THE NATURE OF ELECTRIC CURRENT

An electric current can be broadly defined as charged particles in motion - a flow of charge. The most obvious effect of a current would seem to be the transfer of charge from one place to another. So it is, when a charged body is discharged by touching it with an earthed wire, or when lightning strikes a tree. However, it is important to realise that most currents flow in closed loops or circuits with no net transfer of charge. When there is a steady current the distribution of charge around a circuit remains constant and every part of the circuit remains substantially neutral.

The effects of electric current

You can't see anything move in an electric current but currents do have a number of extremely important effects, which can be broadly classified as shown in the first column of table. This list is by no means exhaustive.

Effect	Applications	Measuring devices
Heating	Electric room heater	Measure i^2
Magnetic	Electromagnet	Clip-on ammeter
Electrolysis	Aluminium smelting	Measure $\int I dt$
Electrochemical	Kolbe's synthesis of ethane	-
Biological	Cardiac defibrillation	-
Mechanical (through magnetism)	Moving coil meter Electric motor Loudspeakers	Deflection of a coil
Emission of light	Lamp filament Fluorescent light Light emitting diode.	-
Voltage drop (potential difference)	Digital ammeter	Measure voltage across a known resistor

ELECTRIC CURRENT AND CHARGE CARRIERS

Movement of charge

Any movement of charge constitutes an electric current. The charge carriers could be electrons in a vacuum, electrons in a metal, 'holes' in a semiconductor or ions in a solution. The charge may move in free space, through a conductor or on a conveyor belt. An obvious manifestation of charge movement is an electric spark. At each spark some charge is transferred. Together a sequence of sparks makes up an intermittent current in which each spark contributes a current pulse. If the spark gap is narrowed so that the sparks become more frequent, they tend to merge to make a continuous current.

Definition and unit of current

The value of a current in a wire at any point is defined to be equal to the rate of flow of net positive charge past that point. The direction of the current is defined to be the direction of flow of positive charge.

Mathematically

$$\boldsymbol{i = \frac{dq}{dt}} \qquad \textbf{(1)}$$

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

$$q = \int dq = \int_0^t i\,dt,$$

If the charge carriers are actually negative then the direction of the current is
opposite to the flow direction of the particles. Thus a current of one ampere to the right in figure could be either positive charge flowing to the right at 1 coulomb per second
or negative charge flowing to the left at 1 coulomb per second, or some combination of
flows in both directions such 0.5 C.s-1 each way.

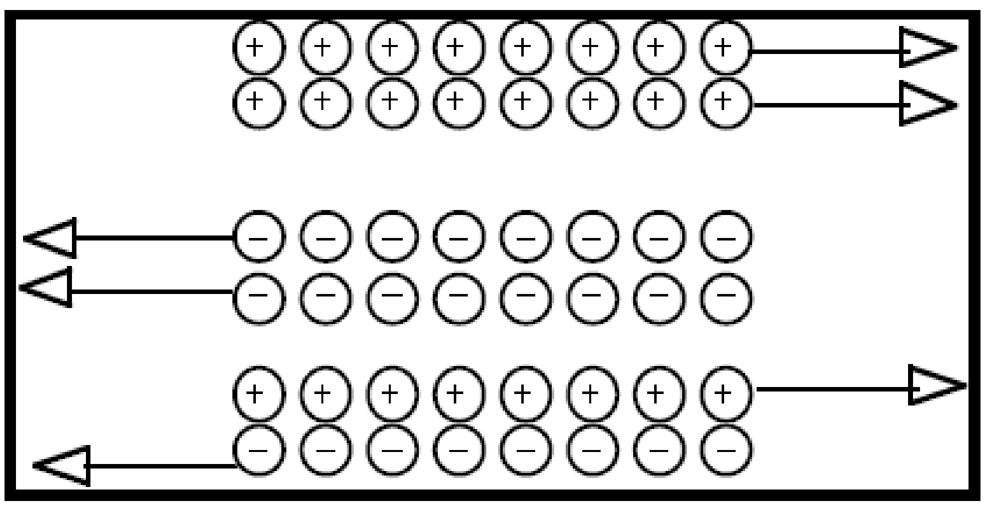


Figure 3.1 Equivalent currents

The SI unit of electric current is the ampere (symbol A), equal to one coulomb per second. Because current is easier to measure than charge, the physical standards have been established using current as the base quantity, so the coulomb is defined as an ampere-second (A.s). The ampere is defined in terms of magnetic effects.

Kinds of current

The simplest kind of current is that carried by a beam of electrons through a vacuum. For example,in a typical TV tube (figure 3.2), the flow rate of electrons from the electron gun to the screen is about 6 ¥ 1013 electrons per second. Since each electron has a charge of -1.6 ¥ 10-19 C, the beam current is about 10 µA from the screen to the electron gun.

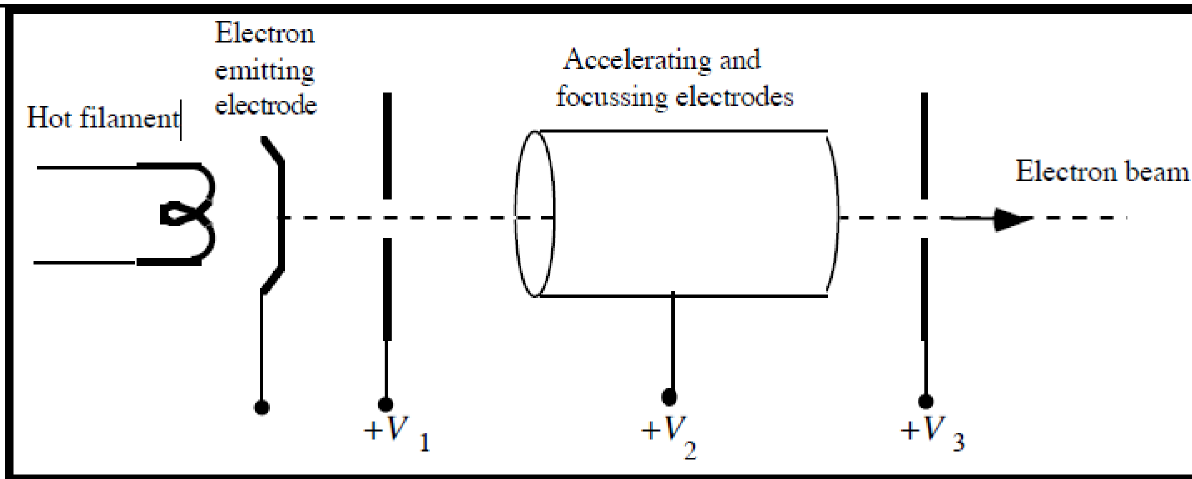


Figure 3.2 An electron gun

This one is electrostatically focussed. Many devices, including electron microscopes, use magnetic focussing

Similarly, in wires the positive charges on the ions of the crystal lattice remain fixed, while the current is carried by the drift of the negatively charged electrons. Where confusion might arise you must distinguish between the direction of electron movement and the direction of the conventional current.

Why didn't we avoid this confusion about current direction by calling the electron's charge positive? The answer goes back to Benjamin Franklin who thought he could see which way charge was flowing in sparks. His choice established the definitions of positive and negative in electricity. In conducting materials only a small fraction of all the electrons is free to move and carry current. The majority are too strongly bound to the respective nuclei. In p-type silicon (and other semiconductors) the number of **mobile electrons** is just less than the number of positive ions in the crystalline lattice of the material. The result is that when there is a current the mobile electrons play a sort of musical chairs, hopping from one vacant point in the lattice to the next. The overall effect can be described as a net flow of positive **holes**. Transistors and other semiconductor devices depend for their operation on simultaneous conduction by electrons and holes.

Current, as defined by Eq. 1, is a scalar because both charge and time in that equation are scalars.Yet, as in Fig. 26-1*b*, we often represent a current with an arrow to indicate that charge is moving. Such arrows are not vectors, however, and they do not require vector addition. Figure 26-3*a* shows a conductor with current *i*0 splitting at a junction into two branches. Because charge is conserved, the magnitudes of the currents in the branches must add to yield the magnitude of the current in the original conductor, so that

$$i_0 = i_1 + i_2$$

As Fig. 26-3*b* suggests, bending or reorienting the wires in space does not change the validity of Eq. 26-3. Current arrows show only a direction (or sense) of flow along a conductor, not a direction in space.

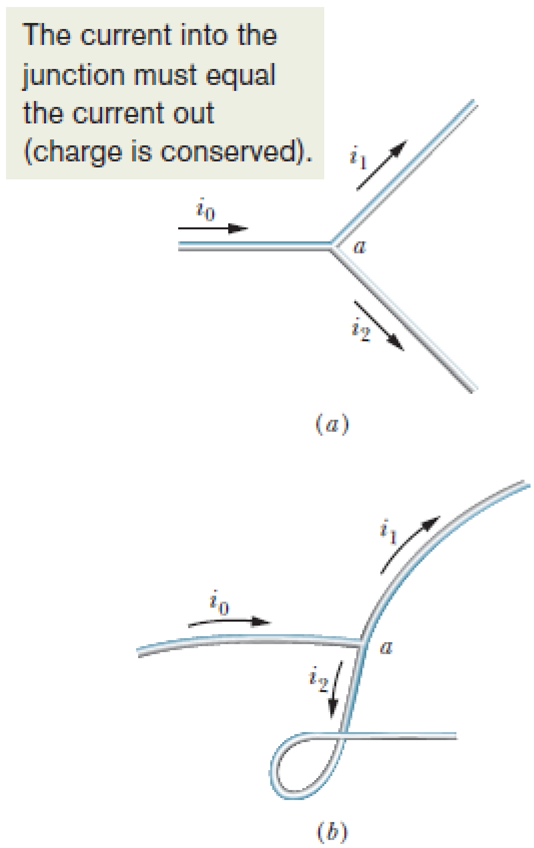


Figure 26-3 The relation $i_0 = i_1 + i_2$ is true at junction a no matter what the orientation in space of the three wires. Currents are scalars, not vectors.

Current Density

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 $\vec{J} \cdot d\vec{A}$, where $d\vec{A}$ is the area vector of the element, perpendicular to the element. The total current through the surface is then

$$i = \int \vec{J} \cdot d\vec{A}. \tag{26-4}$$

If the current is uniform across the surface and parallel to $d\vec{A}$, then $\vec{J}$ is also uniform and parallel to $d\vec{A}$. Then Eq. 26-4 becomes

$$i = \int J\, dA = J \int dA = JA,$$

so

$$J = \frac{i}{A}, \tag{26-5}$$

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/m2). In Chapter 22 we saw that we can represent an electric field with electric field lines. Figure 26-4 shows how current density can be represented with a similar set of lines, which we can call *streamlines*. The current, which is toward the right in Fig. 26-4, makes a transition from the wider conductor at the left to the narrower conductor at the right. Because charge is conserved during the transition, the amount of charge and thus the amount of current cannot change. However, the current density does change—it is greater in the narrower conductor. The spacing of the streamlines suggests this increase in current density; streamlines that are closer together imply greater current density.

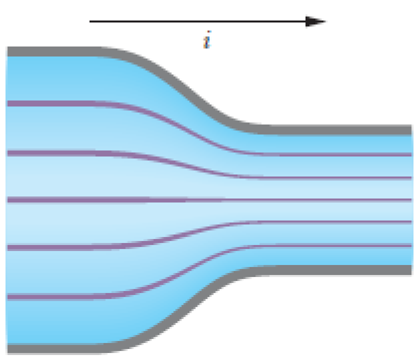
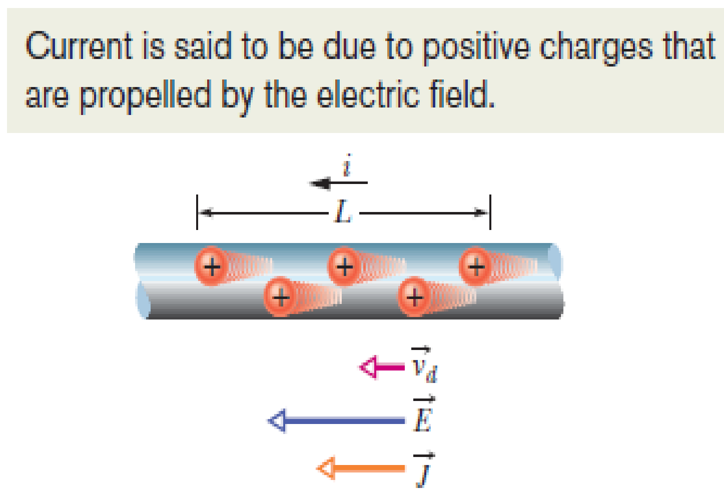


Figure 26-4 Streamlines representing current density in the flow of charge through a constricted conductor.

Drift Speed

When a conductor does not have a current through it, its conduction electrons move randomly, with no net motion in any direction.When the conductor does have a current through it, these electrons actually still move randomly, but now they tend to *drift* with a **drift speed** *vd* in the direction opposite that of the applied electric field that causes the current. The drift speed is tiny compared with the speeds in the random motion. For example, in the copper conductors of household wiring, electron drift speeds are perhaps 10^{-5}or 10^{-4} m/s, whereas the random-motion speeds are around 106 m/s. We can use Fig. 26-5 to relate the drift speed *vd* of the conduction electrons in a current through a wire to the magnitude *J* of the current density in the wire. For

Figure 26-5 Positive charge carriers drift at speed v_d in the direction of the applied electric field $\vec{E}$. By convention, the direction of the current density $\vec{J}$ and the sense of the current arrow are drawn in that same direction.



convenience, Fig. 26-5 shows the equivalent drift of *positive* charge carriers in the direction of the applied electric field $\vec{E}$. Let us assume that these charge carriers all move with the same drift speed v_d and that the current density J is uniform across the wire's cross-sectional area A. The number of charge carriers in a length L of the wire is nAL, where n is the number of carriers per unit volume. The total charge of the carriers in the length L, each with charge e, is then

$$q = (nAL)e.$$

Because the carriers all move along the wire with speed v_d, this total charge moves through any cross section of the wire in the time interval

$$t = \frac{L}{v_d}.$$

Equation 26-1 tells us that the current i is the time rate of transfer of charge across a cross section, so here we have

$$i = \frac{q}{t} = \frac{nALe}{L/v_d} = nAev_d. \tag{26-6}$$

Solving for v_d and recalling Eq. 26-5 ($J = i/A$), we obtain

$$v_d = \frac{i}{nAe} = \frac{J}{ne}$$

or, extended to vector form,

$$\vec{J} = (ne)\vec{v}_d. \tag{26-7}$$

Here the product ne, whose SI unit is the coulomb per cubic meter (C/m^3), is the *carrier charge density.* For positive carriers, ne is positive and Eq. 26-7 predicts that $\vec{J}$ and $\vec{v}_d$ have the same direction. For negative carriers, ne is negative and $\vec{J}$ and $\vec{v}_d$ have opposite directions.