PHYSICS APPLIED
Resistance thermometer

EXAMPLE 18–7 Resistance thermometer. The variation in electrical resistance with temperature can be used to make precise temperature measurements. Platinum is commonly used since it is relatively free from corrosive effects and has a high melting point. Suppose at 20.0°C the resistance of a platinum resistance thermometer is 164.2 Ω. When placed in a particular solution, the resistance is 187.4 Ω. What is the temperature of this solution?

APPROACH Since the resistance R is directly proportional to the resistivity ρ, we can combine Eq. 18–3 with Eq. 18–4 to find R as a function of temperature T, and then solve that equation for T.

SOLUTION Equation 18–3 tells us $R = \rho\ell/A$, so we multiply Eq. 18–4 by (ℓ/A) to obtain

$$R = R_0[1 + \alpha(T - T_0)].$$

Here $R_0 = \rho_0\ell/A$ is the resistance of the wire at $T_0 = 20.0°\mathrm{C}$. We solve this equation for T and find (see Table 18–1 for α)

$$T = T_0 + \frac{R - R_0}{\alpha R_0} = 20.0°\mathrm{C} + \frac{187.4\,\Omega - 164.2\,\Omega}{\left(3.927 \times 10^{-3}(\mathrm{C}°)^{-1}\right)(164.2\,\Omega)} = 56.0°\mathrm{C}.$$

NOTE Resistance thermometers have the advantage that they can be used at very high or low temperatures where gas or liquid thermometers would be useless.

NOTE More convenient for some applications is a **thermistor** (Fig. 18–15), which consists of a metal oxide or semiconductor whose resistance also varies in a repeatable way with temperature. Thermistors can be made quite small and respond very quickly to temperature changes.

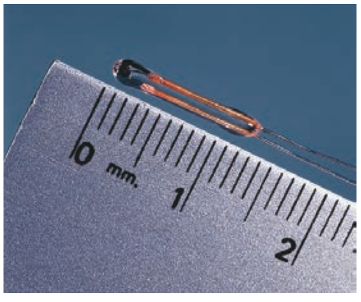

FIGURE 18–15 A thermistor only 13 mm long, shown next to a millimeter ruler.

EXERCISE G The resistance of the tungsten filament of a common incandescent lightbulb is how many times greater at its operating temperature of 2800 K than its resistance at room temperature? (*a*) Less than 1% greater; (*b*) roughly 10% greater; (*c*) about 2 times greater; (*d*) roughly 10 times greater; (*e*) more than 100 times greater.

The value of α in Eq. 18–4 can itself depend on temperature, so it is important to check the temperature range of validity of any value (say, in a handbook of physical data). If the temperature range is wide, Eq. 18–4 is not adequate and terms proportional to the square and cube of the temperature are needed, but these terms are generally very small except when $T - T_0$ is large.

18–5 Electric Power

Electric energy is useful to us because it can be easily transformed into other forms of energy. Motors transform electric energy into mechanical energy, and are examined in Chapter 20.

In other devices such as electric heaters, stoves, toasters, and hair dryers, electric energy is transformed into thermal energy in a wire resistance known as a "heating element." And in an ordinary lightbulb, the tiny wire filament (Fig. 18–5 and Chapter-Opening Photo) becomes so hot it glows; only a few percent of the energy is transformed into visible light, and the rest, over 90%, into thermal energy. Lightbulb filaments and heating elements (Fig. 18–16) in household appliances have resistances typically of a few ohms to a few hundred ohms.

FIGURE 18–16 Hot electric stove burner glows because of energy transformed by electric current.

Electric energy is transformed into thermal energy or light in such devices, and there are many collisions between the moving electrons and the atoms of the wire. In each collision, part of the electron's kinetic energy is transferred to the atom with which it collides. As a result, the kinetic energy of the wire's atoms increases and hence the temperature (Section 13–9) of the wire element increases. The increased thermal energy can be transferred as heat by conduction and convection to the air in a heater or to food in a pan, by radiation to bread in a toaster, or radiated as light.

To find the power transformed by an electric device, recall that the energy transformed when a charge Q moves through a potential difference V is QV (Eq. 17–3). Then the power P, which is the rate energy is transformed, is

$$P = \frac{\text{energy transformed}}{\text{time}} = \frac{QV}{t}.$$

The charge that flows per second, Q/t, is the electric current I. Thus we have

$$P = IV. \tag{18–5}$$

This general relation gives us the power transformed by any device, where I is the current passing through it and V is the potential difference across it. It also gives the power delivered by a source such as a battery. The SI unit of electric power is the same as for any kind of power, the **watt** $(1\text{ W} = 1\text{ J/s})$.

The rate of energy transformation in a resistance R can be written in two other ways, starting with the general relation $P = IV$ and substituting in Ohm's law, $V = IR$:

$$P = IV = I(IR) = I^2R \tag{18–6a}$$

$$P = IV = \left(\frac{V}{R}\right)V = \frac{V^2}{R}. \tag{18–6b}$$

Equations 18–6a and b apply only to resistors, whereas Eq. 18–5, $P = IV$, is more general and applies to any device.

EXAMPLE 18–8 **Headlights.** Calculate the resistance of a 40-W automobile headlight designed for 12 V (Fig. 18–17).

APPROACH We solve for R in Eq. 18–6b, which has the given variables.

SOLUTION From Eq. 18–6b,

$$R = \frac{V^2}{P} = \frac{(12\text{ V})^2}{(40\text{ W})} = 3.6\,\Omega.$$

NOTE This is the resistance when the bulb is burning brightly at 40 W. When the bulb is cold, the resistance is much lower, as we saw in Eq. 18–4 (see also Exercise G). Since the current is high when the resistance is low, lightbulbs burn out most often when first turned on.

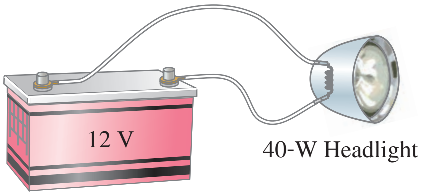

FIGURE 18–17 Example 18–8.

PHYSICS APPLIED
Why lightbulbs burn out when first turned on

CAUTION
You pay for energy, which is power × time, not for power

It is energy, not power, that you pay for on your electric bill. Since power is the *rate* energy is transformed, the total energy used by any device is simply its power consumption multiplied by the time it is on. If the power is in watts and the time is in seconds, the energy will be in joules since $1\text{ W} = 1\text{ J/s}$. Electric companies usually specify the energy with a much larger unit, the **kilowatt-hour** (kWh). One $\text{kWh} = (1000\text{ W})(3600\text{ s}) = 3.60 \times 10^6\text{ J}$.

EXAMPLE 18–9 **Electric heater.** An electric heater draws a steady 15.0 A on a 120-V line. How much power does it require and how much does it cost per month (30 days) if it operates 3.0 h per day and the electric company charges 9.2 cents per kWh?

APPROACH We use Eq. 18–5, $P = IV$, to find the power. We multiply the power (in kW) by the time (h) used in a month and by the cost per energy unit, \$0.092 per kWh, to get the cost per month.

SOLUTION The power is

$$P = IV = (15.0\text{ A})(120\text{ V})$$
$$= 1800\text{ W} = 1.80\text{ kW}.$$

The time (in hours) the heater is used per month is $(3.0\text{ h/d})(30\text{ d}) = 90\text{ h}$, which at 9.2¢/kWh would cost $(1.80\text{ kW})(90\text{ h})(\$0.092/\text{kWh}) = \$15$, just for this heater.

NOTE Household current is actually alternating (ac), but our solution is still valid assuming the given values for V and I are the proper averages (rms) as we discuss in Section 18–7.

PHYSICS APPLIED
Lightning

FIGURE 18–18 Example 18–10. A lightning bolt.

EXAMPLE 18–10 ESTIMATE **Lightning bolt.** Lightning is a spectacular example of electric current in a natural phenomenon (Fig. 18–18). There is much variability to lightning bolts, but a typical event might transfer 10^9 J of energy across a potential difference of perhaps 5×10^7 V during a time interval of about 0.2 s. Use this information to estimate (*a*) the total amount of charge transferred between cloud and ground, (*b*) the current in the lightning bolt, and (*c*) the average power delivered over the 0.2 s.

APPROACH We estimate the charge Q, recalling that potential energy change equals the potential difference ΔV times the charge Q, Eq. 17–3. We equate ΔPE with the energy transferred, $\Delta\text{PE} \approx 10^9$ J. Next, the current I is Q/t (Eq. 18–1) and the power P is energy/time.

SOLUTION (*a*) From Eq. 17–3, the energy transformed is $\Delta\text{PE} = Q\,\Delta V$. We solve for Q:

$$Q = \frac{\Delta\text{PE}}{\Delta V} \approx \frac{10^9\text{ J}}{5 \times 10^7\text{ V}} = 20\text{ coulombs.}$$

(*b*) The current during the 0.2 s is about

$$I = \frac{Q}{t} \approx \frac{20\text{ C}}{0.2\text{ s}} = 100\text{ A.}$$

(*c*) The average power delivered is

$$P = \frac{\text{energy}}{\text{time}} = \frac{10^9\text{ J}}{0.2\text{ s}} = 5 \times 10^9\text{ W} = 5\text{ GW.}$$

We can also use Eq. 18–5:

$$P = IV = (100\text{ A})(5 \times 10^7\text{ V}) = 5\text{ GW.}$$

NOTE Since most lightning bolts consist of several stages, it is possible that individual parts could carry currents much higher than the 100 A calculated above.

EXERCISE H Since $1\text{ kWh} = 3.6 \times 10^6$ J, how much mass must be lifted against gravity through one meter to do the equivalent amount of work?

18–6 Power in Household Circuits

PHYSICS APPLIED
Safety—wires getting hot

PHYSICS APPLIED
Fuses, circuit breakers, and shorts

The electric wires that carry electricity to lights and other electric appliances in houses and buildings have some resistance, although usually it is quite small. Nonetheless, if the current is large enough, the wires will heat up and produce thermal energy at a rate equal to I^2R, where R is the wire's resistance. One possible hazard is that the current-carrying wires in the wall of a building may become so hot as to start a fire. Thicker wires have less resistance (see Eq. 18–3) and thus can carry more current without becoming too hot. When a wire carries more current than is safe, it is said to be "overloaded." To prevent overloading, **fuses** or **circuit breakers** are installed in circuits. They are basically switches (Fig. 18–19, top of next page) that open the circuit when the current exceeds a safe value. A 20-A fuse or circuit breaker, for example, opens when the current passing through it exceeds 20 A. If a circuit repeatedly burns out a fuse or opens a circuit breaker, and no connected device requires more than 20 A, there are two possibilities: there may be too many devices drawing current in that circuit; or there is a fault somewhere, such as a "short." A short, or "short circuit," means that two wires have touched that should not have (perhaps because the insulation has worn through) so the path of the current is shortened through a path of very low resistance. With reduced resistance, the current becomes very large and can make a wire hot enough to start a fire. Short circuits should be remedied immediately.

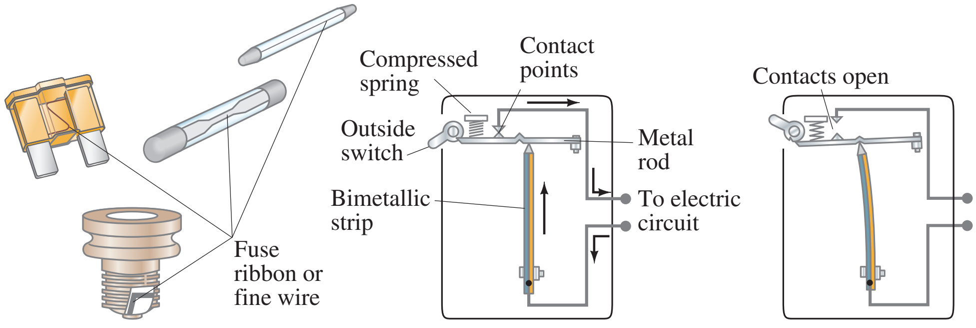

FIGURE 18–19 (a) Fuses. When current exceeds a certain value, the metallic ribbon or wire inside melts and the circuit opens. Then the fuse must be replaced. (b) One type of circuit breaker. Current passes through a bimetallic strip. When the current exceeds a safe level, the heating of the bimetallic strip causes the strip to bend so far to the left that the notch in the spring-loaded metal rod drops down over the end of the bimetallic strip (c) and the circuit opens at the contact points (one is attached to the rod) and the outside switch is also flipped. When the bimetallic strip cools, it can be reset using the outside switch. Better magnetic-type circuit breakers are discussed in Chapters 20 and 21.

Household circuits are designed with the various devices connected so that each receives the standard voltage (Fig. 18–20) from the electric company (usually 120 V in the United States). Circuits with the devices arranged as in Fig. 18–20 are called *parallel circuits*, as we will discuss in the next Chapter. When a fuse blows or circuit breaker opens, it is important to check the total current being drawn on that circuit, which is the sum of the currents in each device.

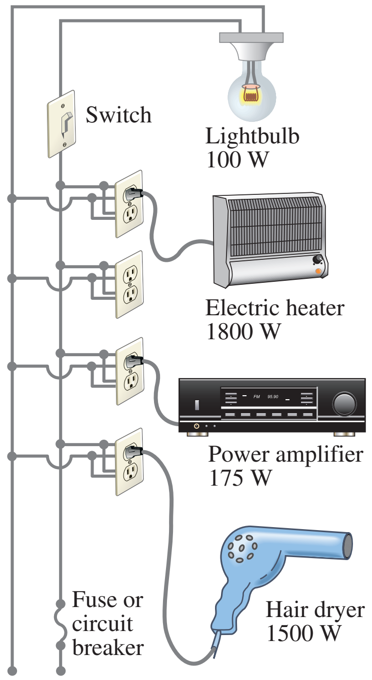

FIGURE 18–20 Connection of household appliances.

EXAMPLE 18–11 **Will a fuse blow?** Determine the total current drawn by all the devices in the circuit of Fig. 18–20.

APPROACH Each device has the same 120-V voltage across it. The current each draws from the source is found from $I = P/V$, Eq. 18–5.

SOLUTION The circuit in Fig. 18–20 draws the following currents: the lightbulb draws $I = P/V = 100\,\mathrm{W}/120\,\mathrm{V} = 0.8\,\mathrm{A}$; the heater draws $1800\,\mathrm{W}/120\,\mathrm{V} = 15.0\,\mathrm{A}$; the power amplifier draws a maximum of $175\,\mathrm{W}/120\,\mathrm{V} = 1.5\,\mathrm{A}$; and the hair dryer draws $1500\,\mathrm{W}/120\,\mathrm{V} = 12.5\,\mathrm{A}$. The total current drawn, if all devices are used at the same time, is

$$0.8\,\mathrm{A} + 15.0\,\mathrm{A} + 1.5\,\mathrm{A} + 12.5\,\mathrm{A} = 29.8\,\mathrm{A}.$$

NOTE The heater draws as much current as 18 100-W lightbulbs. For safety, the heater should probably be on a circuit by itself.

If the circuit in Fig. 18–20 is designed for a 20-A fuse, the fuse should blow, and we hope it will, to prevent overloaded wires from getting hot enough to start a fire. Something will have to be turned off to get this circuit below 20 A. (Houses and apartments usually have several circuits, each with its own fuse or circuit breaker; try moving one of the devices to another circuit.) If the circuit is designed with heavier wire and a 30-A fuse, the fuse shouldn't blow—if it does, a short may be the problem. (The most likely place for a short is in the cord of one of the devices.) Proper fuse size is selected according to the wire used to supply the current. A properly rated fuse should *never* be replaced by a higher-rated one, even in a car. A fuse blowing or a circuit breaker opening is acting like a switch, making an "open circuit." By an open circuit, we mean that there is no longer a complete conducting path, so no current can flow; it is as if $R = \infty$.

PHYSICS APPLIED
Proper fuses and shorts

CONCEPTUAL EXAMPLE 18–12 **A dangerous extension cord.** Your 1800-W portable electric heater is too far from your desk to warm your feet. Its cord is too short, so you plug it into an extension cord rated at 11 A. Why is this dangerous?

RESPONSE 1800 W at 120 V draws a 15-A current. The wires in the extension cord rated at 11 A could become hot enough to melt the insulation and cause a fire.

PHYSICS APPLIED
Extension cords and possible danger

EXERCISE I How many 60-W 120-V lightbulbs can operate on a 20-A line? (*a*) 2; (*b*) 3; (*c*) 6; (*d*) 20; (*e*) 40.