1.1 THE ELECTRIC CHARGE

1.1.1 Electrification by Friction

Try this: dry your hair, and comb it with a plastic comb. Then, bring the comb near bits of paper. You will find that the rubbed comb attracts pieces of paper (Fig. 1.1). Whenever two dissimilar materials are rubbed against one another they tend to develop attraction for one another and towards other objects.

Ancient Greeks knew of this property, as recorded by Thales of Miletus (circa. 635 BC - 543 BC), when it was found that an amber rubbed with silk attracted light objects. A serious study of these effects began with **William Gilbert** of England, the "father of the science of electricity and magnetism", who coined the word **electrification**, after the Greek word $\eta\lambda\epsilon\kappa\tau\rho o\nu$ (elektron) for amber. A rubbed body, which attracts light objects, is said to be electrified, or electrically charged.

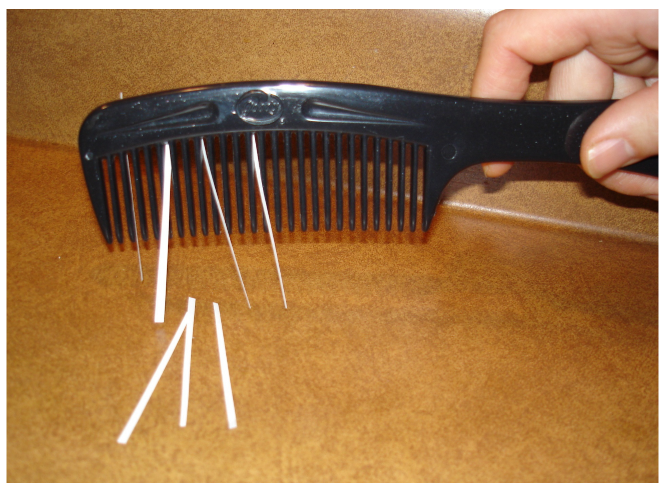

Figure 1.1: Charged comb picking up bits of paper due to electrical attraction.

When you rub two dissimilar objects, both objects become electrically charged. The charges on the two, however, are not of the same type as you can easily demonstrate by the following experiments with a cellophane tape that has one sticky side (Fig. 1.2).

Take two pieces of a cellophane tape and tape one on the non-sticky side of the other. Now, quickly pull them apart. If you bring them closer with their non-sticky sides facing each other (so that they do not get stuck again), you will notice that they attract each other. Tear one of the tapes, and then bring the two new pieces closer, you will notice that they repel each other.

You can explain these observations based on the hypothesis that there are two types of charges, and they are balanced in any uncharged material. But when the tapes are pulled apart, some charges of one type move from one tape to the other. As a result an imbalance of charges develops in both tapes. The attraction of the two tapes and the repulsion among parts of the same tape tells us that the unlike charges attract and the like charges repel. Any name could be given to the charges. Traditionally we call the two types of charges as **positive and negative charges**, and represent them by positive and negative real numbers respectively.

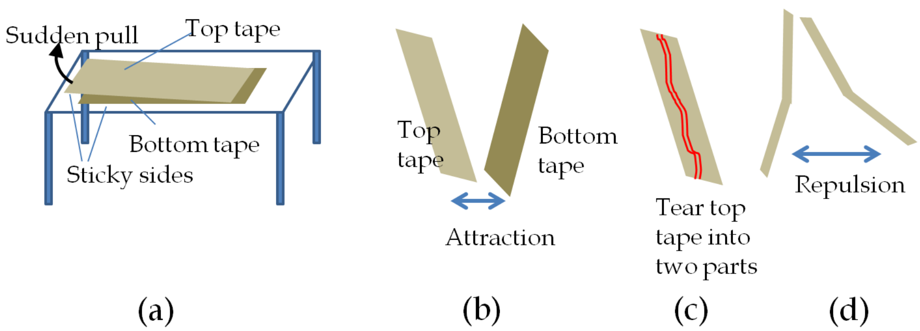

Figure 1.2: Sticky tape experiment demonstrating the existence of two types of electric charges. (a) Tape one tape on the non-sticky side of anther tape and then quickly pull them apart. (b) Bringing top and bottom tapes near one another shows attraction between them. (c) Tear one of the two tapes, the top tape. (d) Bringing the two pieces of the top tape near one another shows repulsion.

1.1.2 Microscopic Origin of Electric Charge

If you rub a neutral plastic rod with a neutral paper towel, you will find that the plastic rod and the paper towel become charged. What is going on inside these materials for them to develop excess charges? In order to understand the electrification process, we must look at the atomic level. Atoms have an equal number of electrons and protons. It is a fundamental fact of nature that electrons and protons have exactly equal charges of opposite types. Traditionally, an electron's charge, denoted as $-e$, has been given a negative sign; therefore all objects with the same type of charges as that of an electron are called negatively charged. A proton then has a positive charge $+e$, and all objects whose charges are of the same type as that of a proton are called positively charged.

The SI unit for electric charge is called a **Coulomb** (C), named after the French physicist Charles Augustin de Coulomb (1736-1806), who conducted valuable experiments with static electricity. The charge of an electron is one of the most precisely measured quantities in physics with the following experimental value. The **electronic charge** is given in terms of the basic unit of charge denoted by e whose magnitude in Coulomb is given by

$$e = (1.60217733 \pm 0.00000049) \times 10^{-19}\ \text{C}. \tag{1.1}$$

In atoms, electrons are distributed around a tiny nucleus, which contains all the protons. Nucleus also contains neutral particles called neutrons. Atoms of different chemical elements differ in their abilities to hold onto their own electrons and to attract charges from outside the atom. Some atoms readily lose an entire electron and become positively charged ions, while others gain an entire electron and become negatively charged ions.

Metals behave as if some electrons of each atom, called the conduction electrons, are not bound to any one particular atom but free to roam about in the entire metal. In non-metals, also called insulators, electrons are localized near each atom. When two atoms of different elements are next to each other a polarization of charges results with one atom developing a negative charge and the other developing the same amount of positive charge. For instance, in the water molecule, the oxygen atom is negatively charged while the two hydrogen atoms are positively charged. Such substances are called polar. Much of useful properties of water can be traced to the electrical polarization of its molecules.

The competition for electrons is also at play when two dissimilar materials are rubbed or pressed against each other. In the case of a plastic rod rubbed with a paper towel, the electrons move from paper towel to the plastic rod making the rod negatively charged since the molecules in the plastic rod have greater attraction for the electrons than the molecules in the paper. After rubbing, the towel has a fewer electrons than what is needed to balance the charges on its protons, and therefore would be positively charged on the whole. When you rub two dissimilar materials, you do not create charges, but rather, you transfer electrons from one material to the other. The net charge is still the same after the process as before.

1.1.3 Principle Of Conservation Of Electric Charge

A fundamental property of nature is that the electric charge is conserved in every process. That is, the net charge of the universe does not change with time. If you count the charges that enter or leave any region of space in some interval Δt, then you will find that the charge at the end of the interval will be equal to the charge at the beginning plus the charges that entered minus the charges that left the region in that time.

$$|\text{Net change}| = |\text{Amount entered} - \text{Amount exited}| \tag{1.2}$$

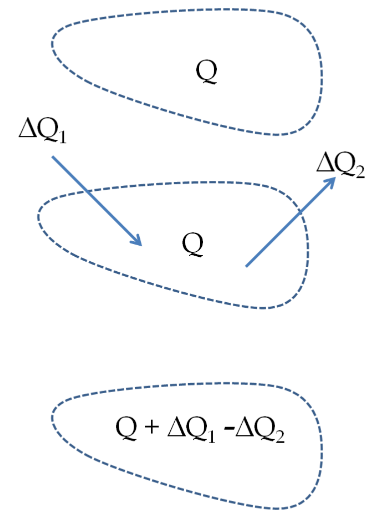

Figure 1.3: Conservation of charge: in any space, the charge at the end equals charge at the beginning plus charge entering minus charge leaving.

No experiment has led to the creation or destruction of the net charge. Whenever charges seem to be created in a situation, they always occur in pairs of equal and opposite types. For instance, when a neutron with zero net charge decays in the nuclear beta decay of radioactivity, two charged objects, an electron and a proton, are produced along with a neutral particle called neutrino. Thus, the net charge after the reaction is zero as at the beginning.

$$\begin{array}{lccccccc} \text{Reaction:} & n & \rightarrow & e & + & p & + & \bar{\nu}_e \\ \text{Charges:} & (0) & \rightarrow & (-e) & & (+e) & & (0) \end{array}$$

In electro-chemistry, equal and opposite charges appear at the two electrodes so that the charges separate by equal amount leaving the solution neutral if it was neutral at the start.

1.1.4 Conductors and Insulators

Consider the experiment illustrated in Fig. 1.4. Suspend an electrically charged ebonite rod that has been rubbed with a cat's fur. Fix a metal ball near one end of the suspended rod, and another metal ball a distance away. Now, connect the two metal balls by a metal wire. If you touch the far away metal ball, by another charged ebonite, then you will find that suspended ebonite rod swings away, demonstrating that electricity has traveled through the metal wire to the nearby metal ball, which exerts the electric force on the suspended charged ebonite.

Suppose, you repeat the experiment the two metal balls, with a thread of silk, wool or cotton, rather than a metal wire, you will not find any force on the suspended charged ebonite rod. But, if you were to repeat the experiment with cotton thread that has been moistened with a salty water, there will be a slowly rising force on the suspended rod. The ions in the salty water allow the charges to flow from one metal ball to the other.

These experiments help us classify all material objects according to their **ability to conduct electricity**. Metals and ionized water are considered to be good conductors, and silk, cotton, wool, and wood are called insulators or poor conductors.

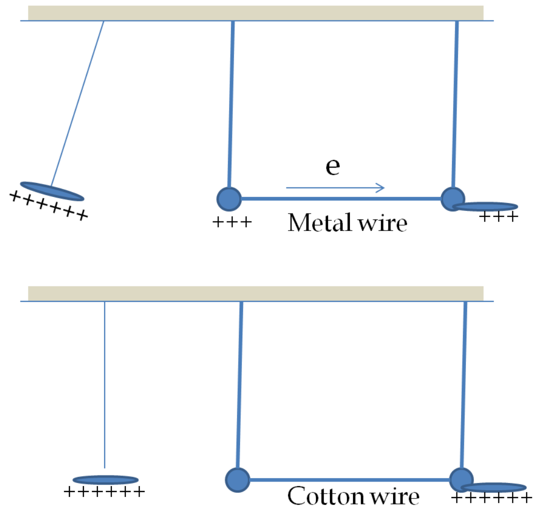

Figure 1.4: Charges flow through a conductor and do not flow through an insulator.

1.1.5 Electroscope and Electrostatic Induction

The repulsion of like charges is demonstrated by an elegant instrument called electroscope invented by the French physicist **Jean Antoine Nollet** in 1748. To make an electroscope you will need a metallic strip, so thin that it is limp and flexible. You can also cut two thin strips of aluminum or some other metal foil and put a pin through them at one end so that the pair can rotate away from each other at the other end. The limp metallic strip or metal foil is then hung over a metal support. The structure so constructed is then attached to a metallic rod and placed inside a clear (for viewing) glass jar using a cork stopper. Finally place a metallic knob at the top. See Fig. 1.5.

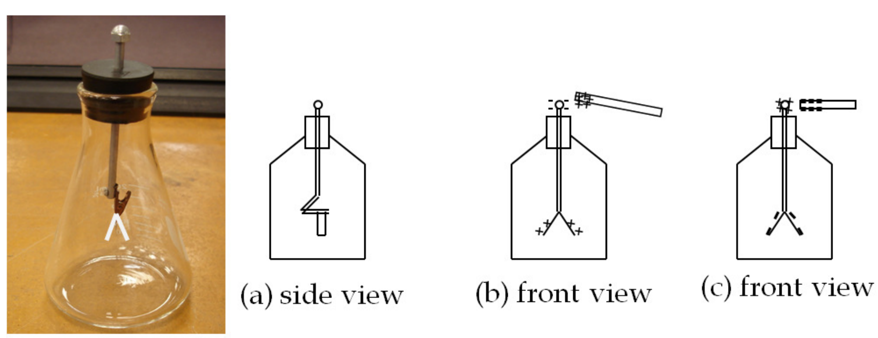

Figure 1.5: An electroscope - the thin aluminum leaves are not visible in the picture. The sketches illustrate the positive and negative charging of the electroscope by induction.

When a charged material, such as glass rod rubbed with silk, is brought near the metallic knob of the electroscope, but not touching the electroscope, the leaves of the electroscope are non-the-less seen to be repelled. This happens because of charge induced in the electroscope as in Fig. 1.5(b). The electrons in the leaves are attracted towards the positive charges on the glass rod and migrate towards the knob of the electroscope, leaving excess of protons over electrons in the atoms of the leaves making them positively charged. Therefore, they repel. We find that, as long as the charged rod is held in place, the leaves stay separated due to the repulsion between the induced charges on the leaves. When the charged rod is removed, the extra electrons from the ball in the electroscope move towards the leaves and the electroscope becomes neutral again.

Induced effect always creates a separation of equal amount of negative and positive charges. Metals contain a large number of easily movable electrons bound to fairly fixed centers of positively charged atomic nuclei. These electrons in a metal are called the **conduction electrons**. When you bring a charge near a metal, the electrons move, creating regions that have excess of electrons and others that have deficiency of electrons. The regions that have excess of electrons are negatively charged while the regions deficient in electrons are positively charged.

In non-metals, such a piece of glass or plastic, electrons are not free to move to large distances. When an external charge is brought near these materials, electrons in their molecules tend to move within the molecules and rearrange so that there is a polarization of molecules with one end more negative than the other end, creating induced dipoles in the material. Induced dipoles are attracted to the external charges as easily seen in the attraction of papers to charges on a brushed comb.

Although the charge separation by an induced effect disappears when the external charge is removed, a conductor can be permanently charged if the charges at the remote part of the conductor can be somehow removed or neutralized. Consider bringing negatively charged ebonite rod near one end of a metal rod (Fig. 1.6). This causes extra negative charges on the far end, and extra positive charges on the near end. Now, if we touch the far-end of the rod with a metallic wire connected to a large conductor, such as earth, then the induced negative charges on the rod migrate to the large body. Removing the wire leaves the metal rod positively charged since it has excess positive charge. Now, when you remove the charged ebonite rod, the metal does not become neutral now. Basically, by severing a conductor, which is under the influence of an external charge, into

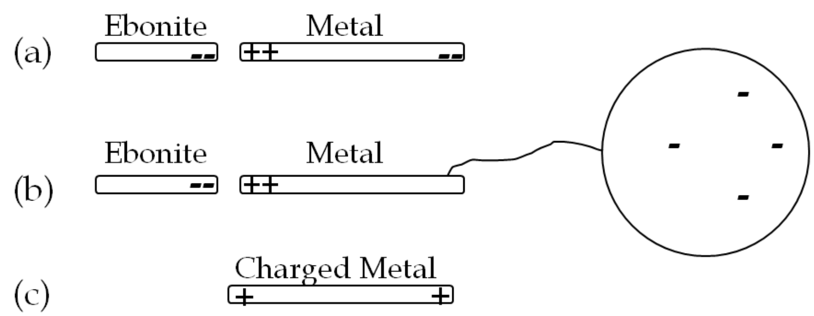

Figure 1.6: Electrification by induction. (a) Induced charges in metal. (b) The far-end of the metal connected to a large conductor by a conducting wire. (c) After the wire is disconnected from the metal, metal rod is left positively charged.

two parts will leave each part with a net charge.

Figure 1.7: The electrophorus.

An instrument called the electrophorus was invented by Allesandro Volta in 1777 that makes use of induction to accumulate large quantities of charge on a conductor. Fig. 1.7 illustrates an electrophorus. In the simplest form, it consists of an insulated plate, here a hard rubber plate of diameter about 30 cm, and a metal plate with a handle.

First, the insulator plate at the base is charged by rubbing it with a rabbit fur giving the plate a net negative charge. Then the metal plate is placed on the charged insulator plate. The negative charge on the insulator plate induces a charge separation in the metal plate with the bottom of the metal plate becoming positive and the top becoming negative. The top part is then touched with hand that drains the negative charge to the body leaving a net positive charge on the metal plate. The positively charged metal plate is then lifted with its plastic handle and transported for static electricity demonstrations.

1.1.6 Quantization of Electric Charge

In 1909 the American physicist **Robert A. Millikan** conducted experiments with charged oil drops. By balancing the electric and gravitational forces on oil drops, he was able to suspend them in mid-air (Fig. 1.8). He found that the electric charges on oil drops were always integral multiples of a basic unit charge, thus establishing the quantization of charge.

The basic unit of charge is the same as the charge on one electron, and is denoted as usual by the letter e. In the SI system of units, the approximate value of e is 1.6×10^{-19} C as given above. The charge on one electron is -1 times e, and the charge on a proton is $+1$ times e. Since atoms have equal number of protons and electrons, they are neutral. It is remarkable that the charge on a proton is exactly equal in magnitude to that of the charge on an electron, although the two particles differ in mass and many other properties. If the charges on electron and proton were slightly different from each other, the atom will have a net charge, and it will be impossible to make stable matter.

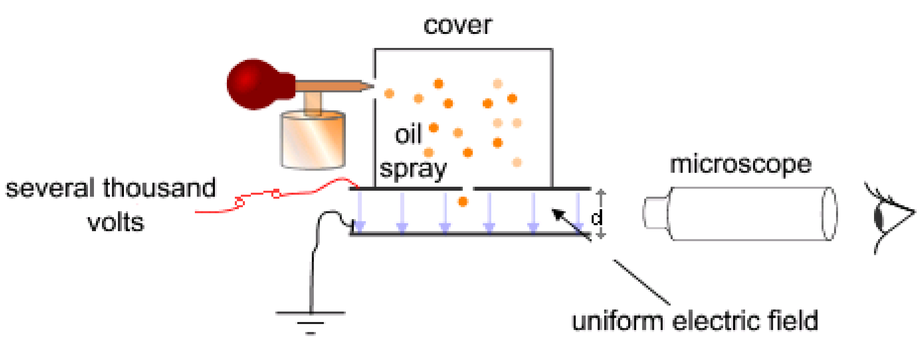

Figure 1.8: Millikan Oil Drop Experiment (Diagram by Theresa Knott, Wikipedia).

Not only is a proton's charge an integral multiple of e, but so are the charges on all other particles which can be isolated in nature. If we believe that matter is ultimately made up of elementary constituents, called elementary particles, then we only need to look at the charges on the elementary particles to verify the assertion of quantization of charge. Presently the standard model of particle physics contains electron, muon, tau, electron-neutrino, mu-neutrino, tau-neutrino, up quark, down-quark, strange-quark, charm-quark, top-quark, bottom quark, W^+, W^-, Z, photon, Higgs particle and their anti-particles. All of these particles have zero, $+e$ or $-e$ of charge except for the quarks which have charges $\pm\frac{2}{3}e$ and $\pm\frac{1}{3}e$. Although, charges on quarks have been hypothesized to be a fraction of e, they have not been found in isolation. Instead, they reside inside other particles, e.g., a proton has two up quarks and a down quark and a neutron has two down quarks and an up quark. Every time an experiment is done with high enough energy that quarks could come out, one gets jets of particles that have integral multiples of charge e. The inability of experiments to knock quarks out of the composite particles has led to a belief that they may be permanently confined.