EXERCISE A If 1 million electrons per second pass a point in a wire, what is the current?

CONCEPTUAL EXAMPLE 18–2 **How to connect a battery.** What is wrong with each of the schemes shown in Fig. 18–7 for lighting a flashlight bulb with a flashlight battery and a single wire?

RESPONSE (*a*) There is no closed path for charge to flow around. Charges might briefly start to flow from the battery toward the lightbulb, but there they run into a "dead end," and the flow would immediately come to a stop.

(*b*) Now there is a closed path passing to and from the lightbulb; but the wire touches only one battery terminal, so there is no potential difference in the circuit to make the charge move. Neither here, nor in (*a*), does the bulb light up.

(*c*) Nothing is wrong here. This is a complete circuit: charge can flow out from one terminal of the battery, through the wire and the bulb, and into the other terminal. This scheme will light the bulb.

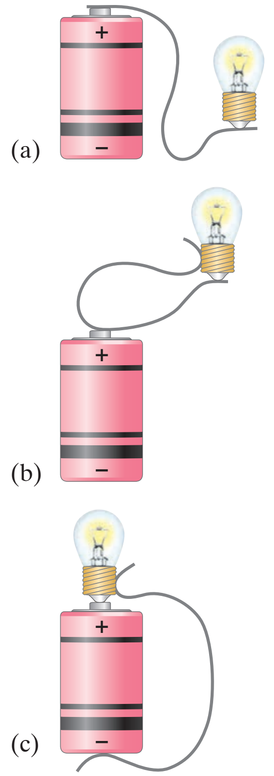


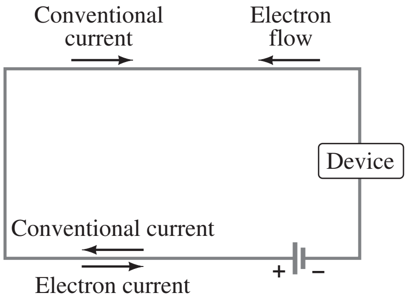
FIGURE 18–7 Example 18–2.

In many real circuits, wires are connected to a common conductor that provides continuity. This common conductor is called **ground**, usually represented as ⏚ or ⏚, and really is connected to the ground for a building or house. In a car, one terminal of the battery is called "ground," but is not connected to the earth itself—it is connected to the frame of the car, as is one connection to each lightbulb and other devices. Thus the car frame is a conductor in each circuit, ensuring a continuous path for charge flow, and is called "ground" for the car's circuits. (Note that the car frame is well insulated from the earth by the rubber tires.)

We saw in Chapter 16 that conductors contain many free electrons. Thus, if a continuous conducting wire is connected to the terminals of a battery, negatively charged electrons flow in the wire. When the wire is first connected, the potential difference between the terminals of the battery sets up an electric field inside the wire and parallel to it. Free electrons at one end of the wire are attracted into the positive terminal, and at the same time other electrons enter the other end of the wire at the negative terminal of the battery. There is a continuous flow of electrons throughout the wire that begins as soon as the wire is connected to *both* terminals.

When the conventions of positive and negative charge were invented two centuries ago, however, it was assumed that positive charge flowed in a wire. For nearly all purposes, positive charge flowing in one direction is exactly equivalent to negative charge flowing in the opposite direction, as shown in Fig. 18–8. Today, we still use the historical convention of positive charge flow when discussing the direction of a current. So when we speak of the current direction in a circuit, we mean the direction positive charge would flow. This is sometimes referred to as **conventional current**. When we want to speak of the direction of electron flow, we will specifically state it is the electron current. In liquids and gases, both positive and negative charges (ions) can move.

FIGURE 18–8 Conventional current from + to − is equivalent to a negative electron flow from − to +.



CAUTION
Distinguish conventional current from electron flow

In practical life, such as rating the total charge of a car battery, you may see the unit **ampere-hour** $(\mathrm{A \cdot h})$: from Eq. 18–1, $\Delta Q = I\,\Delta t$.

EXERCISE B How many coulombs is $1.00\ \mathrm{A \cdot h}$?

18–3 Ohm's Law: Resistance and Resistors

To produce an electric current in a circuit, a difference in potential is required. One way of producing a potential difference along a wire is to connect its ends to the opposite terminals of a battery. It was Georg Simon Ohm (1787–1854) who established experimentally that the current in a metal wire is proportional to the potential difference V applied to its two ends:

$$I \propto V.$$

If, for example, we connect a wire to the two terminals of a 6-V battery, the current in the wire will be twice what it would be if the wire were connected to a 3-V battery. It is also found that reversing the sign of the voltage does not affect the magnitude of the current.

Exactly how large the current is in a wire depends not only on the voltage between its ends, but also on the resistance the wire offers to the flow of electrons. Electron flow is impeded because of collisions with the atoms of the wire. We define electrical **resistance** R as the proportionality factor between the voltage V (between the ends of the wire) and the current I (passing through the wire):

OHM'S "LAW"

$$V = IR. \tag{18–2}$$

Ohm found experimentally that in metal conductors R is a constant independent of V, a result known as **Ohm's law**. Equation 18–2, $V = IR$, is itself sometimes called Ohm's law, but only when referring to materials or devices for which R is a constant independent of V. But R is not a constant for many substances other than metals, nor for devices such as diodes, vacuum tubes, transistors, and so on. Even for metals, R is not constant if the temperature changes much: for a lightbulb filament the measured resistance is low for small currents, but is much higher at the filament's normal large operating current that puts it at the high temperature needed to make it glow (≈ 3000 K). Thus Ohm's "law" is not a fundamental law of nature, but rather a description of a certain class of materials: metal conductors, whose temperature does not change much. Such materials are said to be "ohmic." Materials or devices that do not follow Ohm's law are said to be *nonohmic*. See Fig. 18–9.

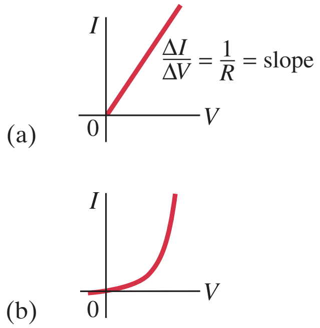
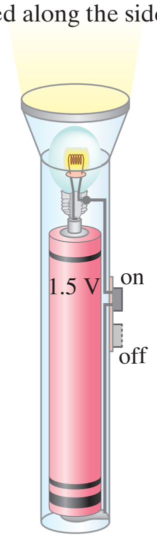


FIGURE 18–9 Graphs of current vs. voltage (a) for a metal conductor which obeys Ohm's law, and (b) for a nonohmic device, in this case a semiconductor diode.

The unit for resistance is called the **ohm** and is abbreviated Ω (Greek capital letter omega). Because $R = V/I$, we see that 1.0 Ω is equivalent to 1.0 V/A.

FIGURE 18–10 Flashlight (Example 18–3). Note how the circuit is completed along the side strip.



EXAMPLE 18–3 **Flashlight bulb resistance.** A small flashlight bulb (Fig. 18–10) draws 300 mA from its 1.5-V battery. (*a*) What is the resistance of the bulb? (*b*) If the battery becomes weak and the voltage drops to 1.2 V, how would the current change? Assume the bulb is approximately ohmic.

APPROACH We apply Ohm's law to the bulb, where the voltage applied across it is the battery voltage.

SOLUTION (*a*) We change 300 mA to 0.30 A and use Eq. 18–2:

$$R = \frac{V}{I} = \frac{1.5\text{ V}}{0.30\text{ A}} = 5.0\ \Omega.$$

(*b*) If the resistance stays the same, the current would be

$$I = \frac{V}{R} = \frac{1.2\text{ V}}{5.0\ \Omega} = 0.24\text{ A} = 240\text{ mA},$$

or a decrease of 60 mA.

NOTE With the smaller current in part (*b*), the bulb filament's temperature would be lower and the bulb less bright. Also, resistance does depend on temperature (Section 18–4), so our calculation is only a rough approximation.

EXERCISE C What is the resistance of a lightbulb if 0.50 A flows through it when 120 V is connected across it?

All electric devices, from heaters to lightbulbs to stereo amplifiers, offer resistance to the flow of current. The filaments of lightbulbs (Fig. 18–5) and electric heaters are special types of wires whose resistance results in their becoming very hot. Generally, the connecting wires have very low resistance in comparison to the resistance of the wire filaments or coils, so the connecting wires usually have a minimal effect on the magnitude of the current.†

†A useful analogy compares the flow of electric charge in a wire to the flow of water in a river, or in a pipe, acted on by gravity. If the river (or pipe) is nearly level, the flow rate is small. But if one end is somewhat higher than the other, the water flow rate—or current—is greater. The greater the difference in height, the swifter the current. We saw in Chapter 17 that electric potential is analogous to the height of a cliff for gravity. Just as an increase in height can cause a greater flow of water, so a greater electric potential difference, or voltage, causes a greater electric current. Resistance in a wire is analogous to rocks in a river that retard water flow.

In many circuits, particularly in electronic devices, **resistors** are used to control the amount of current. Resistors have resistances ranging from less than an ohm to millions of ohms (see Figs. 18–11 and 18–12). The main types are "wire-wound" resistors which consist of a coil of fine wire, "composition" resistors which are usually made of carbon, resistors made of thin carbon or metal films, and (on tiny integrated circuit "chips") undoped semiconductors.

When we draw a diagram of a circuit, we use the symbol

[resistor symbol]

to indicate a resistance. Wires whose resistance is negligible, however, are shown simply as straight lines. Figure 18–12 and its Table show one way to specify the resistance of a resistor.

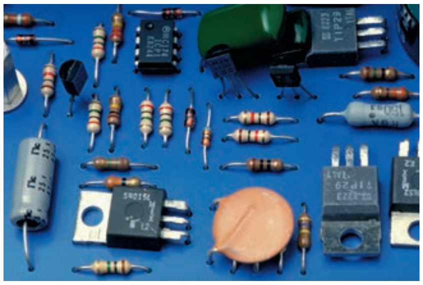
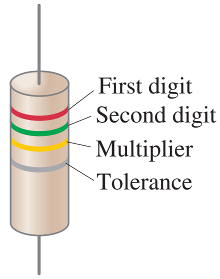


FIGURE 18–11 Photo of resistors (striped), plus other devices on a circuit board.

Resistor Color Code

Color	Number	Multiplier	Tolerance
Black	0	1	
Brown	1	10^1	1%
Red	2	10^2	2%
Orange	3	10^3	
Yellow	4	10^4	
Green	5	10^5	
Blue	6	10^6	
Violet	7	10^7	
Gray	8	10^8	
White	9	10^9	
Gold		10^{-1}	5%
Silver		10^{-2}	10%
No color			20%

FIGURE 18–12 The resistance value of a given resistor is written on the exterior, or may be given as a color code as shown below and in the Table: the first two colors represent the first two digits in the value of the resistance, the third color represents the power of ten that it must be multiplied by, and the fourth is the manufactured tolerance. For example, a resistor whose four colors are red, green, yellow, and silver has a resistance of $25 \times 10^4\,\Omega = 250{,}000\,\Omega = 250\,\mathrm{k}\Omega$, plus or minus 10%. [An alternative code is a number such as 104, which means $R = 1.0 \times 10^4\,\Omega$.]

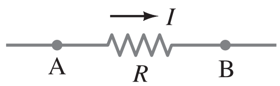


CONCEPTUAL EXAMPLE 18–4 **Current and potential.** Current I enters a resistor R as shown in Fig. 18–13. (*a*) Is the potential higher at point A or at point B? (*b*) Is the current greater at point A or at point B?

RESPONSE (*a*) Positive charge always flows from + to −, from high potential to low potential. So if current I is conventional (positive) current, point A is at a higher potential than point B.

(*b*) Conservation of charge requires that whatever charge flows into the resistor at point A, an equal amount of charge emerges at point B. Charge or current does not get "used up" by a resistor. So the current is the same at A and B.

FIGURE 18–13 Example 18–4.



An electric potential decrease, as from point A to point B in Example 18–4, is often called a **potential drop** or a **voltage drop**.

Some Helpful Clarifications

Here we briefly summarize some possible misunderstandings and clarifications. Batteries do not put out a constant current. Instead, batteries are intended to maintain a constant potential difference, or very nearly so. (Details in the next Chapter.) Thus a battery should be considered a source of voltage. The voltage is applied *across* a wire or device.

CAUTION
Voltage is applied across *a device; current passes* through *a device*

Electric current passes *through* a wire or device (connected to a battery), and its magnitude depends on that device's resistance. The resistance is a *property* of the wire or device. The voltage, on the other hand, is external to the wire or device, and is applied across the two ends of the wire or device. The current through the device might be called the "response": the current increases if the voltage increases or the resistance decreases, as $I = V/R$.

Current is *not* a vector, even though current does have a direction. In a thin wire, the direction of the current is always parallel to the wire at each point, no matter how the wire curves, just like water in a pipe. The direction of conventional (positive) current is from high potential $(+)$ toward lower potential $(-)$.

CAUTION
Current is not consumed

Current and charge do not increase or decrease or get "used up" when going through a wire or other device. The amount of charge that goes in at one end comes out at the other end.

18–4 Resistivity

It is found experimentally that the resistance R of a uniform wire is directly proportional to its length ℓ and inversely proportional to its cross-sectional area A. That is,

$$R = \rho \frac{\ell}{A}, \tag{18–3}$$

where ρ (Greek letter "rho"), the constant of proportionality, is called the **resistivity** and depends on the material used. Typical values of ρ, whose units are $\Omega \cdot \mathrm{m}$ (see Eq. 18–3), are given for various materials in the middle column of Table 18–1 which is divided into the categories *conductors*, *insulators*, and *semiconductors* (Section 16–3). The values depend somewhat on purity, heat treatment, temperature, and other factors. Notice that silver has the lowest resistivity and is thus the best conductor (although it is expensive). Copper is close, and much less expensive, which is why most wires are made of copper. Aluminum, although it has a higher resistivity, is much less dense than copper; it is thus preferable to copper in some situations, such as for transmission lines, because its resistance for the same weight is less than that for copper.[†]

EXERCISE D Return to the Chapter-Opening Question, page 501, and answer it again now. Try to explain why you may have answered differently the first time.

[†] The reciprocal of the resistivity, called the **electrical conductivity**, is $\sigma = 1/\rho$ and has units of $(\Omega \cdot \mathrm{m})^{-1}$.

TABLE 18–1 Resistivity and Temperature Coefficients (at 20°C)

Material	Resistivity, ρ ($\Omega \cdot$ m)	Temperature Coefficient, α $(\mathrm{C}^\circ)^{-1}$
Conductors		
Silver	1.59×10^{-8}	0.0061
Copper	1.68×10^{-8}	0.0068
Gold	2.44×10^{-8}	0.0034
Aluminum	2.65×10^{-8}	0.00429
Tungsten	5.6×10^{-8}	0.0045
Iron	9.71×10^{-8}	0.00651
Platinum	10.6×10^{-8}	0.003927
Mercury	98×10^{-8}	0.0009
Nichrome (Ni, Fe, Cr alloy)	100×10^{-8}	0.0004
Semiconductors[‡]		
Carbon (graphite)	$(3–60) \times 10^{-5}$	-0.0005
Germanium	$(1–500) \times 10^{-3}$	-0.05
Silicon	0.1–60	-0.07
Insulators		
Glass	$10^{9}–10^{12}$	
Hard rubber	$10^{13}–10^{15}$	

[‡] Values depend strongly on the presence of even slight amounts of impurities.

EXERCISE E A copper wire has a resistance of 10 Ω. What would its resistance be if it had the same diameter but was only half as long? (*a*) 20 Ω, (*b*) 10 Ω, (*c*) 5 Ω, (*d*) 1 Ω, (*e*) none of these.

EXAMPLE 18–5 **Speaker wires.** Suppose you want to connect your stereo to remote speakers (Fig. 18–14). (*a*) If each wire must be 20 m long, what diameter copper wire should you use to keep the resistance less than 0.10 Ω per wire? (*b*) If the current to each speaker is 4.0 A, what is the potential difference, or voltage drop, across each wire?

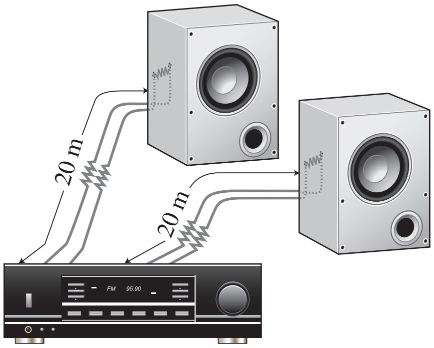


FIGURE 18–14 Example 18–5.

APPROACH We solve Eq. 18–3 to get the area A, from which we can calculate the wire's radius using $A = \pi r^2$. The diameter is $2r$. In (*b*) we can use Ohm's law, $V = IR$.

SOLUTION (*a*) We solve Eq. 18–3 for the area A and find ρ for copper in Table 18–1:

$$A = \rho\frac{\ell}{R} = \frac{(1.68 \times 10^{-8}\,\Omega\cdot\text{m})(20\,\text{m})}{(0.10\,\Omega)} = 3.4 \times 10^{-6}\,\text{m}^2.$$

The cross-sectional area A of a circular wire is $A = \pi r^2$. The radius must then be at least

$$r = \sqrt{\frac{A}{\pi}} = 1.04 \times 10^{-3}\,\text{m} = 1.04\,\text{mm}.$$

The diameter is twice the radius and so must be at least $2r = 2.1$ mm.

(*b*) From $V = IR$ we find that the voltage drop across each wire is

$$V = IR = (4.0\,\text{A})(0.10\,\Omega) = 0.40\,\text{V}.$$

NOTE The voltage drop across the wires reduces the voltage that reaches the speakers from the stereo amplifier, thus reducing the sound level a bit.

CONCEPTUAL EXAMPLE 18–6 **Stretching changes resistance.** Suppose a wire of resistance R could be stretched uniformly until it was twice its original length. What would happen to its resistance? Assume the amount of material, and therefore its volume, doesn't change.

RESPONSE If the length ℓ doubles, then the cross-sectional area A is halved, because the volume ($V = A\ell$) of the wire remains the same. From Eq. 18–3 we see that the resistance would increase by a factor of four $\left(2/\tfrac{1}{2} = 4\right)$.

EXERCISE F Copper wires in houses typically have a diameter of about 1.5 mm. How long a wire would have a 1.0-Ω resistance?

Temperature Dependence of Resistivity

The resistivity of a material depends somewhat on temperature. The resistance of metals generally increases with temperature. This is not surprising, because at higher temperatures, the atoms are moving more rapidly and are arranged in a less orderly fashion. So they might be expected to interfere more with the flow of electrons. If the temperature change is not too great, the resistivity of metals usually increases nearly linearly with temperature. That is,

$$\rho_T = \rho_0\left[1 + \alpha(T - T_0)\right] \tag{18–4}$$

where ρ_0 is the resistivity at some reference temperature T_0 (such as 0°C or 20°C), ρ_T is the resistivity at a temperature T, and α is the **temperature coefficient of resistivity**. Values for α are given in Table 18–1. Note that the temperature coefficient for semiconductors can be negative. Why? It seems that at higher temperatures, some of the electrons that are normally not free in a semiconductor become free and can contribute to the current. Thus, the resistance of a semiconductor can decrease with an increase in temperature.

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 $T_0 = 20.0°\text{C}$. We solve this equation for T and find (see Table 18–1 for α)

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

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.

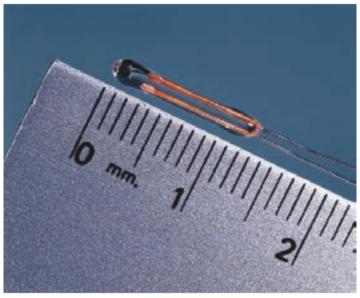


FIGURE 18–15 A thermistor only 13 mm long, shown next to a millimeter ruler.

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.