

Naturally the steady flow of current in a dc circuit requires some source of energy capable of maintaining the electric field that drives the charge carriers. Until now we have avoided the question of the *electromotive force* by studying only parts of entire circuits; we kept the “battery” out of the picture. In Section 4.9 we shall discuss some sources of electromotive force.

ELECTROMOTIVE FORCE AND THE VOLTAIC CELL

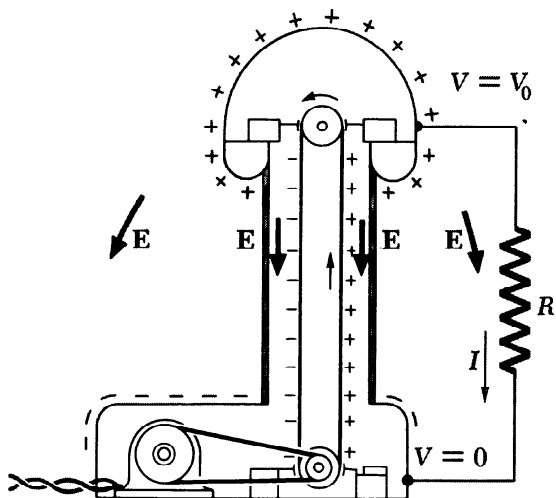
4.9 The origin of the electromotive force in a direct-current circuit is some mechanism that transports charge carriers in a direction *opposite* that in which the electric field is trying to move them. A Van de Graaff electrostatic generator (Fig. 4.19) is an example on a large scale. With everything running steadily, we find current in the external resistance flowing in the direction of the electric field \mathbf{E} , and energy being dissipated there (appearing as heat) at the rate IV_0 , or $I^2 R$. Inside the column of the machine, too, there is a downward-directed electric field. Here charge carriers can be moved against the field if they are stuck to a nonconducting belt. They are stuck so tightly that they can't slide backward along the belt in the generally downward electric field. (They can still be removed from the belt by a much stronger field localized at the brush in the terminal. We need not consider here the means for putting charge on and off the belt near the pulleys.) The energy needed to pull the belt is supplied from elsewhere—usually by an electric motor connected to a power line, but it could be a gasoline engine, or even a person turning a crank. This Van de Graaff generator is in effect a battery with an electromotive force, under these conditions, of V_0 volts.

In ordinary batteries it is chemical energy that makes the charge carriers move through a region where the electric field opposes their motion. That is, a *positive* charge carrier may move to a place of *higher* electric potential if by so doing it can engage in a chemical reaction that will yield more energy than it costs to climb the electrical hill.

To see how this works, let us examine one particular voltaic cell. *Voltaic cell* is the generic name for a chemical source of electromotive force. In the experiments of Galvani around 1790 the famous twitching frogs' legs had signaled the chemical production of electric current. It was Volta who proved that the source was not “animal electricity,” as Galvani maintained, but the contact of dissimilar metals in the circuit. Volta went on to construct the first battery, a stack of elementary cells, each of which consisted of a zinc disk and a silver disk separated by cardboard moistened with brine. The battery that powers your transistor radio comes in a tidier package, but the principle of operation is the same. Several kinds of voltaic cells are in use, differing in their chemistry but having common features: two elec-

FIGURE 4.19

In the Van de Graaff generator, charge carriers are mechanically transported in a direction opposite that in which the electric field would move them.



trodes of different material immersed in an ionized fluid, or electrolyte.

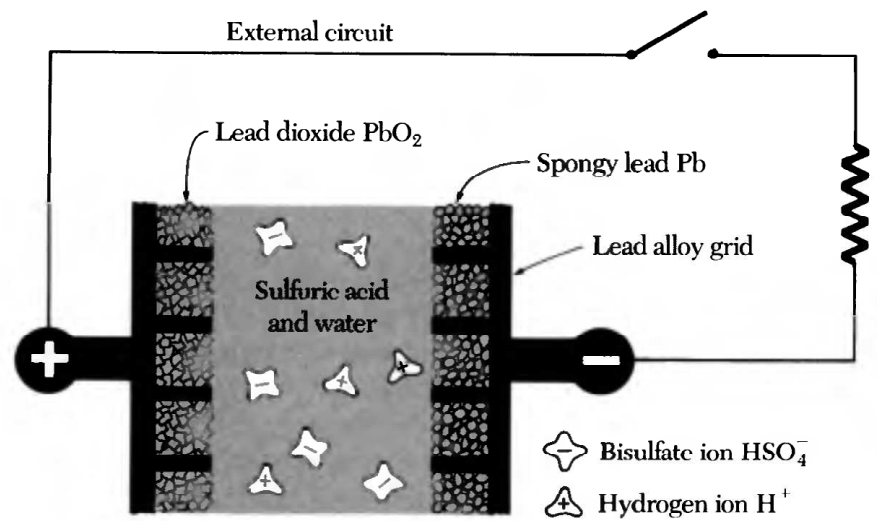
As an example, we'll describe the lead-sulfuric acid cell which is the basic element of the automobile battery. This cell has the important property that its operation is readily reversible. With a *storage battery* made of such cells, which can be charged and discharged repeatedly, energy can be stored and recovered electrically.

A fully charged lead-sulfuric acid cell has positive plates which hold lead dioxide, PbO_2 , as a porous powder, and negative plates which hold pure lead of a spongy texture. The mechanical framework, or grid, is made of a lead alloy. All the positive plates are connected together and to the positive terminal of the cell. The negative plates, likewise connected, are interleaved with the positive plates, with a small separation. The schematic diagram in Fig. 4.20 shows only a small portion of a positive and a negative plate. The sulfuric acid electrolyte fills the cell, including the interstices of the active material, the porosity of which provides a large surface area for chemical reaction.

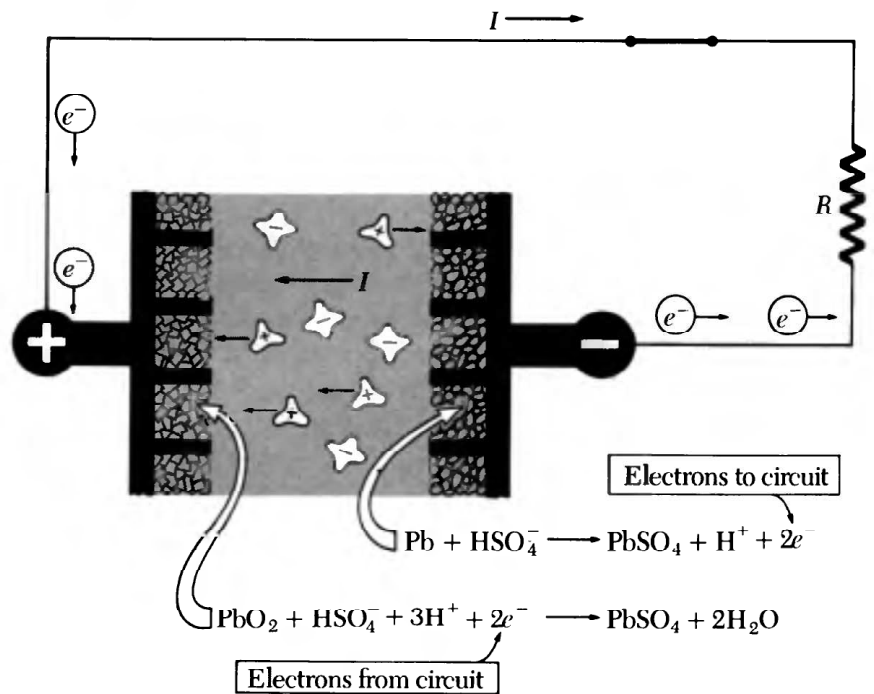
The cell will remain indefinitely in this condition if there is no external circuit connecting its terminals. The potential difference between its terminals will be close to 2.1 volts. This open-circuit potential difference is established "automatically" by the chemical interaction of the constituents. This is the *electromotive force* of the cell, for which the symbol \mathcal{E} will be used. Its value depends on the concentration of sulfuric acid in the electrolyte, but not at all on the size, number, or separation of the plates.

Now connect the cell's terminals through an external circuit with resistance R . If R is not too small, the potential difference V between the cell terminals will drop only a little below its open-circuit value \mathcal{E} , and a current $I = V/R$ will flow around the circuit (Fig. 4.20b). Electrons flow *into* the positive terminal; other electrons flow *out* of the negative terminal. At each electrode chemical reactions are proceeding, the overall effect of which is to convert lead, lead dioxide, and sulfuric acid into lead sulfate and water. For every molecule of lead sulfate thus made, one charge e is passed around the circuit and an amount of energy $e\mathcal{E}$ is released. Of this energy the amount eV appears as heat in the external resistance R . The difference between \mathcal{E} and V is caused by the resistance of the electrolyte itself, through which the current I must flow inside the cell. If we represent this internal resistance by R_i , the system can be quite well described by the equivalent circuit in Fig. 4.21.

As discharge goes on and the electrolyte becomes more diluted with water, the electromotive force \mathcal{E} decreases somewhat. Normally, the cell is considered discharged when \mathcal{E} has fallen below 1.75 volts. To recharge the cell, current must be forced around the circuit in the opposite direction by connecting a voltage source greater than \mathcal{E} across the cell's terminals. The chemical reactions then run backward



(a) Charged cell.



(b) Discharging cell.

FIGURE 4.20

A schematic diagram, not to scale, showing how the lead-sulfuric acid cell works. The electrolyte, sulfuric acid solution, permeates the lead dioxide granules in the positive plate and the spongy lead in the negative plate. The potential difference between the positive and negative terminals is 2.1 volts. With the external circuit closed, chemical reactions proceed at the solid-liquid interfaces in both plates, the depletion of sulfuric acid in the electrolyte, and the transfer of electrons through the external circuit from negative terminal to positive terminal, which constitutes the current I . To recharge the cell, replace the load R by a source with electromotive force greater than 2.1 volts, thus forcing current to flow through the cell in the opposite direction and reversing both reactions.

until all the lead sulfate is turned back into lead dioxide and lead. The investment of energy in charging the cell is somewhat more than the cell will yield on discharge, for the internal resistance R_i causes a power loss $I^2 R_i$ whichever way the current is flowing.

Notice in Fig. 4.20*b* that the current I in the electrolyte is produced by a net drift of positive ions toward the positive plate. Evidently the electric field in the electrolyte points toward, not away from, the positive plate. Nevertheless, the line integral of \mathbf{E} around the whole circuit is zero, as it must be for any electrostatic field. The explanation is this: There are two very steep jumps in potential at the interface of the positive plate and the electrolyte and at the interface of the negative plate and the electrolyte. That is where the ions are moved *against* a strong electric field by forces arising in the chemical reactions. It is this region that corresponds to the belt in a Van de Graaff generator.

Every kind of voltaic cell has its characteristic electromotive force, falling generally in the range of 1 to 3 volts. The energy involved, per molecule, in any chemical reaction is essentially the gain or loss in the transfer of an outer electron from one atom to a different atom. That is never more than a few electron volts. We can be pretty sure that no one is going to invent a voltaic cell with a 12-volt electromotive force. The 12-volt automobile battery consists of six separate lead-sulfuric acid cells connected in series.

NETWORKS WITH VOLTAGE SOURCES

4.10 A network of resistors could contain more than one electromotive force, or voltage source. The circuit in Fig. 4.22 contains two batteries with electromotive force \mathcal{E}_1 and \mathcal{E}_2 , respectively. The positive terminal of each battery is indicated next to the conventional battery symbol. Assume that R_1 includes the internal resistance of one battery, R_2 that of the other. Supposing the resistances given, let us find the currents in this network. Having assigned directions arbitrarily to

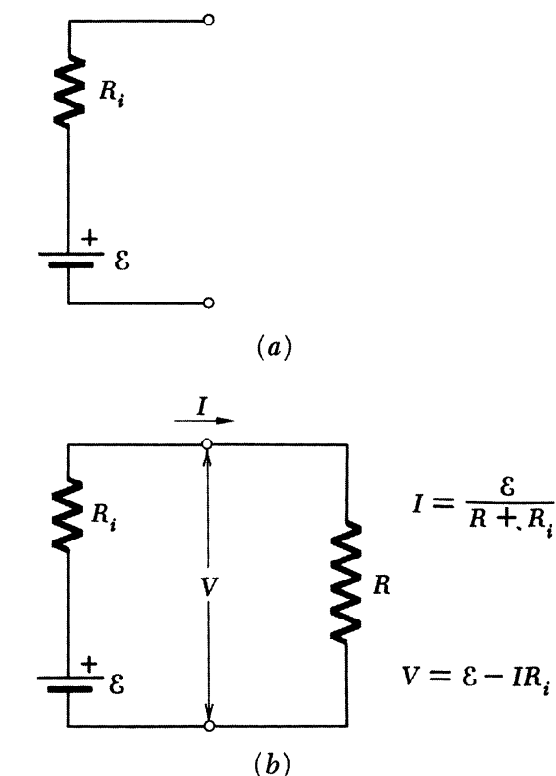
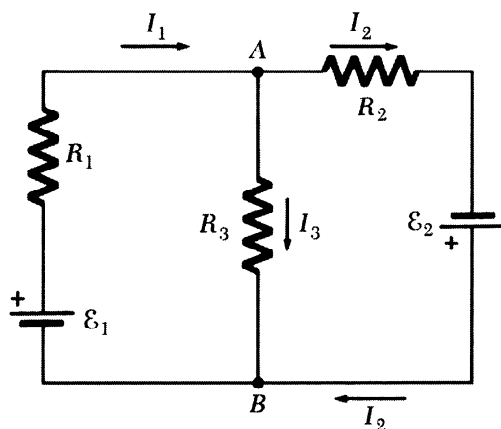


FIGURE 4.21

(a) The equivalent circuit for a voltaic cell is simply a resistance R_i in series with an electromotive force \mathcal{E} of fixed value. (b) Calculation of the current in a circuit containing a voltaic cell.

FIGURE 4.22

A network with two voltage sources.