6.2 THE ELECTROMOTIVE FORCE

What makes a current flow in a metal? The conduction electrons in a metal move at high speeds randomly due to the themal energy as if the metal were a gas of electrons. You might get a sense of the speed of the random motion of electrons by setting kinetic energy to $\frac{3}{2}k_BT$ where k_B is the Boltzmann constant and T the temperture in Kelvin scale, which gives the speed $\sim 10^5$ m/s.

Since the thermal motion is random, overall the same number of electrons go in every direction and there is no net flow along a wire. For electrons to flow predominantly in one direction, we need a force on the electron. When a potential difference exists between the ends of a metal wire, there is also an electric field inside the wire. The conduction electrons drift as a result of the electric force due to the electric field.

Suppose, at $t = 0$ a potential difference is created by putting $+q$ at one end and $-q$ at the other end of a copper wire, then the flow of electrons will occur from the lower potential place ($-$ end) to the higher potential place ($+$ end) which is in the opposite direction of the electric field.

If we wish to maintain the current in the wire then we need a mechanism by which electrons arriving at the $+$ end are continuously removed and new electrons are placed at the $-$ end so that the potential difference between the ends could continue to exist (Fig. 6.5).

This task will require work by an agent since it will be moving negatively charged electrons from a higher potential ($+$ end) to a lower potential ($-$ end) in the space between the plates. After the transfer the electrons would move in the wire from the negative plate to the positive plate guided by the electric field. That means, for the electron to go around in the circuit, the external agent will need to do work for transfer of electrons between the plates, where the electric force is opposite to the displacement required.

The work required per unit of charge is called the **electromotive force** or **EMF**. Clearly EMF is not a force, but energy per unit charge, and has units of potential or volt. Perhaps a better name for electromotive force would be **electromotive energy** (EME). It is also common to call a source of EMF a voltage source.

In a **voltaic cell** or a **battery**, the EMF is provided by chemical reactions at the electrodes - electrons are taken away from the positive electrode, called anode and deposited at the negative electrode, called

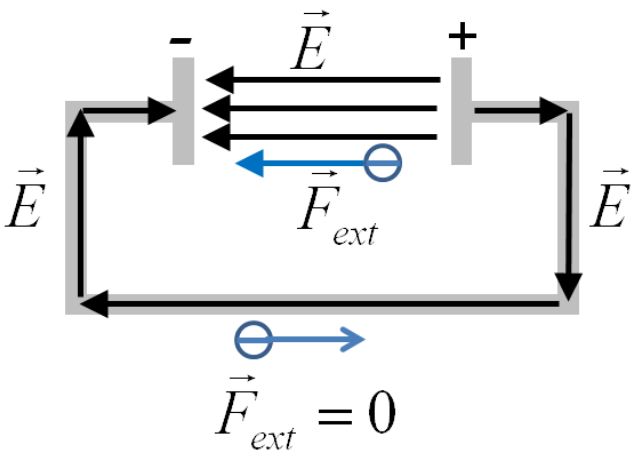

Figure 6.5: Connecting two oppositely charged plates by a metallic wire gives rise to flow of electron in the wire from negative plate to the positive plate, neutralizing the charges on the plates. To maintain a steady current an external agent or device such as a battery must do work against the electric force between the plates. Amount of work per unit charge is called the EMF of the agent.

cathode making use of appropriate chemical reactions (Fig. 6.6). Chemicals that are used up in the process get replenished by the

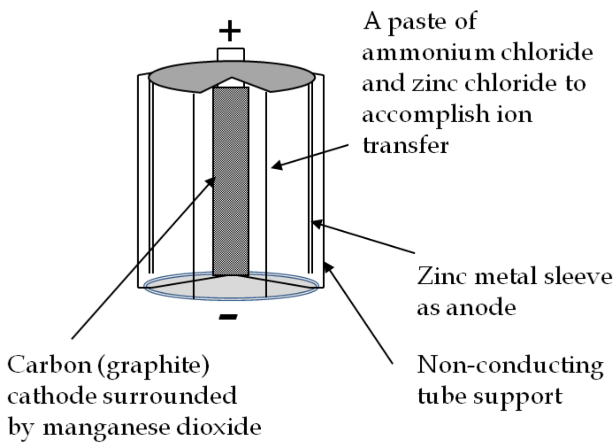

Figure 6.6: Example of a Voltaic Cell: A Carbon-Zinc Cell.

migration of chemicals in the medium between the electrodes. To allow the movement of ions, the mixture in dry cell batteries is kept in the form of an emulsion, while in car batteries, the chemicals are in a liquid mixture. When a battery runs out of chemicals needed for the EMF, it stops functioning.

Since the sources of EMF in a battery are chemical reactions, the electromotive force of a single cell is limited by the energy generated when electrons are transferred from one chemical ion to another. These energies typically lie in the range of 1-3 electron volts, which corresponds to an EMF of 1-3 volt. Thus, you can make only 1-3 volt cells based on chemical reactions. To make a 3-volt battery out of two 1.5-V single voltaic cells, you connect voltaic cells in series, connecting + terminal of one to the − terminal of another as shown in Fig. 6.7. Higher voltage batteries can be constructed this way.

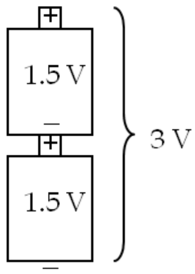

Figure 6.7: Voltages add when voltaic cells are put in series.

A mechanical device called the **van de Graff generator**, which is often used in physics demonstrations of static electricity, creates a large EMF (Fig. 6.8). In the van de Graff generator, electrons are transported from a high potential to a low potential by way of a mechanical transport over a non-conducting rubber belt. Mechanical work is needed because electrons are moved in the direction opposite to how the electrons will move in the prevailing electric field. Electrons are stripped off from the rubber belt by high field on the brushes, although at other places electric field is not high enough to slide the electrons on the belt itself. The mechanical motor in the van de Graff generator does work in transporting the charge on the belt.

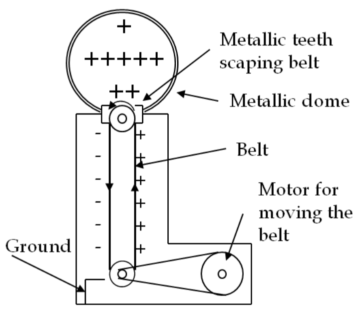

Figure 6.8: The van de Graff generator