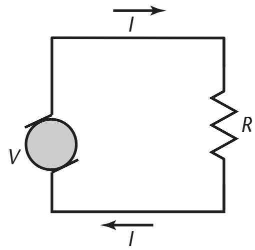
A heater has a resistance of 10.0 Ω. It operates on 120.0 V.

**a.** What is the current through the resistance?

**b.** What thermal energy is supplied by the heater in 10.0 s?

#### Sketch the Problem

- Draw a circuit with a 120.0-V potential difference source and a 10.0 Ω resistor.




#### Calculate Your Answer

**Known:**

$R = 10.0\ \Omega$

$V = 120.0\ \text{V}$

$t = 10.0\ \text{s}$

**Unknown:**

$I = ?$

$E = ?$

**Strategy:**

**a.** Use $I = V/R$ to determine the current.

**b.** Use $E = I^2Rt$ to determine the energy.

**Calculations:**

$$I = V/R = (120.0\ \text{V})/(10.0\ \Omega) = 12.0\ \text{A}$$

$$E = I^2Rt = (12.0\ \text{A})^2(10.0\ \Omega)(10.0\ \text{s}) = 14.4 \times 10^3\ \text{J} = 14.4\ \text{kJ}$$

#### Check Your Answer

- Are the units correct? Current is measured in amperes, and energy is measured in joules.
- Is the magnitude realistic? Current produced by heating elements is about 10 A. Energy values of resistance heaters are large.



CONTENTS

## Pocket Lab

### Heating Up

Look at the markings on three resistors. Predict which resistor would allow the most current through it using a constant voltage. Under the same conditions, predict which resistor will heat the most. Explain your prediction.

**Test Your Predictions** Tape a thermometer bulb to the resistor. Turn on the power for one minute. Measure the temperature. Allow the resistor to cool off and then repeat the procedure with the remaining two resistors.

**CAUTION:** *Do not touch the resistors with power supplied. They may be extremely hot. Wait two minutes after turning off the power to remove the thermometer.*

## Practice Problems

**10.** A 15-Ω electric heater operates on a 120-V outlet.
  **a.** What is the current through the heater?
  **b.** How much energy is used by the heater in 30.0 s?
  **c.** How much thermal energy is liberated in this time?

**15.** A 30-Ω resistor is connected across a 60-V battery.
  **a.** What is the current in the circuit?
  **b.** How much energy is used by the resistor in 5.0 min?

**16.** A 100.0-W lightbulb is 20.0 percent efficient. This means that 20.0 percent of the electric energy is converted to light energy.
  **a.** How many joules does the lightbulb convert into light each minute it is in operation?
  **b.** How many joules of thermal energy does the lightbulb produce each minute?

**17.** The resistance of an electric stove element at operating temperature is 11 Ω.
  **a.** If 220 V are applied across it, what is the current through the stove element?
  **b.** How much energy does the element convert to thermal energy in 30.0 s?
  **c.** The element is being used to heat a kettle containing 1.20 kg of water. Assume that 70 percent of the heat is absorbed by the water. What is its increase in temperature during the 30.0s?

## Transmission of Electric Energy

Niagara Falls and Hoover Dam can produce electric energy with little pollution. This hydroelectric energy, however, often must be transmitted long distances to reach homes and industries. How can the transmission take place with as little loss to thermal energy as possible?

Thermal energy is produced at a rate represented by $P = I^2R$. Electrical engineers call this unwanted thermal energy the joule heating or $I^2R$ loss. To reduce this loss, either the current, $I$, or the resistance, $R$, must be reduced. All wires have some resistance, even though this resistance is small. For example, 1 km of the large wire used to carry electric current into a home has a resistance of 0.20 Ω.

Suppose that a farmhouse were connected directly to a power plant 3.5 km away, as depicted in **Figure 22–12.** The resistance in the wires needed to carry a current in a circuit to the home and back to the plant is 2(3.5 km)(0.20 Ω/km) = 1.4 Ω. An electric stove might cause a 41-A current through the wires. The power dissipated in the wires is represented by the following relationship.

$$P = I^2R = (41\ \text{A})^2 \times 1.4\ \Omega = 2400\ \text{W}$$

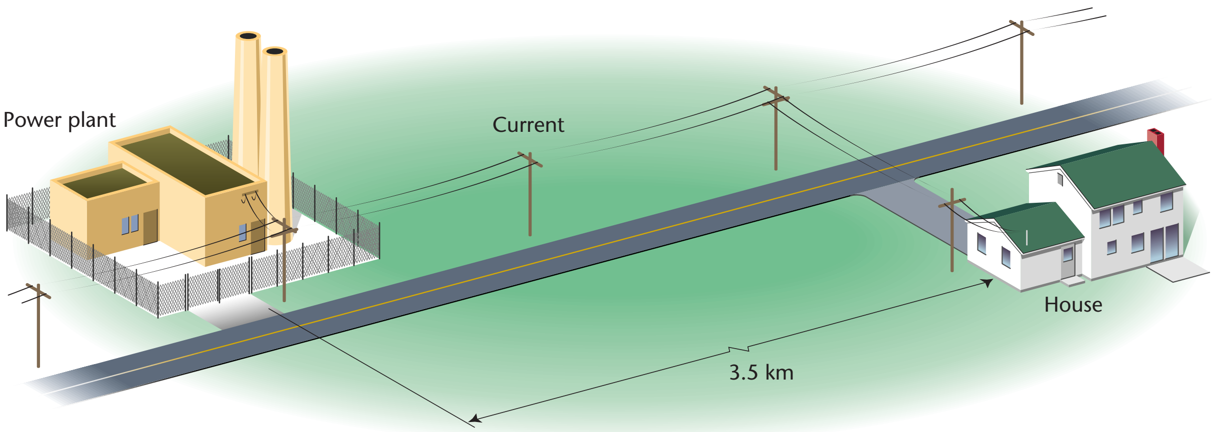



**FIGURE 22–12** Electrical energy is transferred over long distances at high voltages to minimize $I^2R$ losses.

All this power is converted to thermal energy and is wasted. This loss could be minimized by reducing the resistance. Cables of high conductivity and large diameter are currently used, but such cables are expensive and heavy. Because the loss is also proportional to the square of the current in the conductors, it is even more important to keep the current in the transmission lines low.

So why not just transmit the potential difference at household voltages directly instead of using the high-voltage transmission lines? The electrical energy per second (power) transferred over a long-distance transmission line is determined by the relationship $P = IV$. The current can be reduced without the power being reduced by increasing the voltage. Some long-distance lines use voltages of more than 500 000 volts. The resulting lower current reduces the $I^2R$ loss in the lines by keeping the $I^2$ factor low. Long-distance transmission lines always operate at high voltage to reduce $I^2R$ loss. The output voltage from the generating plant can be reduced upon arrival at electric substations to 2400 V and again to 240 V or 120 V before use at home.

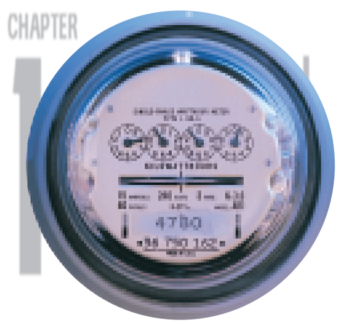
## More for Less

*Answers question from page 506.*

Picture not available on CD

## The Kilowatt-Hour

While electric companies often are called “power” companies, they really provide energy. When consumers pay their home electric bills, an example of which is shown in **Figure 22–13,** they actually pay for electric energy, not power.



**a**

**b**

**FIGURE 22–13** Watt-hour meters measure the amount of electric energy used by a consumer **(a).** The more current being used at a given time, the faster the horizontal disk in the center of the meter turns. Meter readings are then used in calculating the cost of energy **(b).**

The electric energy used by any device is its rate of energy consumption, in joules per second (watts) times the number of seconds it is operated. Joules per second times seconds, J·s/s, equals total joules of energy. The joule, also defined as a watt-second, is a relatively small amount of energy. This is too small for commercial sales use. For that reason, electric companies measure their energy sales in a unit of a large number of joules called a kilowatt-hour, kWh. A **kilowatt-hour** is equal to 1000 watts delivered continuously for 3600 seconds (1 hour).

$$1 \text{ kWh} = (1000 \text{ J/s})(3600 \text{ s}) = 3.6 \times 10^6 \text{ J}$$

Not many devices in homes other than hot-water heaters, stoves, heaters, curling irons, and hair dryers require more than 1000 watts of power. Ten 100-watt lightbulbs operating all at once would use one kilowatt hour of energy if they were left on for one full hour.

## Example Problem

### The Cost of Operating an Electric Device

A television set draws 2.0 A when operated on 120 V.

**a.** How much power does the set use?

**b.** If the set is operated for an average of 7.0 h/day, what energy in kWh does it consume per month (30 days)?

**c.** At 11¢ per kWh, what is the cost of operating the set per month?

### Calculate Your Answer

**Known:**

$I = 2.0$ A

$V = 120.0$ V

$t = (7.0 \text{ h/day})(30 \text{ day})$

cost = 11¢/kWh

**Unknown:**

$E = ?$

total cost = ?

**Strategy:**

**a.** Use $P = IV$ to determine the power.

**b.** Use $E = Pt$ to determine the energy.

**c.** Use $E$/unit cost to determine the cost.

**Calculations:**

$P = IV = (2.0 \text{ A})(120.0 \text{ V}) = 2.4 \times 10^2 \text{ W}$

$E = Pt = (2.4 \times 10^2 \text{ W})(7.0 \text{ h/d})(30 \text{ d}) = 5.0 \times 10^4 \text{ Wh}$
$= 5.0 \times 10^1 \text{ kWh}$

cost = $(5.0 \times 10^1 \text{ kWh})(11¢\text{/kWh})$ = \$5.50

### Check Your Answer:

- Are the units correct? Power is in watts, energy is in kilowatt-hours, and cost is in dollars.
- Is the magnitude realistic? A television does not require much power to operate. However, if you watch a lot of television, the cost of operation will be more than the cost for operating an appliance that requires more power.

## Practice Problems

**18.** An electric space heater draws 15.0 A from a 120-V source. It is operated, on the average, for 5.0 h each day.

**a.** How much power does the heater use?

**b.** How much energy in kWh does it consume in 30 days?

**c.** At 11¢ per kWh, how much does it cost to operate the heater for 30 days?

**19.** A digital clock has a resistance of 12 000 Ω and is plugged into a 115-V outlet.

**a.** How much current does it draw?

**b.** How much power does it use?

**c.** If the owner of the clock pays 9¢ per kWh, how much does it cost to operate the clock for 30 days?

**20.** A four-slice toaster is rated at 1200 W and designed for use with 120-V circuits.

**a.** What is the resistance of the toaster?

**b.** How much current will flow when the toaster is turned on?

**c.** At what rate is heat generated in the toaster?

**d.** If all the heat generated were concentrated into 500 g of water at room temperature, at what rate would the temperature be rising?

**e.** The nichrome heating wires in the toaster total 2.00 m long if pulled straight. What is the electric field in the wire during operation if all the energy is converted in the nichrome wire?

**f.** If it takes 3 minutes to properly make toast and the cost per kilowatt-hour is 10 cents, how much does it cost to make one slice of toast?

## F.Y.I.

In Ohm's day it was not possible to go to the hardware store and buy wire, something we take for granted today. Fortunately, he learned how to make wire while helping his father, who was a locksmith.

## 22.2 Section Review

**1.** A battery charges a capacitor. The capacitor is discharged through a photo flashlamp. List the forms of energy in these two operations.

**2.** A hair dryer operating from 120 V has two settings, hot and warm. In which setting is the resistance likely to be smaller? Why?

**3.** Evaluate the impact of research to improve power transmission lines on society and the environment.

**4.** Why would a home using an electric range and hot-water heater have these appliances connected to 240 V rather than 120 V?

**5.** **Critical Thinking** When demand for electric power is high, power companies sometimes reduce the voltage, thereby producing a "brown out." What is being saved?

# CHAPTER 22 REVIEW

## Key Terms

**22.1**

- electric current
- conventional current
- battery
- photovoltaic cell
- electric circuit
- ampere
- resistance
- resistor
- potentiometer
- schematic
- parallel connection
- series connection

**22.2**

- kilowatt-hour

## *Summary*

### 22.1 Current and Circuits

- Batteries, generators, and solar cells convert various forms of energy to electric energy.
- In an electric circuit, electric energy is transmitted from a device that produces electric energy to a resistor or other device that converts electric energy into the form needed.
- As a charge moves through resistors in a circuit, its potential energy is reduced. The energy released when the charge moves around the remainder of the circuit equals the work done to give the charge its initial potential energy.
- One ampere is one coulomb per second.
- Electric power is found by multiplying voltage by current.
- The resistance of a device is the ratio of the voltage across it divided by the current through it.
- In a device that obeys Ohm's law, the resistance remains constant as the voltage and current change.
- The current in a circuit can be varied by changing either the voltage or the resistance, or both.
- In a circuit diagram, conventional current is used. This is the direction in which a positive charge would move.

### 22.2 Using Electric Energy

- The thermal energy produced in a circuit from electric energy is equal to $I^2Rt$.
- In long-distance transmission, current is reduced without power being reduced by increasing the voltage.
- A kilowatt-hour, kWh, is an energy unit. It is equal to $3.6 \times 10^6$ J.

### Key Equations

**22.1**

$$P = IV$$

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

**22.2**

$$P = I^2R$$

## *Reviewing Concepts*

### Section 22.1

1. Describe the energy conversions that occur in each of these devices.
   **a.** incandescent lightbulb
   **b.** clothes dryer
   **c.** digital clock radio
2. Define the unit of electric current in terms of fundamental MKS units.
3. Which wire conducts electricity with the least resistance: one with a large cross-sectional diameter or one with a small cross-sectional diameter?
4. How many electrons flow past a point in a wire each second if the wire has a current of 1 A?

### Section 22.2

5. Why do lightbulbs burn out more frequently just as they are switched on rather than while they are operating?
6. A simple circuit consists of a battery, a resistor, and some connecting wires. Draw a circuit schematic of this simple circuit. Show the polarity of the battery and the direction of the conventional current.
7. A simple circuit consists of a resistor, a battery, and connecting wires.
   **a.** How must an ammeter be connected in a circuit to correctly read the current?



CONTENTS

b. How must a voltmeter be connected to a resistor in order to read the potential difference across it?

8. If a battery is short-circuited by a heavy copper wire being connected from one terminal to the other, the temperature of the copper wire rises. Why does this happen?

9. Why does a wire become warmer as charges flow through it?

10. What electrical quantities must be kept small to transmit electric energy economically over long distances?

## Applying Concepts

11. When a battery is connected to a complete circuit, charges flow in the circuit almost instantaneously. Explain.

12. Explain why a cow that touches an electric fence experiences a mild shock.

13. Why can birds perch on high-voltage lines without being injured?

14. Describe two ways to increase the current in a circuit.

15. You have two lightbulbs that work on a 120-V circuit. One is 50 W, the other is 100 W. Which bulb has a higher resistance? Explain.

16. If the voltage across a circuit is kept constant and the resistance is doubled, what effect does this have on the circuit's current?

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

18. Sue finds a device that looks like a resistor. When she connects it to a 1.5-V battery, only $45 \times 10^{-6}$ A is measured, but when a 3.0-V battery is used, $25 \times 10^{-3}$ A is measured. Does the device obey Ohm's law?

19. If the ammeter in **Figure 22–5** were moved to the bottom of the diagram, would the ammeter have the same reading? Explain.

20. Two wires can be placed across the terminals of a 6.0-V battery. One has a high resistance, and the other has a low resistance. Which wire will produce thermal energy at the faster rate? Why?

## Problems

### Section 22.1

21. The current through a toaster connected to a 120-V source is 8.0 A. What power is dissipated by the toaster?

22. A current of 1.2 A is measured through a lightbulb when it is connected across a 120-V source. What power is dissipated by the bulb?

23. A lamp draws 0.50 A from a 120-V generator.
    a. How much power is delivered?
    b. How much energy does the lamp convert in 5.0 min?

24. A 12-V automobile battery is connected to an electric starter motor. The current through the motor is 210 A.
    a. How many joules of energy does the battery deliver to the motor each second?
    b. What power, in watts, does the motor use?

25. A 4000-W clothes dryer is connected to a 220-V circuit. How much current does the dryer draw?

26. A flashlight bulb is connected across a 3.0-V potential difference. The current through the lamp is 1.5 A.
    a. What is the power rating of the lamp?
    b. How much electric energy does the lamp convert in 11 min?

27. A resistance of 60.0 Ω has a current of 0.40 A through it when it is connected to the terminals of a battery. What is the voltage of the battery?

28. What voltage is applied to a 4.0-Ω resistor if the current is 1.5 A?

29. What voltage is placed across a motor of 15-Ω operating resistance if there is 8.0 A of current?

30. A voltage of 75 V is placed across a 15-Ω resistor. What is the current through the resistor?

31. A 20.0-Ω resistor is connected to a 30.0-V battery. What is the current through the resistor?

32. A 12-V battery is connected to a device and 24 mA of current is measured. If the device obeys Ohm's law, how much current is present when a 24-V battery is used?

33. A person with dry skin has a resistance from one arm to the other of about $1 \times 10^5$ Ω. When skin is wet, resistance drops to about $1.5 \times 10^3$ Ω. (Refer to **Table 22–1.**)

**a.** What is the minimum voltage placed across the arms that would produce a current that could be felt by a person with dry skin?
**b.** What effect would the same voltage have if the person had wet skin?
**c.** What would be the minimum voltage that would produce a current that could be felt when the skin is wet?

**34.** A lamp draws a 66-mA current when connected to a 6.0-V battery. When a 9.0-V battery is used, the lamp draws 75 mA.
**a.** Does the lamp obey Ohm's law?
**b.** How much power does the lamp dissipate at 6.0 V?
**c.** How much power does it dissipate at 9.0 V?

**35.** How much energy does a 60.0-W lightbulb use in half an hour? If the lightbulb is 12 percent efficient, how much thermal energy does it generate during the half hour?

**36.** Some students connected a length of nichrome wire to a variable power supply that could produce from 0.00 V to 10.00 V across the wire. They then measured the current through the wire for several voltages. They recorded the data showing the voltages used and currents measured. These are presented in **Table 22–2.**

**TABLE 22–2**

| Voltage $V$ (volts) | Current $I$ (amps) | Resistance $R = V/I$ (ohms) |
|---|---|---|
| 2.00 | 0.014 | |
| 4.00 | 0.027 | |
| 6.00 | 0.040 | |
| 8.00 | 0.052 | |
| 10.00 | 0.065 | |
| - 2.00 | - 0.014 | |
| - 4.00 | - 0.028 | |
| - 6.00 | - 0.039 | |
| - 8.00 | - 0.051 | |
| - 10.00 | - 0.064 | |

**a.** For each measurement, calculate the resistance.
**b.** Graph $I$ versus $V$.
**c.** Does the nichrome wire obey Ohm's law? If not, for all the voltages, specify the voltage range for which Ohm's law holds.

**37.** The current through a lamp connected across 120 V is 0.40 A when the lamp is on.
**a.** What is the lamp's resistance when it is on?
**b.** When the lamp is cold, its resistance is one fifth as large as it is when the lamp is hot. What is its cold resistance?
**c.** What is the current through the lamp as it is turned on if it is connected to a potential difference of 120 V?

**38.** The graph in **Figure 22–14** shows the current through a device called a silicon diode.
**a.** A potential difference of +0.70 V is placed across the diode. What resistance would be calculated?
**b.** What resistance would be calculated if a +0.60-V potential difference were used?
**c.** Does the diode obey Ohm's law?

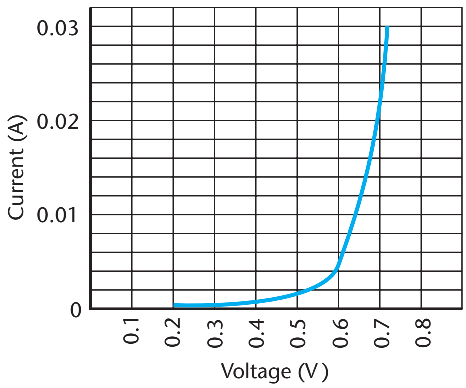



**FIGURE 22–14**

**39.** Draw a schematic diagram to show a circuit that includes a 90-V battery, an ammeter, and a resistance of 45 Ω connected in series. What is the ammeter reading? Draw arrows showing the direction of conventional current.

**40.** Draw a series circuit diagram to include a 16-Ω resistor, a battery, and an ammeter that reads 1.75 A. Conventional current is measured through the meter from left to right. Indicate the positive terminal and the voltage of the battery.

## Section 22.2

**41.** What is the maximum current that should be allowed in a 5.0-W, 220-Ω resistor?

**42.** The wire in a house circuit is rated at 15.0 A and has a resistance of 0.15 Ω.

**a.** What is its power rating?
**b.** How much heat does the wire give off in 10.0 min?

**43.** A current of 1.2 A is measured through a 50.0-Ω resistor for 5.0 min. How much heat is generated by the resistor?

**44.** A 6.0-Ω resistor is connected to a 15-V battery.
**a.** What is the current in the circuit?
**b.** How much thermal energy is produced in 10.0 min?

**45.** A 110-V electric iron draws 3.0 A of current. How much thermal energy is developed each hour?

**46.** An electric motor operates a pump that irrigates a farmer's crop by pumping 10 000 L of water a vertical distance of 8.0 m into a field each hour. The motor has an operating resistance of 22.0 Ω and is connected across a 110-V source.
**a.** What current does it draw?
**b.** How efficient is the motor?

**47.** A transistor radio operates by means of a 9.0-V battery that supplies it with a 50-mA current.
**a.** If the cost of the battery is $0.90 and it lasts for 300 h, what is the cost per kWh to operate the radio in this manner?
**b.** The same radio, by means of a converter, is plugged into a household circuit by a homeowner who pays 8¢ per kWh. What does it now cost to operate the radio for 300 h?

**Extra Practice** For more practice solving problems, go to Extra Practice Problems, Appendix B.

## Critical Thinking Problems

**48.** A heating coil has a resistance of 4.0 Ω and operates on 120 V.
**a.** What is the current in the coil while it is operating?
**b.** What energy is supplied to the coil in 5.0 min?
**c.** If the coil is immersed in an insulated container holding 20.0 kg of water, what will be the increase in the temperature of the water? Assume that 100 percent of the heat is absorbed by the water.
**d.** At 8¢ per kWh, how much does it cost to operate the heating coil 30 min per day for 30 days?

**49.** An electric heater is rated at 500 W.
**a.** How much energy is delivered to the heater in half an hour?
**b.** The heater is being used to heat a room containing 50 kg of air. If the specific heat of air is 1.10 kJ/kg·°C, and 50 percent of the thermal energy heats the air in the room, what is the change in air temperature in half an hour?
**c.** At 8¢ per kWh, how much does it cost to run the heater 6.0 h per day for 30 days?

## Going Further

**Formulating Models** How much energy is stored in a capacitor? The energy needed to increase the potential difference of a charge, $q$ is represented by $E = qV$. But in a capacitor, $V = q/C$. Thus, as charge is added, the potential difference increases. But as more charge is added, it takes more energy to add the additional charge.

Consider a 1.0-F "supercap" used as an energy storage device in a personal computer. Plot a graph of $V$ as the capacitor is charged by adding 5.0 C to it. What is the voltage across the capacitor? The area under the curve is the energy stored in the capacitor. Find the energy in joules. Is it equal to the total charge times the final potential difference? Explain.

PHYSICS Online

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