*18–8 Microscopic View of Electric Current

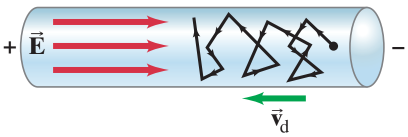
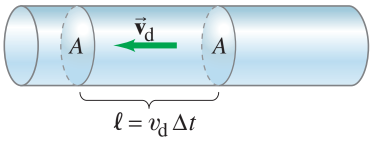


FIGURE 18–24 Electric field $\vec{\mathbf{E}}$ in a wire gives electrons in random motion a drift velocity $\vec{\mathbf{v}}_d$. Note $\vec{\mathbf{v}}_d$ is in the opposite direction of $\vec{\mathbf{E}}$ because electrons have a negative charge $(\vec{\mathbf{F}} = q\vec{\mathbf{E}})$.

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

$$I = \frac{\Delta Q}{\Delta t} = neAv_d. \qquad \textbf{(18–10)}$$

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

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

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

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 $1.6 \times 10^6\,\text{m/s}$ 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.