Electric Current

Although an electric current is a stream of moving charges, not all moving charges constitute an electric current. If there is to be an electric current through a given surface, there must be a net flow of charge through that surface. Two examples clarify our meaning.

1. The free electrons (conduction electrons) in an isolated length of copper wire are in random motion at speeds of the order of 106 m/s. If you pass a hypothetical plane through such a wire, conduction electrons pass through it *in both directions* at the rate of many billions per second—but there is *no net transport* of charge and thus *no current* through the wire. However, if you connect the ends of the wire to a battery, you slightly bias the flow in one direction, with the result that there now is a net transport of charge and thus an electric current through the wire.

2. The flow of water through a garden hose represents the directed flow of positive charge (the protons in the water molecules) at a rate of perhaps several million coulombs per second. There is no net transport of charge, however, because there is a parallel flow of negative charge (the electrons in the water molecules) of exactly the same amount moving in exactly the same direction.

As Fig. 26-1*a* reminds us, any isolated conducting loop—regardless of whether it has an excess charge—is all at the same potential. No electric field can exist within it or along its surface. Although conduction electrons are available, no net electric force acts on them and thus there is no current.

If, as in Fig. 26-1*b*, we insert a battery in the loop, the conducting loop is no longer at a single potential. Electric fields act inside the material making up the loop, exerting forces on the conduction electrons, causing them to move and thus establishing a current. After a very short time, the electron flow reaches a constant value and the current is in its *steady state* (it does not vary with time).

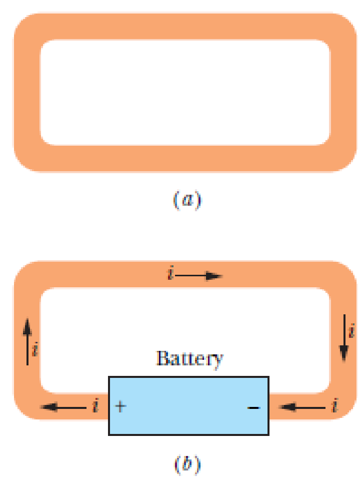


Fig. 26-1

Figure 26-2 shows a section of a conductor, part of a conducting loop in which current has been established. If charge *dq* passes through a hypothetical plane (such as *aa*’) in time *dt*, then the current *i* through that plane is defined as:

$$i = \frac{dq}{dt} \qquad \text{(definition of current).} \qquad (26\text{-}1)$$

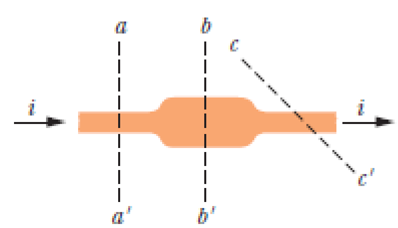


Fig. 26-2

We can find the charge that passes through the plane in a time interval extending from 0 to *t* by integration:

$$q = \int dq = \int_0^t i\, dt, \qquad (26\text{-}2)$$

Under steady-state conditions, the current is the same for planes *aa*', *bb*', and *cc*' and indeed for all planes that pass completely through the conductor, no matter what their location or orientation.This follows from the fact that charge is conserved. Under the steady-state conditions assumed here, an electron must pass through plane *aa*' for every electron that passes through plane *cc*'.

The SI unit for current is the coulomb per second, or the ampere (A), which is an SI base unit:

1 ampere = 1 A = 1 coulomb per second = 1 C/s.

The Directions of Currents

In Fig. 26-1*b* we drew the current arrows in the direction in which positively charged particles would be forced to move through the loop by the electric field. Such positive *charge carriers,* as they are often called, would move away from the positive battery terminal and toward the negative terminal. Actually, the charge carriers in the copper loop of Fig. 26-1*b* are electrons and thus are negatively charged. The electric field forces them to move in the direction opposite the current arrows, from the negative terminal to the positive terminal. For historical reasons, however, we use the following convention:

> A current arrow is drawn in the direction in which positive charge carriers would move, even if the actual charge carriers are negative and move in the opposite direction.

Current Density

Current is the rate at which charge passes a point. Sometimes we are interested in the current *i* in a particular conductor. At other times we take a localized view and study the flow of charge through a cross section of the conductor at a particular point. To describe this flow, we can use the **current density** $\vec{J}$ which has the same direction as the velocity of the moving charges if they are positive and the opposite direction if they are negative. For each element of the cross section, the magnitude *J* is equal to the current per unit area through that element.We can write the amount of current through the element as $\vec{J}.d\vec{A}$ where is $d\vec{A}$ the area vector of the element, perpendicular to the element.The total current through the surface is then

$$i = \int \vec{J} \cdot d\vec{A}. \qquad (26\text{-}4)$$

$$i = JA, \qquad \text{so } J = \frac{i}{A} \qquad (26\text{-}5)$$

where A is the total area of the surface. From Eq. 26-4 or 26-5 we see that the SI unit for current density is the ampere per square meter (A/m^2).

Resistance and Resistivity

If we apply the same potential difference between the ends of geometrically similar rods of copper and of glass, very different currents result.The characteristic of the conductor that enters here is its electrical **resistance.**We determine the resistance between any two points of a conductor by applying a potential difference V between those points and measuring the current i that results.The resistance R is then

$$R = \frac{V}{i} \quad \text{(definition of } R\text{).} \qquad (26\text{-}8)$$

The SI unit for resistance that follows from Eq. 26-8 is the volt per ampere.This combination occurs so often that we give it a special name, the **ohm** (symbol Ω); that is,

1 ohm = 1 Ω = 1 volt per ampere = 1 V/A.

A conductor whose function in a circuit is to provide a specified resistance is called a **resistor.** In a circuit diagram, we represent a resistor and a resistance with the symbol . If we write Eq. 26-8 as $i = \frac{V}{R}$, we see that, for a given V, the greater the resistance, the smaller the current.

Resistivity

In a water pipe, the length and cross-sectional area of the pipe determine the resistance that the pipe offers to the flow of water. Longer pipes with smaller cross-sectional areas offer greater resistance. Analogous effects are found in the electrical case. For a wide range of materials, the resistance of a piece of material of length L and cross-sectional area A is

$$R = \rho \frac{L}{A} \qquad (20.3)$$

where ρ is a proportionality constant known as the ***resistivity*** of the material. It can be seen from Equation 20.3 that the unit for resistivity is the **ohm . meter (Ω.m),**

Ohm's Law

The current that a battery can push through a wire is analogous to the water flow that a pump can push through a pipe. Greater pump pressures lead to larger water flow rates, and, similarly, greater battery voltages lead to larger electric currents. In the simplest case, the current I is directly proportional to the voltage V; that is, $I \propto V$. Thus, a voltage of 12 V leads to twice as much current as a voltage of 6 V, when each is connected to the same circuit.

The ***resistance*** R is defined as the ratio of the voltage V applied across a piece of material to the current I through the material, or $R = V/I$. When only a small current results from a large voltage, there is a high resistance to the moving charge. For many materials (e.g., metals), the ratio V/I is the same for a given piece of material over a wide range of voltages and currents. In such a case, the resistance is a constant. Then, the relation $R = V/I$ is referred to as ***Ohm's law,*** after the German physicist Georg Simon Ohm (1789–1854), who discovered it.

Example 1: A Flashlight

The filament in a light bulb is a resistor in the form of a thin piece of wire. The wire becomes hot enough to emit light because of the current in it. Figure 20.5 shows a flashlight that uses two 1.5-V batteries (effectively a single 3.0-V battery) to provide a current of 0.40 A in the filament. Determine the resistance of the glowing filament.

Reasoning The filament resistance is assumed to be the only resistance in the circuit. The potential difference applied across the filament is that of the 3.0-V battery. The resistance, given by Equation 20.2, is equal to this potential difference divided by the current.

Solution The resistance of the filament is

$$R = \frac{V}{I} = \frac{3.0\ \text{V}}{0.40\ \text{A}} = \boxed{7.5\ \Omega}$$

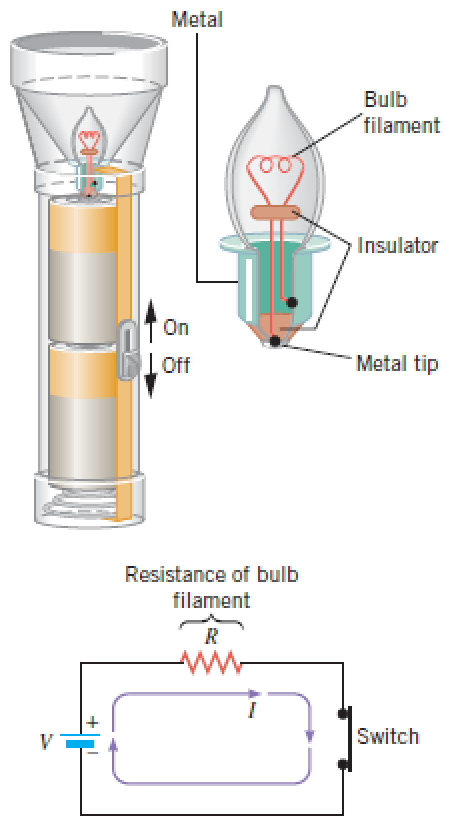


Figure 20.5 The circuit in this flashlight consists of a resistor (the filament of the light bulb) connected to a 3.0-V battery (two 1.5-V batteries).

Example 2: The Physics of Electrical Extension Cords

The instructions for an electric lawn mower suggest that a 20-gauge extension cord can be used for distances up to 35 m, but a thicker 16-gauge cord should be used for longer distances, to keep the resistance of the wire as small as possible. The cross-sectional area of 20-gauge wire is 5.2×10^{-7} m^2, while that of 16-gauge wire is 13×10^{-7} m^2. The resistivity of copper is 1.72×10^{-8} Ω.m. Determine the resistance of **(a)** 35 m of 20-gauge copper wire and **(b)** 75 m of 16-gauge copper wire.

Solution The resistance of the wires can be found using Equation 20.3:

20-gauge wire
$$R = \frac{\rho L}{A} = \frac{(1.72 \times 10^{-8}\ \Omega\cdot\text{m})(35\ \text{m})}{5.2 \times 10^{-7}\ \text{m}^2} = \boxed{1.2\ \Omega}$$

16-gauge wire
$$R = \frac{\rho L}{A} = \frac{(1.72 \times 10^{-8}\ \Omega\cdot\text{m})(75\ \text{m})}{13 \times 10^{-7}\ \text{m}^2} = \boxed{0.99\ \Omega}$$

Electromotive Force

In an electric circuit there must be a device somewhere in the loop that acts like the water pump in a water fountain. In this device a charge travels "uphill," from lower to higher potential energy, even though the electrostatic force is trying to push it from higher to lower potential energy. The direction of current in such a device is from lower to higher potential, just the opposite of what happens in an ordinary conductor. The influence that makes current flow from lower to higher potential is called **electromotive force** (abbreviated **emf**). This is a poor term because emf is *not* a force but an energy-per-unit-charge quantity, like potential. The SI unit of emf is the same as that for potential, the volt (1 V = 1 J/C). A typical flashlight battery has an emf of this means that the battery does of work on every coulomb of charge that passes through it. We'll use the symbol ε (a script capital E) for emf.

Within a battery, a chemical reaction occurs that transfers electrons from one terminal (leaving it positively charged) to another terminal (leaving it negatively charged). Figure 20.2 shows the two terminals of a car battery and a flashlight battery. The drawing also illustrates the symbol  used to represent a battery in circuit drawings.

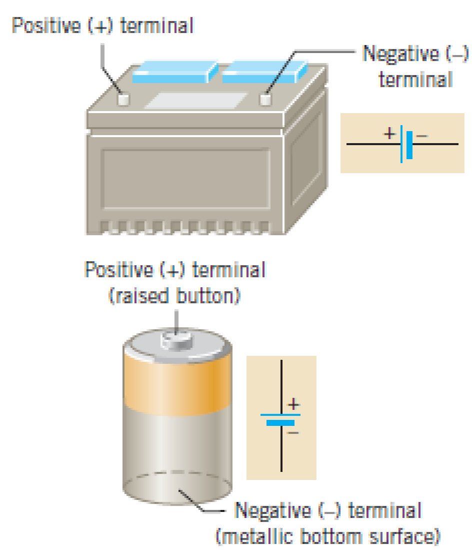


Figure 20.2 Typical batteries and the symbol (+|–) used to represent them in electric circuits.

Because of the positive and negative charges on the battery terminals, an electric potential difference exists between them.

Internal Resistance

Real sources of emf in a circuit don't behave in exactly the way we have described; the potential difference across a real source in a circuit is *not* equal to the emf as in Eq. (25.14). The reason is that charge moving through the material of any real source encounters *resistance*. We call this the **internal resistance** of the source, denoted by *r*. If this resistance behaves according to Ohm's law, *r* is constant and independent of the current *I*. As the current moves through *r*, it experiences an associated drop in potential equal to *Ir*. Thus, when a current is flowing through a source from the negative terminal *b* to the positive terminal *a*, the potential difference between the terminals is:

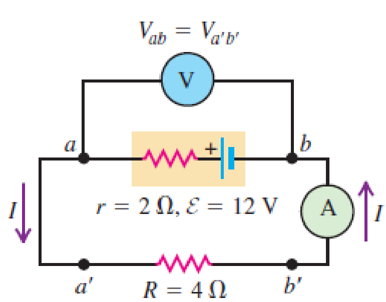
$$V_{ab} = \mathcal{E} - Ir \quad \text{(terminal voltage, source with internal resistance)} \qquad (25.15)$$

Example 25.5 A source in a complete circuit

We add a 4-Ω resistor to the battery in Conceptual Example 25.4, forming a complete circuit (Fig. 25.17). What are the voltmeter and ammeter readings V_{ab} and I now?

SOLUTION

IDENTIFY and SET UP: Our target variables are the current I through the circuit $aa'b'b$ and the potential difference V_{ab}. We first find I using Eq. (25.16). To find V_{ab}, we can use either Eq. (25.11) or Eq. (25.15).



25.17 A source of emf in a complete circuit.

EXECUTE: The ideal ammeter has zero resistance, so the total resistance external to the source is $R = 4\ \Omega$. From Eq. (25.16), the current through the circuit $aa'b'b$ is then

$$I = \frac{\mathcal{E}}{R + r} = \frac{12\text{ V}}{4\ \Omega + 2\ \Omega} = 2\text{ A}$$

Our idealized conducting wires and the idealized ammeter have zero resistance, so there is no potential difference between points a and a' or between points b and b'; that is, $V_{ab} = V_{a'b'}$. We find V_{ab} by considering a and b as the terminals of the resistor: From Ohm's law, Eq. (25.11), we then have

$$V_{a'b'} = IR = (2\text{ A})(4\ \Omega) = 8\text{ V}$$

Alternatively, we can consider a and b as the terminals of the source. Then, from Eq. (25.15),

$$V_{ab} = \mathcal{E} - Ir = 12\text{ V} - (2\text{ A})(2\ \Omega) = 8\text{ V}$$

Either way, we see that the voltmeter reading is 8 V.

EVALUATE: With current flowing through the source, the terminal voltage V_{ab} is less than the emf $\mathcal{E}$. The smaller the internal resistance r, the less the difference between V_{ab} and $\mathcal{E}$.