The glow of the thin wire filament of incandescent lightbulbs is caused by the electric current passing through it. Electric energy is transformed to thermal energy (via collisions between moving electrons and atoms of the wire), which causes the wire's temperature to become so high that it glows. In halogen lamps (tungsten–halogen), shown on the right, the tungsten filament is surrounded by a halogen gas such as bromine or iodine in a clear tube. Halogens, via chemical reactions, restore many of the tungsten atoms that were evaporated from the hot filament, allowing longer life, higher temperature (typically 2900 K versus 2700 K), better efficiency, and whiter light.

Electric current and electric power in electric circuits are of basic importance in everyday life. We examine both dc and ac in this Chapter, and include the microscopic analysis of electric current.

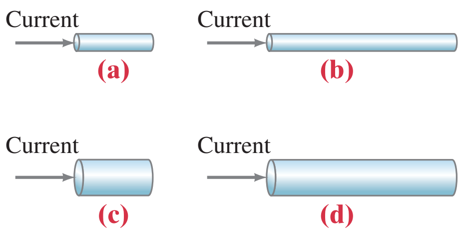
CHAPTER 18

Electric Currents

CONTENTS

CHAPTER-OPENING QUESTION—Guess now!

The conductors shown are all made of copper and are at the same temperature. Which conductor would have the greatest resistance to the flow of charge entering from the left? Which would offer the least resistance?



In the previous two Chapters we have been studying static electricity: electric charges at rest. In this Chapter we begin our study of charges in motion, and we call a flow of charge an electric current.

In everyday life we are familiar with electric currents in wires and other conductors. Most practical electrical devices depend on electric current: current through a lightbulb, current in the heating element of a stove, hair dryer, or electric heater, as well as currents in electronic devices. Electric currents can exist in conductors such as wires, but also in semiconductor devices, human cells and their membranes (Section 18–10), and in empty space.

In electrostatic situations, we saw in Section 16–9 that the electric field must be zero inside a conductor (if it weren't, the charges would move). But when charges are *moving* along a conductor, an electric field is needed to set charges into motion, and to keep them in motion against even low resistance in any normal conductor. We can control the flow of charge using electric fields and electric potential (voltage), concepts we have just been discussing. In order to have a current in a wire, a potential difference is needed, which can be provided by a battery.

We first look at electric current from a macroscopic point of view. Later in the Chapter we look at currents from a microscopic (theoretical) point of view as a flow of electrons in a wire.

18–1 The Electric Battery

FIGURE 18–1 Alessandro Volta. In this portrait, Volta demonstrates his battery to Napoleon in 1801.

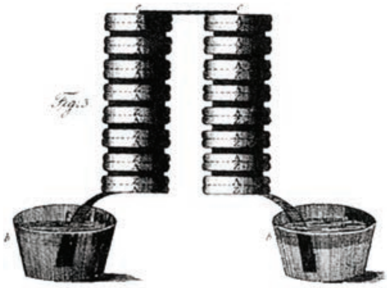
Until the year 1800, the technical development of electricity consisted mainly of producing a static charge by friction. It all changed in 1800 when Alessandro Volta (1745–1827; Fig. 18–1) invented the electric battery, and with it produced the first steady flow of electric charge—that is, a steady electric current.

The events that led to the discovery of the battery are interesting. Not only was this an important discovery, but it also gave rise to a famous scientific debate.

In the 1780s, Luigi Galvani (1737–1798), professor at the University of Bologna, carried out a series of experiments on the contraction of a frog's leg muscle by using static electricity. Galvani found that the muscle also contracted when dissimilar metals were inserted into the frog. Galvani believed that the source of the electric charge was in the frog muscle or nerve itself, and that the metal merely transmitted the charge to the proper points. When he published his work in 1791, he termed this charge "animal electricity." Many wondered, including Galvani himself, if he had discovered the long-sought "life-force."

Volta, at the University of Pavia 200 km away, was skeptical of Galvani's results, and came to believe that the source of the electricity was not in the animal itself, but rather in the *contact between the dissimilar metals*. Volta realized that a moist conductor, such as a frog muscle or moisture at the contact point of two dissimilar metals, was necessary in the circuit if it was to be effective. He also saw that the contracting frog muscle was a sensitive instrument for detecting electric "tension" or "electromotive force" (his words for what we now call voltage), in fact more sensitive than the best available electroscopes that he and others had developed.†

FIGURE 18–2 A voltaic battery, from Volta's original publication.



Volta's research found that certain combinations of metals produced a greater effect than others, and, using his measurements, he listed them in order of effectiveness. (This "electrochemical series" is still used by chemists today.) He also found that carbon could be used in place of one of the metals.

Volta then conceived his greatest contribution to science. Between a disc of zinc and one of silver, he placed a piece of cloth or paper soaked in salt solution or dilute acid and piled a "battery" of such couplings, one on top of another, as shown in Fig. 18–2. This "pile" or "battery" produced a much increased potential difference. Indeed, when strips of metal connected to the two ends of the pile were brought close, a spark was produced. Volta had designed and built the first electric battery. He published his discovery in 1800.

†Volta's most sensitive electroscope (Section 16–4) measured about 40 V per degree (angle of leaf separation). Nonetheless, he was able to estimate the potential differences produced by combinations of dissimilar metals in contact. For a silver–zinc contact he got about 0.7 V, remarkably close to today's value of 0.78 V.

Electric Cells and Batteries

A battery produces electricity by transforming chemical energy into electrical energy. Today a great variety of electric cells and batteries are available, from flashlight batteries to the storage battery of a car. The simplest batteries contain two plates or rods made of dissimilar metals (one can be carbon) called **electrodes**. The electrodes are immersed in a solution or paste, such as a dilute acid, called the **electrolyte**. Such a device is properly called an **electric cell**, and several cells connected together is a **battery**, although today even a single cell is called a battery. The chemical reactions involved in most electric cells are quite complicated. Here we describe how one very simple cell works, emphasizing the physical aspects.

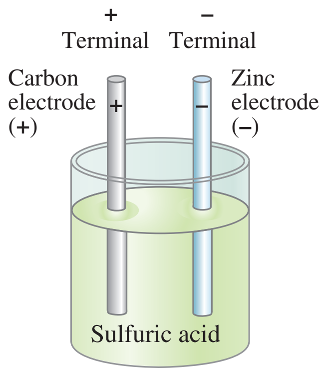


FIGURE 18–3 Simple electric cell.

The cell shown in Fig. 18–3 uses dilute sulfuric acid as the electrolyte. One of the electrodes is made of carbon, the other of zinc. The part of each electrode outside the solution is called the **terminal**, and connections to wires and circuits are made here. The acid tends to dissolve the zinc electrode. Each zinc atom leaves two electrons behind on the electrode and enters the solution as a positive ion. The zinc electrode thus acquires a negative charge. The electrolyte becomes positively charged, and can pull electrons off the carbon electrode. Thus the carbon electrode becomes positively charged. Because there is an opposite charge on the two electrodes, there is a potential difference between the two terminals.

In a cell whose terminals are not connected, only a small amount of the zinc is dissolved, for as the zinc electrode becomes increasingly negative, any new positive zinc ions produced are attracted back to the electrode. Thus, a particular potential difference (or voltage) is maintained between the two terminals. If charge is allowed to flow between the terminals, say, through a wire (or a lightbulb), then more zinc can be dissolved. After a time, one or the other electrode is used up and the cell becomes "dead."

The voltage that exists between the terminals of a battery depends on what the electrodes are made of and their relative ability to be dissolved or give up electrons.

When two or more cells are connected so that the positive terminal of one is connected to the negative terminal of the next, they are said to be connected in *series* and their voltages add up. Thus, the voltage between the ends of two 1.5-V AA flashlight batteries connected in series is 3.0 V, whereas the six 2-V cells of an automobile storage battery give 12 V. Figure 18–4a shows a diagram of a common "dry cell" or "flashlight battery" used not only in flashlights but in many portable electronic devices, and Fig. 18–4b shows two smaller ones connected in series to a flashlight bulb. An incandescent lightbulb consists of a thin, coiled wire (filament) inside an evacuated glass bulb, as shown in Fig. 18–5 and in the Chapter-Opening Photos, page 501. When charge passes through the filament, it gets very hot (≈ 2800 K) and glows. Other bulb types, such as fluorescent, work differently.

FIGURE 18–4 (a) Diagram of an ordinary dry cell (like a D-cell or AA). The cylindrical zinc cup is covered on the sides; its flat bottom is the negative terminal. (b) Two dry cells (AA type) connected in series. Note that the positive terminal of one cell pushes against the negative terminal of the other.

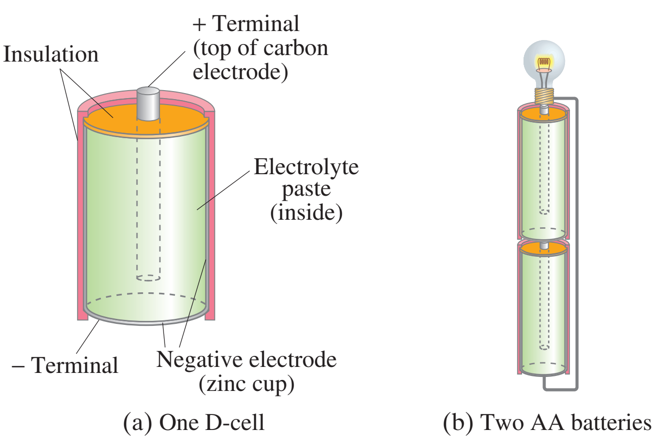
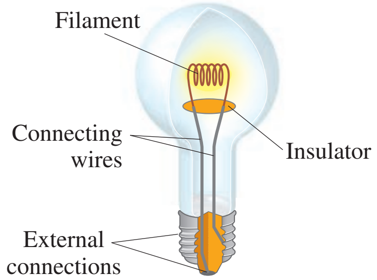


FIGURE 18–5 An ordinary incandescent lightbulb: the fine wire of the filament becomes so hot that it glows. Incandescent halogen bulbs enclose the filament in a small quartz tube filled with a halogen gas (bromine or iodine) which allows longer filament life and higher filament temperature for greater efficiency and whiteness.



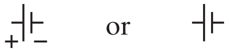
PHYSICS APPLIED
Electric cars

Electric Cars

Considerable research is being done to improve batteries for electric cars and for hybrids (which use both a gasoline internal combustion engine and an electric motor). One type of battery is lithium-ion, in which the anode contains lithium and the cathode is carbon. Electric cars need no gear changes and can develop full torque starting from rest, and so can accelerate quickly and smoothly. The distance an electric car can go between charges of the battery (its "range") is an important parameter because each recharging of an electric car battery may take hours, not minutes like a gas fill-up. Because charging an electric car can draw a large current over a period of several hours, electric power companies may need to upgrade their power grids so they won't fail when many electric cars are being charged at the same time in a small urban area.

18–2 Electric Current

The purpose of a battery is to produce a potential difference, which can then make charges move. When a continuous conducting path is connected between the terminals of a battery, we have an electric **circuit**, Fig. 18–6a. On any diagram of a circuit, as in Fig. 18–6b, we use the symbol


or [battery symbol]

to represent a battery. The device connected to the battery could be a lightbulb, a heater, a radio, or some other device. When such a circuit is formed, charge can move (or flow) through the wires of the circuit, from one terminal of the battery to the other, as long as the conducting path is continuous. Any flow of charge such as this is called an **electric current**.

More precisely, the electric current in a wire is defined as the net amount of charge that passes through the wire's full cross section at any point per unit time. Thus, the current I is defined as

$$I = \frac{\Delta Q}{\Delta t}, \tag{18–1}$$

where ΔQ is the amount of charge that passes through the conductor at any location during the time interval Δt.

Electric current is measured in coulombs per second; this is given a special name, the **ampere** (abbreviated amp or A), after the French physicist André Ampère (1775–1836). Thus, $1\text{ A} = 1\text{ C/s}$. Smaller units of current are often used, such as the milliampere $(1\text{ mA} = 10^{-3}\text{ A})$ and microampere $(1\ \mu\text{A} = 10^{-6}\text{ A})$.

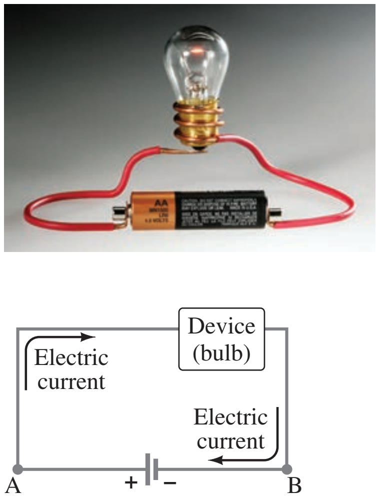


FIGURE 18–6 (a) A simple electric circuit. (b) Schematic drawing of the same circuit, consisting of a battery, connecting wires (thick gray lines), and a lightbulb or other device.

A current can flow in a circuit only if there is a *continuous* conducting path. We then have a **complete circuit**. If there is a break in the circuit, say, a cut wire, we call it an **open circuit** and no current flows. In any single circuit, with only a single path for current to follow such as in Fig. 18–6b, a steady current at any instant is the same at one point (say, point A) as at any other point (such as B). This follows from the conservation of electric charge: charge doesn't disappear. A battery does not create (or destroy) any net charge, nor does a lightbulb absorb or destroy charge.

CAUTION
A battery does not create charge; a lightbulb does not destroy charge

EXAMPLE 18–1 Current is flow of charge. A steady current of 2.5 A exists in a wire for 4.0 min. (*a*) How much total charge passes by a given point in the circuit during those 4.0 min? (*b*) How many electrons would this be?

APPROACH (*a*) Current is flow of charge per unit time, Eq. 18–1, so the amount of charge passing a point is the product of the current and the time interval. (*b*) To get the number of electrons, we divide the total charge by the charge on one electron.

SOLUTION (*a*) Since the current was 2.5 A, or 2.5 C/s, then in 4.0 min (= 240 s) the total charge that flowed past a given point in the wire was, from Eq. 18–1,

$$\Delta Q = I\,\Delta t = (2.5\text{ C/s})(240\text{ s}) = 600\text{ C}.$$

(*b*) The charge on one electron is 1.60×10^{-19} C, so 600 C would consist of

$$\frac{600\text{ C}}{1.6 \times 10^{-19}\text{ C/electron}} = 3.8 \times 10^{21}\text{ electrons}.$$

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.

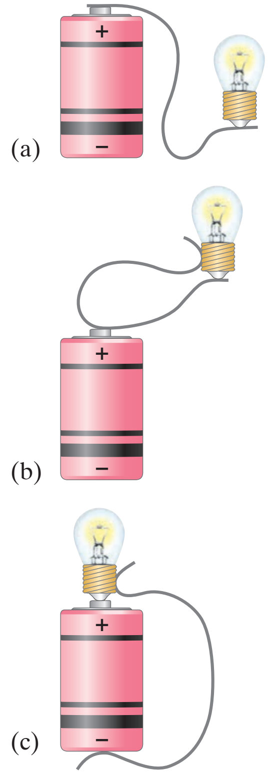
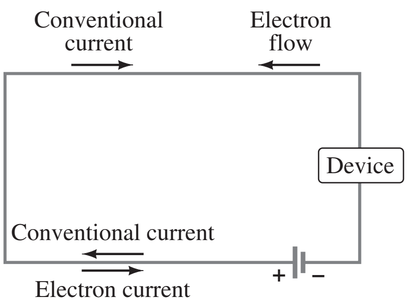


FIGURE 18–7 Example 18–2.

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.

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



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.

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.

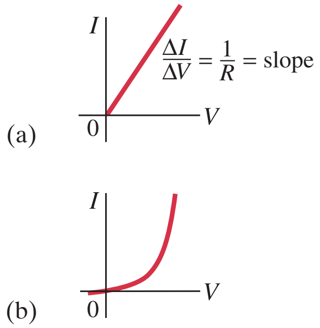
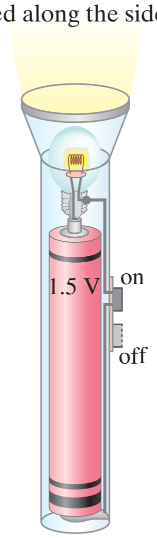


FIGURE 18–9 Graphs of current vs. voltage (a) for a metal conductor which obeys Ohm's law, and (b) for a nonohmic device, in this case a semiconductor diode.

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

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:

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

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

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

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.

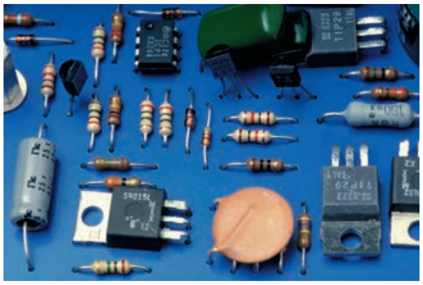


FIGURE 18–11 Photo of resistors (striped), plus other devices on a circuit board.

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

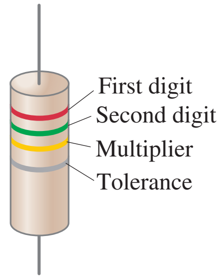
 [resistor symbol]

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.

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 $R = 1.0 \times 10^4\,\Omega$.]

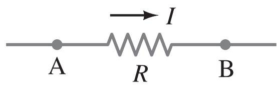


CONCEPTUAL EXAMPLE 18–4 **Current and potential.** Current I enters a resistor R as shown in Fig. 18–13. (a) Is the potential higher at point A or at point B? (b) Is the current greater at point A or at point B?

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 $(\Omega \cdot \mathrm{m})$	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)	$(3\text{–}60) \times 10^{-5}$	-0.0005
Germanium	$(1\text{–}500) \times 10^{-3}$	-0.05
Silicon	0.1–60	-0.07
Insulators		
Glass	$10^{9}\text{–}10^{12}$	
Hard rubber	$10^{13}\text{–}10^{15}$	

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

EXERCISE E A copper wire has a resistance of $10\ \Omega$. What would its resistance be if it had the same diameter but was only half as long? (*a*) $20\ \Omega$, (*b*) $10\ \Omega$, (*c*) $5\ \Omega$, (*d*) $1\ \Omega$, (*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 $0.10\ \Omega$ per wire? (*b*) If the current to each speaker is 4.0 A, what is the potential difference, or voltage drop, across each wire?

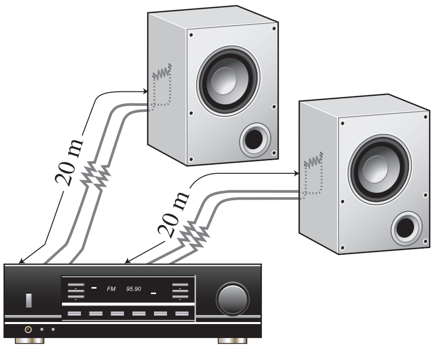


FIGURE 18–14 Example 18–5.

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:

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

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

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

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

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

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 $\left(2/\frac{1}{2} = 4\right)$.

EXERCISE F Copper wires in houses typically have a diameter of about 1.5 mm. How long a wire would have a $1.0\text{-}\Omega$ 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,

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

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

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

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.

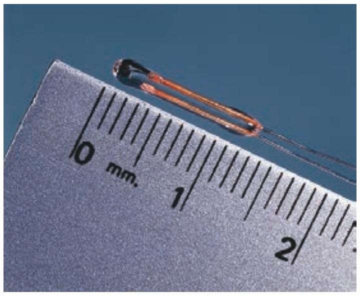


FIGURE 18–15 A thermistor only 13 mm long, shown next to a millimeter ruler.

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.

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

$$P = IV. \qquad \textbf{(18–5)}$$

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, $V = IR$:

$$P = IV = I(IR) = I^2R \qquad \textbf{(18–6a)}$$

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

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.

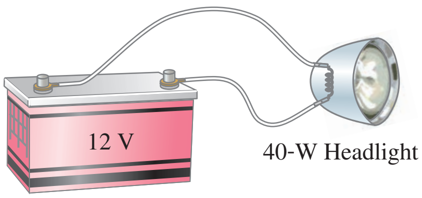


FIGURE 18–17 Example 18–8.

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

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

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 $\Delta \mathrm{PE}$ with the energy transferred, $\Delta \mathrm{PE} \approx 10^9$ 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 $\Delta \mathrm{PE} = Q\,\Delta V$. We solve for Q:

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

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

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

(*c*) The average power delivered is

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

We can also use Eq. 18–5:

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

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 $1\ \mathrm{kWh} = 3.6 \times 10^6$ 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.

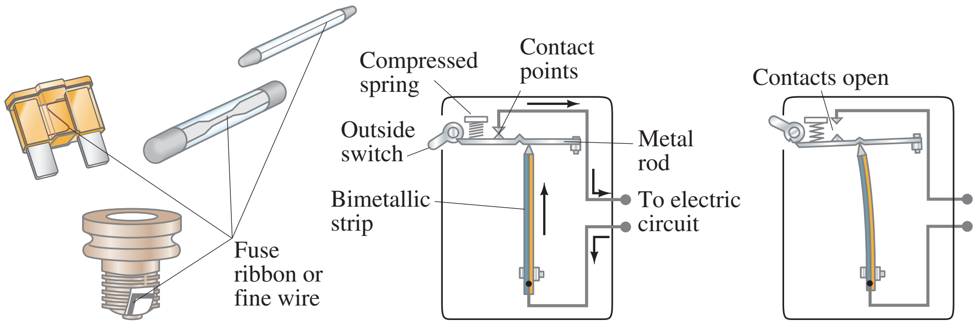
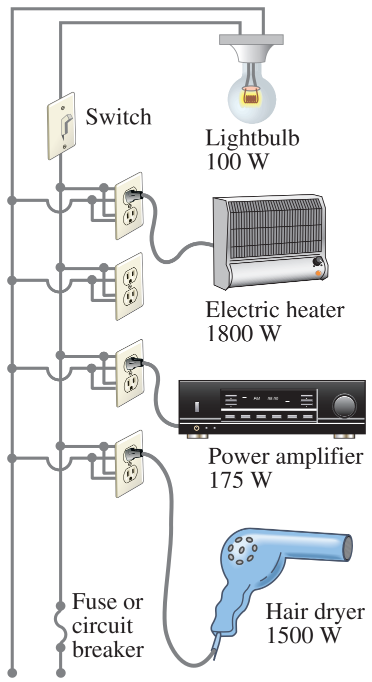


FIGURE 18–19 (a) Fuses. When current exceeds a certain value, the metallic ribbon or wire inside melts and the circuit opens. Then the fuse must be replaced. (b) One type of circuit breaker. Current passes through a bimetallic strip. When the current exceeds a safe level, the heating of the bimetallic 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 $I = P/V = 100\text{ W}/120\text{ V} = 0.8\text{ A}$; the heater draws $1800\text{ W}/120\text{ V} = 15.0\text{ A}$; the power amplifier draws a maximum of $175\text{ W}/120\text{ V} = 1.5\text{ A}$; and the hair dryer draws $1500\text{ W}/120\text{ V} = 12.5\text{ A}$. The total current drawn, if all devices are used at the same time, is

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

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.

18–7 Alternating Current

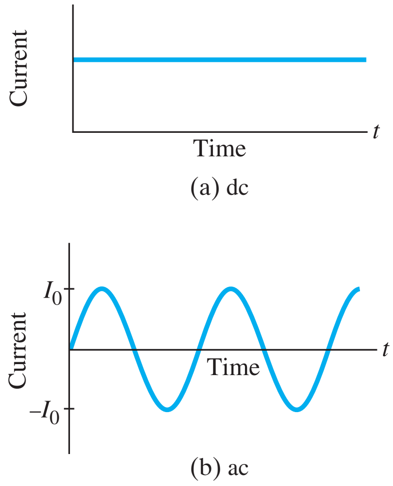


FIGURE 18–21 (a) Direct current, and (b) alternating current, as functions of time.

When a battery is connected to a circuit, the current moves steadily in one direction. This is called a **direct current**, or **dc**. Electric generators at electric power plants, however, produce **alternating current**, or **ac**. (Sometimes capital letters are used, DC and AC.) An alternating current reverses direction many times per second and is commonly sinusoidal, Fig. 18–21. The electrons in a wire first move in one direction and then in the other. The current supplied to homes and businesses by electric companies is ac throughout virtually the entire world. We will discuss and analyze ac circuits in detail in Chapter 21. But because ac circuits are so common in real life, we will discuss some of their basic aspects here.

The voltage produced by an ac electric generator is sinusoidal, as we shall see later. The current it produces is thus sinusoidal (Fig. 18–21b). We can write the voltage as a function of time as

$$V = V_0 \sin 2\pi f t = V_0 \sin \omega t. \qquad \textbf{(18–7a)}$$

The potential V oscillates between $+V_0$ and $-V_0$, and V_0 is referred to as the **peak voltage**. The frequency f is the number of complete oscillations made per second, and $\omega = 2\pi f$. In most areas of the United States and Canada, f is 60 Hz (the unit "hertz," as we saw in Chapters 8 and 11, means cycles per second). In many countries, 50 Hz is used.

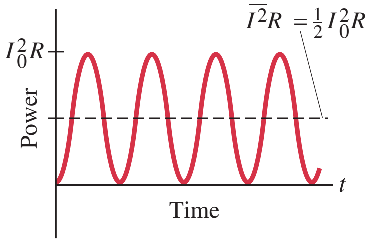
Equation 18–2, $V = IR$, works also for ac: if a voltage V exists across a resistance R, then the current I through the resistance is

$$I = \frac{V}{R} = \frac{V_0}{R} \sin \omega t = I_0 \sin \omega t. \qquad \textbf{(18–7b)}$$

The quantity $I_0 = V_0/R$ is the **peak current**. The current is considered positive when the electrons flow in one direction and negative when they flow in the opposite direction. It is clear from Fig. 18–21b that an alternating current is as often positive as it is negative. Thus, the average current is zero. This does not mean, however, that no power is needed or that no heat is produced in a resistor. Electrons do move back and forth, and do produce heat. Indeed, the power transformed in a resistance R at any instant is (Eq. 18–7b)

$$P = I^2 R = I_0^2 R \sin^2 \omega t.$$

FIGURE 18–22 Power transformed in a resistor in an ac circuit.



Because the current is squared, we see that the power is always positive, as graphed in Fig. 18–22. The quantity $\sin^2 \omega t$ varies between 0 and 1; and it is not too difficult to show† that its average value is $\frac{1}{2}$, as indicated in Fig. 18–22. Thus, the *average power* transformed, $\overline{P}$, is

$$\overline{P} = \tfrac{1}{2} I_0^2 R.$$

Since power can also be written $P = V^2/R = \left(V_0^2/R\right)\sin^2 \omega t$, we also have that the average power is

$$\overline{P} = \frac{1}{2}\frac{V_0^2}{R}.$$

The average or mean value of the *square* of the current or voltage is thus what is important for calculating average power: $\overline{I^2} = \frac{1}{2} I_0^2$ and $\overline{V^2} = \frac{1}{2} V_0^2$. The square root of each of these is the **rms** (root-mean-square) value of the current or voltage:

$$I_{\text{rms}} = \sqrt{\overline{I^2}} = \frac{I_0}{\sqrt{2}} = 0.707 I_0, \qquad \textbf{(18–8a)}$$

$$V_{\text{rms}} = \sqrt{\overline{V^2}} = \frac{V_0}{\sqrt{2}} = 0.707 V_0. \qquad \textbf{(18–8b)}$$

†A graph of $\cos^2 \omega t$ versus t is identical to that for $\sin^2 \omega t$ in Fig. 18–22, except that the points are shifted (by $\frac{1}{4}$ cycle) on the time axis. Thus the average value of $\sin^2$ and $\cos^2$, averaged over one or more full cycles, will be the same. From the trigonometric identity $\sin^2\theta + \cos^2\theta = 1$, we can write

$$\overline{(\sin^2 \omega t)} + \overline{(\cos^2 \omega t)} = 2\overline{(\sin^2 \omega t)} = 1.$$

Hence the average value of $\sin^2 \omega t$ is $\frac{1}{2}$.

The rms values of V and I are sometimes called the *effective values*. They are useful because they can be substituted directly into the power formulas, Eqs. 18–5 and 18–6, to get the average power:

$$\overline{P} = I_{\mathrm{rms}} V_{\mathrm{rms}} \tag{18–9a}$$

$$\overline{P} = \tfrac{1}{2} I_0^2 R = I_{\mathrm{rms}}^2 R \tag{18–9b}$$

$$\overline{P} = \tfrac{1}{2} \frac{V_0^2}{R} = \frac{V_{\mathrm{rms}}^2}{R}. \tag{18–9c}$$

Thus, a direct current whose values of I and V equal the rms values of I and V for an alternating current will produce the same power. Hence it is usually the rms value of current and voltage that is specified or measured. For example, in the United States and Canada, standard line voltage is 120-V ac. The 120 V is V_{rms}; the peak voltage V_0 is (Eq. 18–8b)

$$V_0 = \sqrt{2}\, V_{\mathrm{rms}} = 170\ \mathrm{V}.$$

In much of the world (Europe, Australia, Asia) the rms voltage is 240 V, so the peak voltage is 340 V. The line voltage can vary, depending on the total load; the frequency of 60 Hz or 50 Hz, however, remains extremely steady.

EXAMPLE 18–13 **Hair dryer.** (*a*) Calculate the resistance and the peak current in a 1500-W hair dryer (Fig. 18–23) connected to a 120-V ac line. (*b*) What happens if it is connected to a 240-V ac line in Britain?

APPROACH We are given $\overline{P}$ and V_{rms}, so $I_{\mathrm{rms}} = \overline{P}/V_{\mathrm{rms}}$ (Eq. 18–9a or 18–5), and $I_0 = \sqrt{2}\, I_{\mathrm{rms}}$. Then we find R from $V = IR$.

SOLUTION (*a*) We solve Eq. 18–9a for the rms current:

$$I_{\mathrm{rms}} = \frac{\overline{P}}{V_{\mathrm{rms}}} = \frac{1500\ \mathrm{W}}{120\ \mathrm{V}} = 12.5\ \mathrm{A}.$$

Then

$$I_0 = \sqrt{2}\, I_{\mathrm{rms}} = 17.7\ \mathrm{A}.$$

The resistance is

$$R = \frac{V_{\mathrm{rms}}}{I_{\mathrm{rms}}} = \frac{120\ \mathrm{V}}{12.5\ \mathrm{A}} = 9.6\ \Omega.$$

The resistance could equally well be calculated using peak values:

$$R = \frac{V_0}{I_0} = \frac{170\ \mathrm{V}}{17.7\ \mathrm{A}} = 9.6\ \Omega.$$

(*b*) When connected to a 240-V line, more current would flow and the resistance would change with the increased temperature (Section 18–4). But let us make an estimate of the power transformed based on the same 9.6-Ω resistance. The average power would be

$$\overline{P} = \frac{V_{\mathrm{rms}}^2}{R} = \frac{(240\ \mathrm{V})^2}{(9.6\ \Omega)} = 6000\ \mathrm{W}.$$

This is four times the dryer's power rating and would undoubtedly melt the heating element or the wire coils of the motor.

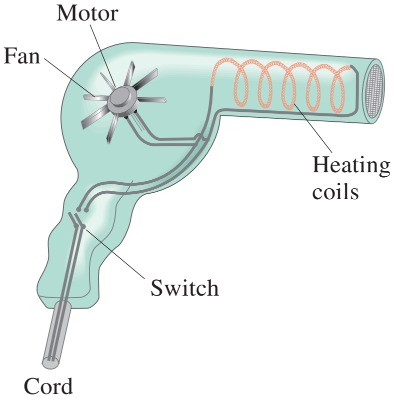


FIGURE 18–23 A hair dryer. Most of the current goes through the heating coils, a pure resistance; a small part goes to the motor to turn the fan. Example 18–13.

This Section has given a brief introduction to the simpler aspects of alternating currents. We will discuss ac circuits in more detail in Chapter 21. In Chapter 19 we will deal with the details of dc circuits only.

*18–8 Microscopic View of Electric Current

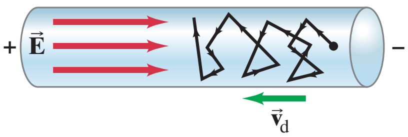
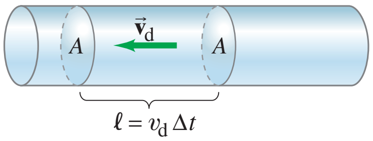


FIGURE 18–24 Electric field $\vec{\mathbf{E}}$ in a wire gives electrons in random motion a drift velocity $\vec{\mathbf{v}}_d$. Note $\vec{\mathbf{v}}_d$ is in the opposite direction of $\vec{\mathbf{E}}$ because electrons have a negative charge $(\vec{\mathbf{F}} = q\vec{\mathbf{E}})$.

FIGURE 18–25 Electrons in the volume $A\ell$ will all pass through the cross section indicated in a time Δt, where $\ell = v_d\,\Delta t$.



It can be useful to analyze a simple model of electric current at the microscopic level of atoms and electrons. In a conducting wire, for example, we can imagine the free electrons as moving about randomly at high speeds, bouncing off the atoms of the wire (somewhat like the molecules of a gas—Sections 13–8 to 13–10). When an electric field exists in the wire, Fig. 18–24, the electrons feel a force and initially begin to accelerate. But they soon reach a more or less steady average velocity known as their **drift velocity**, v_d (collisions with atoms in the wire keep them from accelerating further). The drift velocity is normally very much smaller than the electrons' average random speed.

We can relate v_d to the macroscopic current I in the wire. In a time Δt, the electrons will travel a distance $\ell = v_d\,\Delta t$ on average. Suppose the wire has cross-sectional area A. Then in time Δt, electrons in a volume $V = A\ell = Av_d\,\Delta t$ will pass through the cross section A of wire, as shown in Fig. 18–25. If there are n free electrons (each with magnitude of charge e) per unit volume, then the total number of electrons is $N = nV$ (V is volume, not voltage) and the total charge ΔQ that passes through the area A in a time Δt is

$$\begin{aligned}\Delta Q &= (\text{number of charges, } N) \times (\text{charge per particle}) \\ &= (nV)(e) = (nAv_d\,\Delta t)(e).\end{aligned}$$

The magnitude of the current I in the wire is thus

$$I = \frac{\Delta Q}{\Delta t} = neAv_d. \tag{18–10}$$

EXAMPLE 18–14 **Electron speed in wire.** A copper wire 3.2 mm in diameter carries a 5.0-A current. Determine the drift velocity of the free electrons. Assume that one electron per Cu atom is free to move (the others remain bound to the atom).

APPROACH We apply Eq. 18–10 to find the drift velocity v_d if we can determine the number n of free electrons per unit volume. Since we assume there is one free electron per atom, the density of free electrons, n, is the same as the number of Cu atoms per unit volume. The atomic mass of Cu is 63.5 u (see Periodic Table inside the back cover), so 63.5 g of Cu contains one mole or 6.02×10^{23} free electrons. To find the volume V of this amount of copper, and then $n = N/V$, we use the mass density of copper (Table 10–1), $\rho_D = 8.9 \times 10^3\,\text{kg/m}^3$, where $\rho_D = m/V$. (We use ρ_D to distinguish it here from ρ for resistivity.)

SOLUTION The number of free electrons per unit volume, $n = N/V$ (where $V = \text{volume} = m/\rho_D$), is

$$n = \frac{N}{V} = \frac{N}{m/\rho_D} = \frac{N(1\text{ mole})}{m(1\text{ mole})}\rho_D$$

$$n = \left(\frac{6.02 \times 10^{23}\text{ electrons}}{63.5 \times 10^{-3}\text{ kg}}\right)(8.9 \times 10^3\text{ kg/m}^3) = 8.4 \times 10^{28}\text{ m}^{-3}.$$

The cross-sectional area of the wire is $A = \pi r^2 = \pi(1.6 \times 10^{-3}\text{ m})^2 = 8.0 \times 10^{-6}\text{ m}^2$. Then, by Eq. 18–10, the drift velocity has magnitude

$$\begin{aligned}v_d &= \frac{I}{neA} = \frac{5.0\text{ A}}{(8.4 \times 10^{28}\text{ m}^{-3})(1.6 \times 10^{-19}\text{ C})(8.0 \times 10^{-6}\text{ m}^2)} \\ &= 4.6 \times 10^{-5}\text{ m/s} \approx 0.05\text{ mm/s}.\end{aligned}$$

NOTE The actual speed of electrons bouncing around inside the metal is estimated to be about 1.6×10^6 m/s at 20°C, very much greater than the drift velocity.

The drift velocity of electrons in a wire is slow, only about 0.05 mm/s in Example 18–14, which means it takes an electron about 20×10^3 s, or $5\frac{1}{2}$ h, to travel only 1 m. This is not how fast "electricity travels": when you flip a light switch, the light—even if many meters away—goes on nearly instantaneously. Why? Because electric fields travel essentially at the speed of light $(3 \times 10^8\text{ m/s})$. We can think of electrons in a wire as being like a pipe full of water: when a little water enters one end of the pipe, some water immediately comes out the other end.

*18–9 Superconductivity

At very low temperatures, well below 0°C, the resistivity (Section 18–4) of certain metals and certain compounds or alloys becomes zero as measured by the highest-precision techniques. Materials in such a state are said to be **superconducting**. This phenomenon was first observed by H. K. Onnes (1853–1926) in 1911 when he cooled mercury below 4.2 K (−269°C) and found that the resistance of mercury suddenly dropped to zero. In general, superconductors become superconducting only below a certain *transition temperature* or *critical temperature*, T_C, which is usually within a few degrees of absolute zero. Current in a ring-shaped superconducting material has been observed to flow for years in the absence of a potential difference, with no measurable decrease. Measurements show that the resistivity ρ of superconductors is less than $4 \times 10^{-25}\,\Omega\cdot\text{m}$, which is over 10^{16} times smaller than that for copper, and is considered to be zero in practice. See Fig. 18–26.

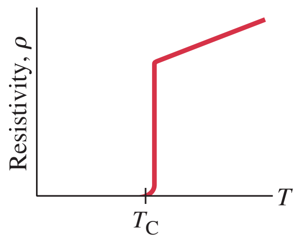


FIGURE 18–26 A superconducting material has zero resistivity when its temperature is below T_C, its "critical temperature." At temperatures above T_C, the resistivity jumps to a "normal" nonzero value and increases with temperature as most materials do (Eq. 18–4).

Before 1986 the highest temperature at which a material was found to superconduct was 23 K, which required liquid helium to keep the material cold. In 1987, a compound of yttrium, barium, copper, and oxygen (YBCO) was developed that can be superconducting at 90 K. Since this is above the boiling temperature of liquid nitrogen, 77 K, liquid nitrogen is sufficiently cold to keep the material superconducting. This was an important breakthrough because liquid nitrogen is much more easily and cheaply obtained than is the liquid helium needed for earlier superconductors. Superconductivity at temperatures as high as 160 K has been reported, though in fragile compounds.

To develop high-T_C superconductors for use as wires (such as for wires in "superconducting electromagnets"—Section 20–7), many applications today utilize a bismuth-strontium-calcium-copper oxide (BSCCO). A major challenge is how to make a useable, bendable wire out of the BSCCO, which is very brittle. (One solution is to embed tiny filaments of the high-T_C superconductor in a metal alloy, which is not resistanceless but has resistance much less than a conventional copper cable.)

*18–10 Electrical Conduction in the Human Nervous System

An interesting example of the flow of electric charge is in the human nervous system, which provides us with the means for being aware of the world, for communication within the body, and for controlling the body's muscles. Although the detailed functioning of the hugely complex nervous system still is not well understood, we do have a reasonable understanding of how messages are transmitted within the nervous system: they are electrical signals passing along the basic element of the nervous system, the **neuron**.

Neurons are living cells of unusual shape (Fig. 18–27). Attached to the main cell body are several small appendages known as *dendrites* and a long tail called the *axon*. Signals are received by the dendrites and are propagated along the axon. When a signal reaches the nerve endings, it is transmitted to the next neuron or to a muscle at a connection called a *synapse*.

FIGURE 18–27 A simplified sketch of a typical neuron.

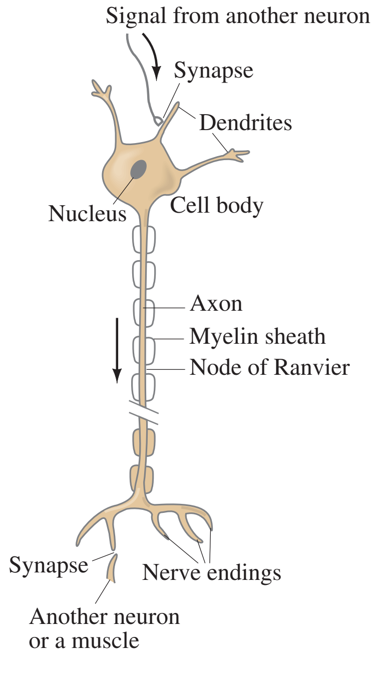


TABLE 18–2
Concentrations of Ions Inside and Outside a Typical Axon

	Concentration inside axon (mol/m^3)	Concentration outside axon (mol/m^3)
K^+	140	5
Na^+	15	140
Cl^-	9	125

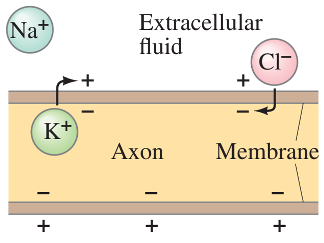


FIGURE 18–28 How a dipole layer of charge forms on a cell membrane.

FIGURE 18–29 Measuring the potential difference between the inside and outside of a nerve cell.

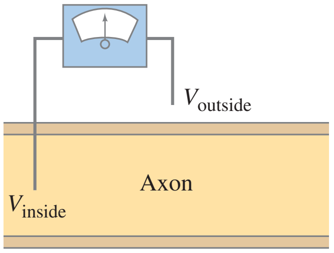
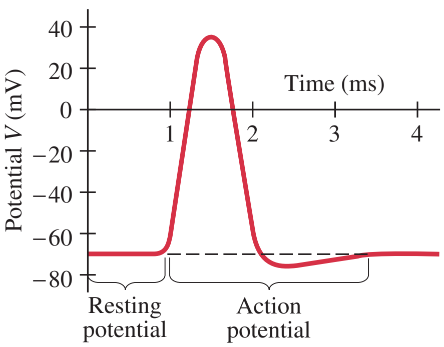


FIGURE 18–30 Action potential.



A neuron, before transmitting an electrical signal, is in the so-called "resting state." Like nearly all living cells, neurons have a net positive charge on the outer surface of the cell membrane and a negative charge on the inner surface. This difference in charge, or **dipole layer**, means that a potential difference exists across the cell membrane. When a neuron is not transmitting a signal, this **resting potential**, normally stated as

$$V_{\text{inside}} - V_{\text{outside}},$$

is typically $-60\,\text{mV}$ to $-90\,\text{mV}$, depending on the type of organism. The most common ions in a cell are K^+, Na^+, and Cl^-. There are large differences in the concentrations of these ions inside and outside an axon, as indicated by the typical values given in Table 18–2. Other ions are also present, so the fluids both inside and outside the axon are electrically neutral. Because of the differences in concentration, there is a tendency for ions to diffuse across the membrane (see Section 13–13 on diffusion). However, in the resting state the cell membrane prevents any net flow of Na^+ through a mechanism of active transport[‡] of Na^+ ions out of the cell by a particular protein to which Na^+ attach; energy needed comes from ATP. But it does allow the flow of Cl^- ions, and less so of K^+ ions, and it is these two ions that produce the dipole charge layer on the membrane. Because there is a greater concentration of K^+ inside the cell than outside, more K^+ ions tend to diffuse outward across the membrane than diffuse inward. A K^+ ion that passes through the membrane becomes attached to the outer surface of the membrane, and leaves behind an equal negative charge that lies on the inner surface of the membrane (Fig. 18–28). The fluids themselves remain neutral. What keeps the ions on the membrane is their attraction for each other across the membrane. Independently, Cl^- ions tend to diffuse *into* the cell since their concentration outside is higher. Both K^+ and Cl^- diffusion tends to charge the interior surface of the membrane negative and the outside positive. As charge accumulates on the membrane surface, it becomes increasingly difficult for more ions to diffuse: K^+ ions trying to move outward, for example, are repelled by the positive charge already there. Equilibrium is reached when the tendency to diffuse because of the concentration difference is just balanced by the electrical potential difference across the membrane. The greater the concentration difference, the greater the potential difference across the membrane ($-60\,\text{mV}$ to $-90\,\text{mV}$).

The most important aspect of a neuron is not that it has a resting potential (most cells do), but rather that it can respond to a stimulus and conduct an electrical signal along its length. The stimulus could be thermal (when you touch a hot stove) or chemical (as in taste buds); it could be pressure (as on the skin or at the eardrum), or light (as in the eye); or it could be the electric stimulus of a signal coming from the brain or another neuron. In the laboratory, the stimulus is usually electrical and is applied by a tiny probe at some point on the neuron. If the stimulus exceeds some threshold, a voltage pulse will travel down the axon. This voltage pulse can be detected at a point on the axon using a voltmeter or an oscilloscope connected as in Fig. 18–29. This voltage pulse has the shape shown in Fig. 18–30, and is called an **action potential**. As can be seen, the potential increases from a resting potential of about $-70\,\text{mV}$ and becomes a positive $30\,\text{mV}$ or $40\,\text{mV}$. The action potential lasts for about 1 ms and travels down an axon with a speed of $30\,\text{m/s}$ to $150\,\text{m/s}$. When an action potential is stimulated, the nerve is said to have "fired."

What causes the action potential? At the point where the stimulus occurs, the membrane suddenly alters its permeability, becoming much more permeable to Na^+ than to K^+ and Cl^- ions. Thus, Na^+ ions rush into the cell and the inner surface of the wall becomes positively charged, and the potential difference quickly swings positive ($\approx +30\,\text{mV}$ in Fig. 18–30). Just as suddenly, the membrane returns to its original characteristics; it becomes impermeable to Na^+ and in fact pumps out Na^+ ions. The diffusion of Cl^- and K^+ ions again predominates and the original resting potential is restored ($-70\,\text{mV}$ in Fig. 18–30).

‡This transport mechanism is sometimes referred to as the "sodium pump."

What causes the action potential to travel along the axon? The action potential occurs at the point of stimulation, as shown in Fig. 18–31a. The membrane momentarily is positive on the inside and negative on the outside at this point. Nearby charges are attracted toward this region, as shown in Fig. 18–31b. The potential in these adjacent regions then drops, causing an action potential there. Thus, as the membrane returns to normal at the original point, nearby it experiences an action potential, so the action potential moves down the axon (Figs. 18–31c and d).

You may wonder if the number of ions that pass through the membrane would significantly alter the concentrations. The answer is no; and we can show why (and again show the power and usefulness of physics) by treating the axon as a capacitor as we do in Search and Learn Problem 6 (the concentration changes by less than 1 part in 10^4).

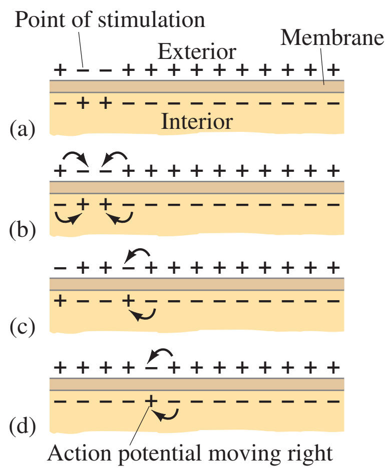


FIGURE 18–31 Propagation of action potential along axon membrane.

Summary

An electric **battery** serves as a source of nearly constant potential difference by transforming chemical energy into electric energy. A simple battery consists of two electrodes made of different metals immersed in a solution or paste known as an electrolyte.

Electric current, I, refers to the rate of flow of electric charge and is measured in **amperes** (A): 1 A equals a flow of 1 C/s past a given point.

The direction of **conventional current** is that of positive charge flow. In a wire, it is actually negatively charged electrons that move, so they flow in a direction opposite to the conventional current. A positive charge flow in one direction is almost always equivalent to a negative charge flow in the opposite direction. Positive conventional current always flows from a high potential to a low potential.

The **resistance** R of a device is defined by the relation

$$V = IR, \tag{18–2}$$

where I is the current in the device when a potential difference V is applied across it. For materials such as metals, R is a constant independent of V (thus $I \propto V$), a result known as **Ohm's law**. Thus, the current I coming from a battery of voltage V depends on the resistance R of the circuit connected to it.

Voltage is applied *across* a device or between the ends of a wire. Current passes *through* a wire or device. Resistance is a property *of* the wire or device.

The unit of resistance is the **ohm** (Ω), where $1\ \Omega = 1\ \text{V/A}$. See Table 18–3.

TABLE 18–3 Summary of Units

Current	$1\ \text{A} = 1\ \text{C/s}$
Potential difference	$1\ \text{V} = 1\ \text{J/C}$
Power	$1\ \text{W} = 1\ \text{J/s}$
Resistance	$1\ \Omega = 1\ \text{V/A}$

The resistance R of a wire is inversely proportional to its cross-sectional area A, and directly proportional to its length ℓ and to a property of the material called its resistivity:

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

The **resistivity**, ρ, increases with temperature for metals, but for semiconductors it may decrease.

The rate at which energy is transformed in a resistance R from electric to other forms of energy (such as heat and light) is equal to the product of current and voltage. That is, the **power** transformed, measured in watts, is given by

$$P = IV, \tag{18–5}$$

which for resistors can be written as

$$P = I^2R = \frac{V^2}{R}. \tag{18–6}$$

The SI unit of power is the **watt** $(1\ \text{W} = 1\ \text{J/s})$.

The total electric energy transformed in any device equals the product of the power and the time during which the device is operated. In SI units, energy is given in joules $(1\ \text{J} = 1\ \text{W}\cdot\text{s})$, but electric companies use a larger unit, the **kilowatt-hour** $(1\ \text{kWh} = 3.6 \times 10^6\ \text{J})$.

Electric current can be **direct current** (**dc**), in which the current is steady in one direction; or it can be **alternating current** (**ac**), in which the current reverses direction at a particular frequency f, typically 60 Hz. Alternating currents are typically sinusoidal in time,

$$I = I_0 \sin \omega t, \tag{18–7b}$$

where $\omega = 2\pi f$, and are produced by an alternating voltage.

The **rms** values of sinusoidally alternating currents and voltages are given by

$$I_{\text{rms}} = \frac{I_0}{\sqrt{2}} \quad \text{and} \quad V_{\text{rms}} = \frac{V_0}{\sqrt{2}}, \tag{18–8}$$

respectively, where I_0 and V_0 are the **peak** values. The power relationship, $P = IV = I^2R = V^2/R$, is valid for the average power in alternating currents when the rms values of V and I are used.

[*The current in a wire, at the microscopic level, is considered to be a slow **drift velocity** of electrons, $\vec{\mathbf{v}}_{\text{d}}$. The current I is given by

$$I = neAv_{\text{d}}, \tag{18–10}$$

where n is the number of free electrons per unit volume, e is the magnitude of the charge on an electron, and A is the cross-sectional area of the wire.]

[*At very low temperatures certain materials become **superconducting**, which means their electrical resistance becomes zero.]

[*The human nervous system operates via electrical conduction: when a nerve "fires," an electrical signal travels as a voltage pulse known as an **action potential**.]

Questions

1. When an electric cell is connected to a circuit, electrons flow away from the negative terminal in the circuit. But within the cell, electrons flow *to* the negative terminal. Explain.
2. When a flashlight is operated, what is being used up: battery current, battery voltage, battery energy, battery power, or battery resistance? Explain.
3. What quantity is measured by a battery rating given in ampere-hours $(\mathrm{A \cdot h})$? Explain.
4. Can a copper wire and an aluminum wire of the same length have the same resistance? Explain.
5. One terminal of a car battery is said to be connected to "ground." Since it is not really connected to the ground, what is meant by this expression?
6. The equation $P = V^2/R$ indicates that the power dissipated in a resistor decreases if the resistance is increased, whereas the equation $P = I^2R$ implies the opposite. Is there a contradiction here? Explain.
7. What happens when a lightbulb burns out?
8. If the resistance of a small immersion heater (to heat water for tea or soup, Fig. 18–32) was increased, would it speed up or slow down the heating process? Explain.

FIGURE 18–32 Question 8.

9. If a rectangular solid made of carbon has sides of lengths a, $2a$, and $3a$, to which faces would you connect the wires from a battery so as to obtain (*a*) the least resistance, (*b*) the greatest resistance?
10. Explain why lightbulbs almost always burn out just as they are turned on and not after they have been on for some time.
11. Which draws more current, a 100-W lightbulb or a 75-W bulb? Which has the higher resistance?
12. Electric power is transferred over large distances at very high voltages. Explain how the high voltage reduces power losses in the transmission lines.
13. A 15-A fuse blows out repeatedly. Why is it dangerous to replace this fuse with a 25-A fuse?
14. When electric lights are operated on low-frequency ac (say, 5 Hz), they flicker noticeably. Why?
15. Driven by ac power, the same electrons pass back and forth through your reading lamp over and over again. Explain why the light stays lit instead of going out after the first pass of electrons.
16. The heating element in a toaster is made of Nichrome wire. Immediately after the toaster is turned on, is the current magnitude (I_{rms}) in the wire increasing, decreasing, or staying constant? Explain.
17. Is current used up in a resistor? Explain.
18. Why is it more dangerous to turn on an electric appliance when you are standing outside in bare feet than when you are inside wearing shoes with thick soles?

*19. Compare the drift velocities and electric currents in two wires that are geometrically identical and the density of atoms is similar, but the number of free electrons per atom in the material of one wire is twice that in the other.

*20. A voltage V is connected across a wire of length ℓ and radius r. How is the electron drift speed affected if (*a*) ℓ is doubled, (*b*) r is doubled, (*c*) V is doubled, assuming in each case that other quantities stay the same?

MisConceptual Questions

1. When connected to a battery, a lightbulb glows brightly. If the battery is reversed and reconnected to the bulb, the bulb will glow
   (*a*) brighter.
   (*b*) dimmer.
   (*c*) with the same brightness.
   (*d*) not at all.
2. When a battery is connected to a lightbulb properly, current flows through the lightbulb and makes it glow. How much current flows through the battery compared with the lightbulb?
   (*a*) More.
   (*b*) Less.
   (*c*) The same amount.
   (*d*) No current flows through the battery.
3. Which of the following statements about Ohm's law is true?
   (*a*) Ohm's law relates the current through a wire to the voltage across the wire.
   (*b*) Ohm's law holds for all materials.
   (*c*) Any material that obeys Ohm's law does so independently of temperature.
   (*d*) Ohm's law is a fundamental law of physics.
   (*e*) Ohm's law is valid for superconductors.
4. Electrons carry energy from a battery to a lightbulb. What happens to the electrons when they reach the lightbulb?
   (*a*) The electrons are used up.
   (*b*) The electrons stay in the lightbulb.
   (*c*) The electrons are emitted as light.
   (*d*) Fewer electrons leave the bulb than enter it.
   (*e*) None of the above.
5. Where in the circuit of Fig. 18–33 is the current the largest, (*a*), (*b*), (*c*), or (*d*)? Or (*e*) it is the same at all points?

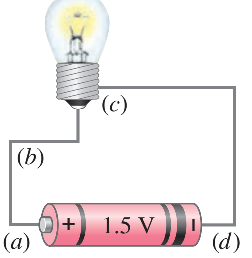


FIGURE 18–33 MisConceptual Question 5.

6. When you double the *voltage* across a certain material or device, you observe that the *current* increases by a factor of 3. What can you conclude?
   (*a*) Ohm's law is obeyed, because the current increases when V increases.
   (*b*) Ohm's law is not obeyed in this case.
   (*c*) This situation has nothing to do with Ohm's law.

7. When current flows through a resistor,
   (*a*) some of the charge is used up by the resistor.
   (*b*) some of the current is used up by the resistor.
   (*c*) Both (*a*) and (*b*) are true.
   (*d*) Neither (*a*) nor (*b*) is true.

8. The unit kilowatt-hour is a measure of
   (*a*) the rate at which energy is transformed.
   (*b*) power.
   (*c*) an amount of energy.
   (*d*) the amount of power used per second.

9. Why might a circuit breaker open if you plug too many electrical devices into a single circuit?
   (*a*) The voltage becomes too high.
   (*b*) The current becomes too high.
   (*c*) The resistance becomes too high.
   (*d*) A circuit breaker will not "trip" no matter how many electrical devices you plug into the circuit.

10. Nothing happens when birds land on a power line, yet we are warned not to touch a power line with a ladder. What is the difference?
    (*a*) Birds have extremely high internal resistance compared to humans.
    (*b*) There is little to no voltage drop between a bird's two feet, but there is a significant voltage drop between the top of a ladder touching a power line and the bottom of the ladder on the ground.
    (*c*) Dangerous current comes from the ground only.
    (*d*) Most birds don't understand the situation.

11. When a light switch is turned on, the light comes on immediately because
    (*a*) the electrons coming from the power source move through the initially empty wires very fast.
    (*b*) the electrons already in the wire are instantly "pushed" by a voltage difference.
    (*c*) the lightbulb may be old with low resistance. It would take longer if the bulb were new and had high resistance.
    (*d*) the electricity bill is paid. The electric company can make it take longer when the bill is unpaid.

For assigned homework and other learning materials, go to the MasteringPhysics website.

Problems

18–2 and 18–3 Electric Current, Resistance, Ohm's Law

(*Note*: The charge on one electron is 1.60×10^{-19} C.)

1. (I) A current of 1.60 A flows in a wire. How many electrons are flowing past any point in the wire per second?
2. (I) A service station charges a battery using a current of 6.7 A for 5.0 h. How much charge passes through the battery?
3. (I) What is the current in amperes if 1200 Na^+ ions flow across a cell membrane in 3.1 μs? The charge on the sodium is the same as on an electron, but positive.
4. (I) What is the resistance of a toaster if 120 V produces a current of 4.6 A?
5. (I) What voltage will produce 0.25 A of current through a 4800-Ω resistor?
6. (I) How many coulombs are there in a 75 ampere-hour car battery?
7. (II) (*a*) What is the current in the element of an electric clothes dryer with a resistance of 8.6 Ω when it is connected to 240 V? (*b*) How much charge passes through the element in 50 min? (Assume direct current.)
8. (II) A bird stands on a dc electric transmission line carrying 4100 A (Fig. 18–34). The line has 2.5×10^{-5} Ω resistance per meter, and the bird's feet are 4.0 cm apart. What is the potential difference between the bird's feet?

FIGURE 18–34 Problem 8.

9. (II) A hair dryer draws 13.5 A when plugged into a 120-V line. (*a*) What is its resistance? (*b*) How much charge passes through it in 15 min? (Assume direct current.)
10. (II) A 4.5-V battery is connected to a bulb whose resistance is 1.3 Ω. How many electrons leave the battery per minute?
11. (II) An electric device draws 5.60 A at 240 V. (*a*) If the voltage drops by 15%, what will be the current, assuming nothing else changes? (*b*) If the resistance of the device were reduced by 15%, what current would be drawn at 240 V?

18–4 Resistivity

12. (I) What is the diameter of a 1.00-m length of tungsten wire whose resistance is 0.32 Ω?
13. (I) What is the resistance of a 5.4-m length of copper wire 1.5 mm in diameter?
14. (II) Calculate the ratio of the resistance of 10.0 m of aluminum wire 2.2 mm in diameter, to 24.0 m of copper wire 1.8 mm in diameter.
15. (II) Can a 2.2-mm-diameter copper wire have the same resistance as a tungsten wire of the same length? Give numerical details.
16. (II) A certain copper wire has a resistance of 15.0 Ω. At what point along its length must the wire be cut so that the resistance of one piece is 4.0 times the resistance of the other? What is the resistance of each piece?
17. (II) Compute the voltage drop along a 21-m length of household no. 14 copper wire (used in 15-A circuits). The wire has diameter 1.628 mm and carries a 12-A current.
18. (II) Two aluminum wires have the same resistance. If one has twice the length of the other, what is the ratio of the diameter of the longer wire to the diameter of the shorter wire?

19. (II) A rectangular solid made of carbon has sides of lengths 1.0 cm, 2.0 cm, and 4.0 cm, lying along the x, y, and z axes, respectively (Fig. 18–35). Determine the resistance for current that passes through the solid in (a) the x direction, (b) the y direction, and (c) the z direction. Assume the resistivity is $\rho = 3.0 \times 10^{-5}\ \Omega \cdot \mathrm{m}$.

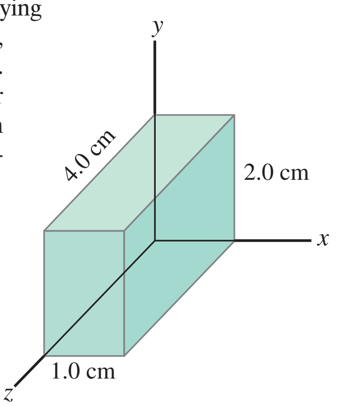


FIGURE 18–35 Problem 19.

20. (II) A length of wire is cut in half and the two lengths are wrapped together side by side to make a thicker wire. How does the resistance of this new combination compare to the resistance of the original wire?

21. (II) How much would you have to raise the temperature of a copper wire (originally at 20°C) to increase its resistance by 12%?

22. (II) Determine at what temperature aluminum will have the same resistivity as tungsten does at 20°C.

23. (II) A 100-W lightbulb has a resistance of about 12 Ω when cold (20°C) and 140 Ω when on (hot). Estimate the temperature of the filament when hot assuming an average temperature coefficient of resistivity $\alpha = 0.0045\ (\mathrm{C}^\circ)^{-1}$.

24. (III) A length of aluminum wire is connected to a precision 10.00-V power supply, and a current of 0.4212 A is precisely measured at 23.5°C. The wire is placed in a new environment of unknown temperature where the measured current is 0.3818 A. What is the unknown temperature?

25. (III) For some applications, it is important that the value of a resistance not change with temperature. For example, suppose you made a 3.20-kΩ resistor from a carbon resistor and a Nichrome wire-wound resistor connected together so the total resistance is the sum of their separate resistances. What value should each of these resistors have (at 0°C) so that the combination is temperature independent?

18–5 and 18–6 Electric Power

26. (I) What is the maximum power consumption of a 3.0-V portable CD player that draws a maximum of 240 mA of current?

27. (I) The heating element of an electric oven is designed to produce 3.3 kW of heat when connected to a 240-V source. What must be the resistance of the element?

28. (I) What is the maximum voltage that can be applied across a 3.9-kΩ resistor rated at $\frac{1}{4}$ watt?

29. (I) (a) Determine the resistance of, and current through, a 75-W lightbulb connected to its proper source voltage of 110 V. (b) Repeat for a 250-W bulb.

30. (I) An electric car has a battery that can hold 16 kWh of energy (approximately 6×10^7 J). If the battery is designed to operate at 340 V, how many coulombs of charge would need to leave the battery at 340 V and return at 0 V to equal the stored energy of the battery?

31. (I) An electric car uses a 45-kW (160-hp) motor. If the battery pack is designed for 340 V, what current would the motor need to draw from the battery? Neglect any energy losses in getting energy from the battery to the motor.

32. (II) A 120-V hair dryer has two settings: 950 W and 1450 W. (a) At which setting do you guess the resistance to be higher? After making a guess, determine the resistance at (b) the lower setting, and (c) the higher setting.

33. (II) A 12-V battery causes a current of 0.60 A through a resistor. (a) What is its resistance, and (b) how many joules of energy does the battery lose in a minute?

34. (II) A 120-V fish-tank heater is rated at 130 W. Calculate (a) the current through the heater when it is operating, and (b) its resistance.

35. (II) How many kWh of energy does a 550-W toaster use in the morning if it is in operation for a total of 5.0 min? At a cost of 9.0 cents/kWh, estimate how much this would add to your monthly electric energy bill if you made toast four mornings per week.

36. (II) At \$0.095/kWh, what does it cost to leave a 25-W porch light on day and night for a year?

37. (II) What is the total amount of energy stored in a 12-V, 65 A·h car battery when it is fully charged?

38. (II) An ordinary flashlight uses two D-cell 1.5-V batteries connected in series to provide 3.0 V across the bulb, as in Fig. 18–4b (Fig. 18–36). The bulb draws 380 mA when turned on. (a) Calculate the resistance of the bulb and the power dissipated. (b) By what factor would the power increase if four D-cells in series (total 6.0 V) were used with the same bulb? (Neglect heating effects of the filament.) Why shouldn't you try this?

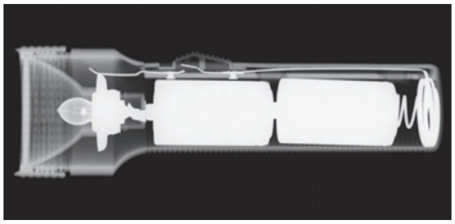


FIGURE 18–36 Problem 38 (X-ray of a flashlight).

39. (II) How many 75-W lightbulbs, connected to 120 V as in Fig. 18–20, can be used without blowing a 15-A fuse?

40. (II) An extension cord made of two wires of diameter 0.129 cm (no. 16 copper wire) and of length 2.7 m (9 ft) is connected to an electric heater which draws 18.0 A on a 120-V line. How much power is dissipated in the cord?

41. (II) You want to design a portable electric blanket that runs on a 1.5-V battery. If you use a 0.50-mm-diameter copper wire as the heating element, how long should the wire be if you want to generate 18 W of heating power? What happens if you accidentally connect the blanket to a 9.0-V battery?

42. (II) A power station delivers 750 kW of power at 12,000 V to a factory through wires with total resistance 3.0 Ω. How much less power is wasted if the electricity is delivered at 50,000 V rather than 12,000 V?

43. (III) A small immersion heater can be used in a car to heat a cup of water for coffee or tea. If the heater can heat 120 mL of water from 25°C to 95°C in 8.0 min, (*a*) approximately how much current does it draw from the car's 12-V battery, and (*b*) what is its resistance? Assume the manufacturer's claim of 85% efficiency.

18–7 Alternating Current

44. (I) Calculate the peak current in a 2.7-kΩ resistor connected to a 220-V rms ac source.

45. (I) An ac voltage, whose peak value is 180 V, is across a 310-Ω resistor. What are the rms and peak currents in the resistor?

46. (II) Estimate the resistance of the 120-V_{rms} circuits in your house as seen by the power company, when (*a*) everything electrical is unplugged, and (*b*) two 75-W lightbulbs are on.

47. (II) The peak value of an alternating current in a 1500-W device is 6.4 A. What is the rms voltage across it?

48. (II) An 1800-W arc welder is connected to a 660-V_{rms} ac line. Calculate (*a*) the peak voltage and (*b*) the peak current.

49. (II) Each channel of a stereo receiver is capable of an average power output of 100 W into an 8-Ω loudspeaker (see Fig. 18–14). What are the rms voltage and the rms current fed to the speaker (*a*) at the maximum power of 100 W, and (*b*) at 1.0 W when the volume is turned down?

50. (II) Determine (*a*) the maximum instantaneous power dissipated by a 2.2-hp pump connected to a 240-V_{rms} ac power source, and (*b*) the maximum current passing through the pump.

*18–8 Microscopic View of Electric Current

*51. (II) A 0.65-mm-diameter copper wire carries a tiny dc current of 2.7 μA. Estimate the electron drift velocity.

*52. (II) A 4.80-m length of 2.0-mm-diameter wire carries a 750-mA dc current when 22.0 mV is applied to its ends. If the drift velocity is 1.7×10^{-5} m/s, determine (*a*) the resistance R of the wire, (*b*) the resistivity ρ, and (*c*) the number n of free electrons per unit volume.

*53. (III) At a point high in the Earth's atmosphere, He^{2+} ions in a concentration of $2.4 \times 10^{12}/m^3$ are moving due north at a speed of 2.0×10^6 m/s. Also, a $7.0 \times 10^{11}/m^3$ concentration of O_2^- ions is moving due south at a speed of 6.2×10^6 m/s. Determine the magnitude and direction of the net current passing through unit area (A/m^2).

*18–10 Nerve Conduction

*54. (I) What is the magnitude of the electric field across an axon membrane 1.0×10^{-8} m thick if the resting potential is −70 mV?

*55. (II) A neuron is stimulated with an electric pulse. The action potential is detected at a point 3.70 cm down the axon 0.0052 s later. When the action potential is detected 7.20 cm from the point of stimulation, the time required is 0.0063 s. What is the speed of the electric pulse along the axon? (Why are two measurements needed instead of only one?)

*56. (III) During an action potential, Na^+ ions move into the cell at a rate of about 3×10^{-7} mol/m²·s. How much power must be produced by the "active Na^+ pumping" system to produce this flow against a +30-mV potential difference? Assume that the axon is 10 cm long and 20 μm in diameter.

General Problems

57. A person accidentally leaves a car with the lights on. If each of the two headlights uses 40 W and each of the two taillights 6 W, for a total of 92 W, how long will a fresh 12-V battery last if it is rated at 75 A·h? Assume the full 12 V appears across each bulb.

58. What is the average current drawn by a 1.0-hp 120-V motor? (1 hp = 746 W.)

59. The **conductance** G of an object is defined as the reciprocal of the resistance R; that is, $G = 1/R$. The unit of conductance is a *mho* $(= \text{ohm}^{-1})$, which is also called the *siemens* (S). What is the conductance (in siemens) of an object that draws 440 mA of current at 3.0 V?

60. The heating element of a 110-V, 1500-W heater is 3.8 m long. If it is made of iron, what must its diameter be?

61. (*a*) A particular household uses a 2.2-kW heater 2.0 h/day ("on" time), four 100-W lightbulbs 6.0 h/day, a 3.0-kW electric stove element for a total of 1.0 h/day, and miscellaneous power amounting to 2.0 kWh/day. If electricity costs $0.115 per kWh, what will be their monthly bill (30 d)? (*b*) How much coal (which produces 7500 kcal/kg) must be burned by a 35%-efficient power plant to provide the yearly needs of this household?

62. A small city requires about 15 MW of power. Suppose that instead of using high-voltage lines to supply the power, the power is delivered at 120 V. Assuming a two-wire line of 0.50-cm-diameter copper wire, estimate the cost of the energy lost to heat per hour per meter. Assume the cost of electricity is about 12 cents per kWh.

63. A 1600-W hair dryer is designed for 117 V. (*a*) What will be the percentage change in power output if the voltage drops to 105 V? Assume no change in resistance. (*b*) How would the actual change in resistivity with temperature affect your answer?

64. The wiring in a house must be thick enough so it does not become so hot as to start a fire. What diameter must a copper wire be if it is to carry a maximum current of 35 A and produce no more than 1.5 W of heat per meter of length?

65. Determine the resistance of the tungsten filament in a 75-W 120-V incandescent lightbulb (*a*) at its operating temperature of about 2800 K, (*b*) at room temperature.

66. Suppose a current is given by the equation $I = 1.40 \sin 210t$, where I is in amperes and t in seconds. (*a*) What is the frequency? (*b*) What is the rms value of the current? (*c*) If this is the current through a 24.0-Ω resistor, write the equation that describes the voltage as a function of time.

67. A microwave oven running at 65% efficiency delivers 950 W to the interior. Find (*a*) the power drawn from the source, and (*b*) the current drawn. Assume a source voltage of 120 V.

68. A 1.00-Ω wire is stretched uniformly to 1.50 times its original length. What is its resistance now?

69. 220 V is applied to two different conductors made of the same material. One conductor is twice as long and twice the diameter of the second. What is the ratio of the power transformed in the first relative to the second?

70. An electric power plant can produce electricity at a fixed power P, but the plant operator is free to choose the voltage V at which it is produced. This electricity is carried as an electric current I through a transmission line (resistance R) from the plant to the user, where it provides the user with electric power P'. (*a*) Show that the reduction in power $\Delta P = P - P'$ due to transmission losses is given by $\Delta P = P^2R/V^2$. (*b*) In order to reduce power losses during transmission, should the operator choose V to be as large or as small as possible?

71. A proposed electric vehicle makes use of storage batteries as its source of energy. It is powered by 24 batteries, each 12 V, 95 A·h. Assume that the car is driven on level roads at an average speed of 45 km/h, and the average friction force is 440 N. Assume 100% efficiency and neglect energy used for acceleration. No energy is consumed when the vehicle is stopped, since the engine doesn't need to idle. (*a*) Determine the horsepower required. (*b*) After approximately how many kilometers must the batteries be recharged?

72. A fish-tank heater is rated at 95 W when connected to 120 V. The heating element is a coil of Nichrome wire. When uncoiled, the wire has a total length of 3.5 m. What is the diameter of the wire?

73. A 100-W, 120-V lightbulb has a resistance of 12 Ω when cold (20°C) and 140 Ω when on (hot). Calculate its power consumption (*a*) at the instant it is turned on, and (*b*) after a few moments when it is hot.

74. In an automobile, the system voltage varies from about 12 V when the car is off to about 13.8 V when the car is on and the charging system is in operation, a difference of 15%. By what percentage does the power delivered to the headlights vary as the voltage changes from 12 V to 13.8 V? Assume the headlight resistance remains constant.

75. A tungsten filament used in a flashlight bulb operates at 0.20 A and 3.0 V. If its resistance at 20°C is 1.5 Ω, what is the temperature of the filament when the flashlight is on?

76. An air conditioner draws 18 A at 220-V ac. The connecting cord is copper wire with a diameter of 1.628 mm. (*a*) How much power does the air conditioner draw? (*b*) If the length of the cord (containing two wires) is 3.5 m, how much power is dissipated in the wiring? (*c*) If no. 12 wire, with a diameter of 2.053 mm, was used instead, how much power would be dissipated in the wiring? (*d*) Assuming that the air conditioner is run 12 h per day, how much money per month (30 days) would be saved by using no. 12 wire? Assume that the cost of electricity is 12 cents per kWh.

77. An electric wheelchair is designed to run on a single 12-V battery rated to provide 100 ampere-hours (100 A·h). (*a*) How much energy is stored in this battery? (*b*) If the wheelchair experiences an average total retarding force (mainly friction) of 210 N, how far can the wheelchair travel on one charge?

78. If a wire of resistance R is stretched uniformly so that its length doubles, by what factor does the power dissipated in the wire change, assuming it remains hooked up to the same voltage source? Assume the wire's volume and density remain constant.

79. Copper wire of diameter 0.259 cm is used to connect a set of appliances at 120 V, which draw 1450 W of power total. (*a*) What power is wasted in 25.0 m of this wire? (*b*) What is your answer if wire of diameter 0.412 cm is used?

80. Battery-powered electricity is very expensive compared with that available from a wall outlet. Estimate the cost per kWh of (*a*) an alkaline D-cell (cost $1.70) and (*b*) an alkaline AA-cell (cost $1.25). These batteries can provide a continuous current of 25 mA for 820 h and 120 h, respectively, at 1.5 V. (*c*) Compare to the cost of a normal 120-V ac house source at $0.10/kWh.

81. A copper pipe has an inside diameter of 3.00 cm and an outside diameter of 5.00 cm (Fig. 18–37). What is the resistance of a 10.0-m length of this pipe?

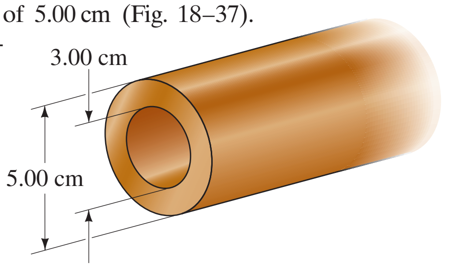


FIGURE 18–37 Problem 81.

***82.** The Tevatron accelerator at Fermilab (Illinois) is designed to carry an 11-mA beam of protons ($q = 1.6 \times 10^{-19}$ C) traveling at very nearly the speed of light (3.0×10^8 m/s) around a ring 6300 m in circumference. How many protons are in the beam?

Search and Learn

1. Why is Ohm's law less of a law than Newton's laws?

2. A traditional incandescent lamp filament may have been lit to a temperature of 2700 K. A contemporary halogen incandescent lamp filament may be at around 2900 K. (*a*) Estimate the percent improvement of the halogen bulb over the traditional one. [*Hint*: See Section 14–8.] (*b*) To produce the same amount of light as a traditional 100-W bulb, estimate what wattage a halogen bulb should use.

3. You find a small cylindrical resistor that measures 9.00 mm in length and 2.15 mm in diameter, and it has a color code of red, yellow, brown, and gold. What is the resistor made of primarily?

4. Small changes in the length of an object can be measured using a **strain gauge** sensor, which is a wire that when undeformed has length ℓ_0, cross-sectional area A_0, and resistance R_0. This sensor is rigidly affixed to the object's surface, aligning its length in the direction in which length changes are to be measured. As the object deforms, the length of the wire sensor changes by $\Delta\ell$, and the resulting change ΔR in the sensor's resistance is measured. Assuming that as the solid wire is deformed to a length ℓ, its density and volume remain constant (only approximately valid), show that the strain $(= \Delta\ell/\ell_0)$ of the wire sensor, and thus of the object to which it is attached, is approximately $\Delta R/2R_0$. [See Sections 18–4 and 9–5.]

5. Household wiring has sometimes used aluminium instead of copper. (*a*) Using Table 18–1, find the ratio of the resistance of a copper wire to that of an aluminum wire of the same length and diameter. (*b*) Typical copper wire used for home wiring in the U.S. has a diameter of 1.63 mm. What is the resistance of 125 m of this wire? (*c*) What would be the resistance of the same wire if it were made of aluminum? (*d*) How much power would be dissipated in each wire if it carried 18 A of current? (*e*) What should be the diameter of the aluminum wire for it to have the same resistance as the copper wire? (*f*) In Section 18–4, a statement is made about the resistance of copper and aluminum wires of the same weight. Using Table 10–1 for the densities of copper and aluminum, find the resistance of an aluminum wire of the same mass and length as the copper wire in part (*b*). Is the statement true?

*6. **Capacitance of an axon.** (*a*) Do an order-of-magnitude estimate for the capacitance of an axon 10 cm long of radius 10 μm. The thickness of the membrane is about 10^{-8} m, and the dielectric constant is about 3. (*b*) By what factor does the concentration (number of ions per volume) of Na^+ ions in the cell change as a result of one action potential?

ANSWERS TO EXERCISES

A: 1.6×10^{-13} A.
B: 3600 C.
C: 240 Ω.
D: (*b*), (*c*).
E: (*c*).
F: 110 m.
G: (*d*).
H: 370,000 kg, or about 5000 people.
I: (*e*) 40.