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.

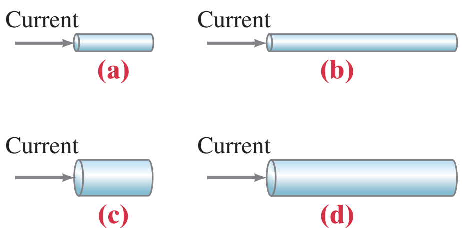
Electric current and electric power in electric circuits are of basic importance in everyday life. We examine both dc and ac in this Chapter, and include the microscopic analysis of electric current.

CHAPTER 18

# Electric Currents

**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.

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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.

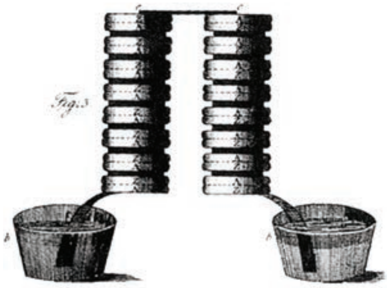
Until the year 1800, the technical development of electricity consisted mainly of producing a static charge by friction. It all changed in 1800 when Alessandro Volta (1745–1827; Fig. 18–1) invented the electric battery, and with it produced the first steady flow of electric charge—that is, a steady electric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

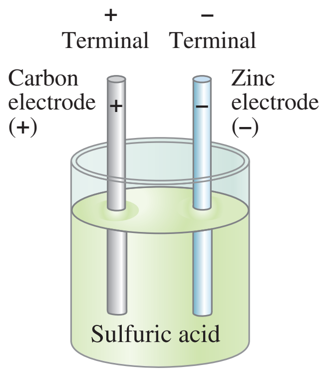



**FIGURE 18–3** Simple electric cell.

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 ($\approx 2800$ 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.

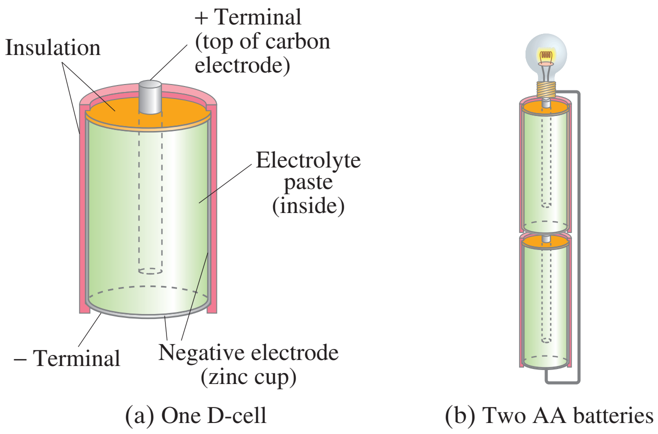
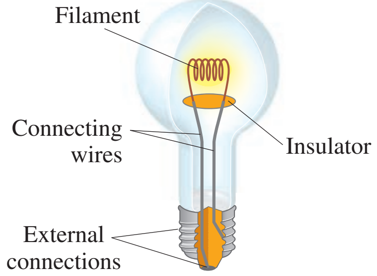



**FIGURE 18–5** An ordinary incandescent lightbulb: the fine wire of the filament becomes so hot that it glows. Incandescent halogen bulbs enclose the filament in a small quartz tube filled with a halogen gas (bromine or iodine) which allows longer filament life and higher filament temperature for greater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



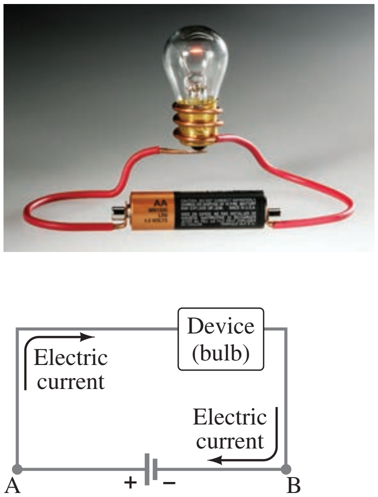
## Electric Cars

**PHYSICS APPLIED**
*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

(a)




(b)

**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.

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 $\Delta Q$ is the amount of charge that passes through the conductor at any location during the time interval $\Delta t$.

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 $(1\,\mu\text{A} = 10^{-6}\text{ A})$.

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

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.

**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 $1.60 \times 10^{-19}$ 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.

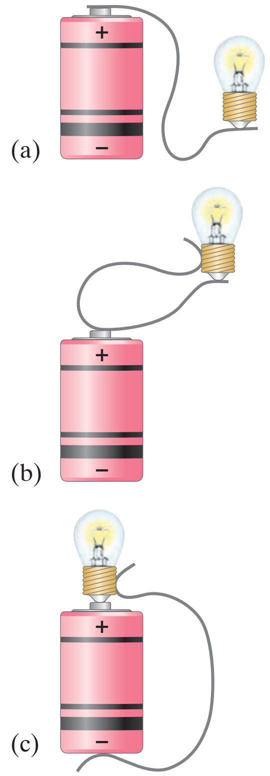


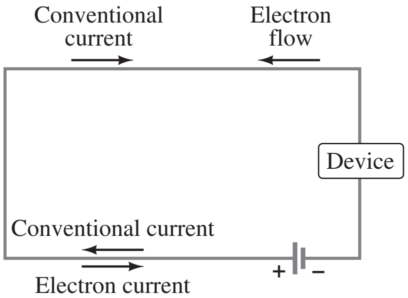

**FIGURE 18–7** Example 18–2.

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.

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

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




**CAUTION**
*Distinguish conventional current from electron flow*

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

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

# 18–3 Ohm's Law: Resistance and Resistors

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

$$I \propto V.$$

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