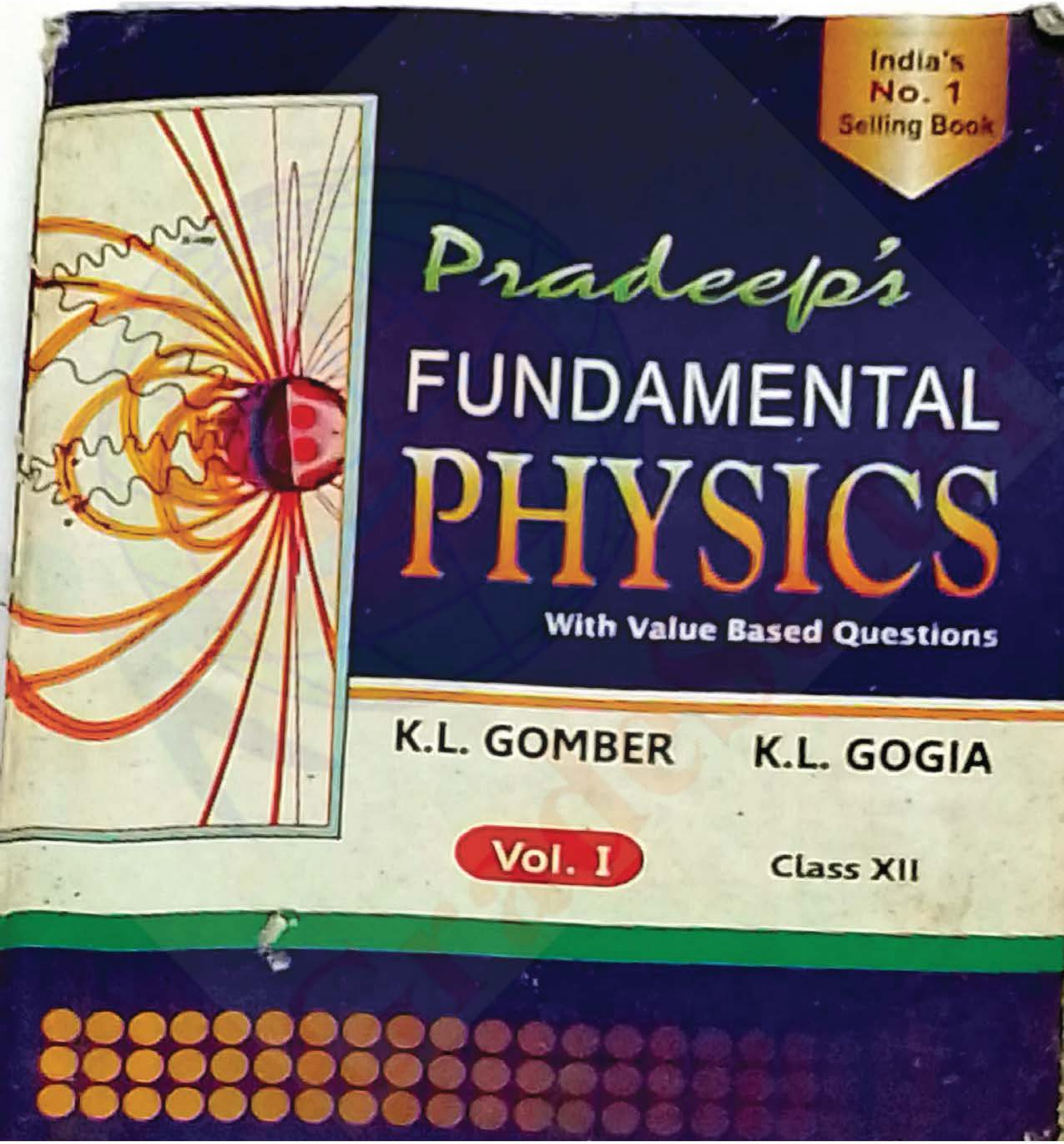

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K.L. GOMBER **K.L. GOGIA**

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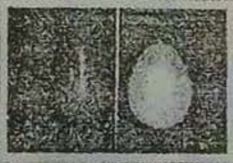
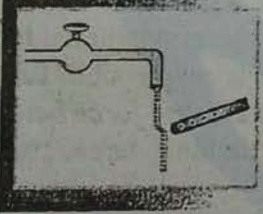
1(a)

ELECTROSTATIC CHARGES





CHAPTER OVERVIEW

1(a).1. INTRODUCTION

Many of us have the experience of seeing a spark or hearing a crackle, when we take off our synthetic shirts or nylon sweaters, particularly in dry weather. Sometimes, we feel the sensation of an electric shock while opening the door of our car or by holding the iron bar of a bus, after sliding from our seat. The reason for these experiences is discharge of electric charges through our body, which were accumulated due to rubbing of insulating surfaces. Another common example of electric discharge is the lightning that we see in the sky during thunderstorms.

We know that when a glass rod is rubbed with a piece of silk, the rod acquires the property of attracting light objects like bits of paper, straw, pith balls, dry leaves or even dust particles towards it. The glass rod is said to be *electrified* or *charged*. Similarly, a plastic comb gets electrified on passing through dry hair.

The metallic bodies of cars and trucks also get charged because of friction between them and the air rushing past them. This charge being large can produce even a spark. Such a spark can be dangerous in case of a petrol tanker. That is why petrol tankers often have a metal chain dragging along the ground. The charge produced leaks to the ground through this chain. Now a days, the tyres of cars and trucks are made by adding a carbon compound to the rubber. This facilitates the charge built up on the body of the vehicle, to leak to the ground.

We learn from above that electric charges are produced due to friction between two insulating bodies, which are rubbed against each other. The charges on insulating bodies cannot move on their own. That is why they are called *static charges.*

The branch of Physics, which deals with the study of charges at rest (i.e., static charges), the forces between the static charges, fields and potentials due to these charges is called Electrostatics or Static Electricity or even Frictional Electricity.

Historically, this phenomenon was discovered around 600 BC by a Greek philosopher *'Thales of Miletus'*. The name electricity was taken from Greek word 'Elecktron'.

Note that most of the early experiments on electrostatics work best on a dry day, because excessive moisture provides a pathway for charge to leak off a charged object.

1(a).2. WHAT IS ELECTRIC CHARGE ?

Electric charge is a characteristic that accompanies fundamental particles, wherever they exist.

According to William Gilbert, ***charge is something possessed by material objects that makes it possible for them to exert electrical force and to respond to electrical force.***

The three most common elementary particles are electrons, protons and neutrons having masses

$$m_e = 9{\cdot}10940 \times 10^{-31}\text{ kg} ;\ m_p = 1{\cdot}67262 \times 10^{-27}\text{ kg}$$

and $$m_n = 1{\cdot}67493 \times 10^{-27}\text{ kg}$$

Because of their mass, these particles attract one another by gravitational forces. Thus, an electron attracts another electron at a distance of 1 cm, with a gravitational force

$$F = \frac{Gm_1m_2}{r^2} = \frac{6{\cdot}67\times10^{-11}\times(9{\cdot}1\times10^{-31})^2}{(10^{-2})^2} = 5{\cdot}5 \times 10^{-67}\text{ N}$$

However, an electron *repels* another electron at a distance of 1 cm with a force = $2{\cdot}3 \times 10^{-24}$ *N*. This force is called ***electric force.*** We observe that electric force is very large compared to the gravitational force. The electrons must have some additional property (other than their mass), which is responsible for the electric force between them. ***This additional property of electron, which gives rise to electric force between two electrons is called electric charge.*** Just as masses are responsible for the gravitational force, charges are responsible for the electric force.

Two protons placed at a distance of 1 cm also repel each other with the same force = $2{\cdot}3 \times 10^{-24}$ *N*. It shows that protons also have charge which in magnitude, must be equal to charge on electron. Two neutrons placed at a distance of 1 cm attract each other with a force = $1{\cdot}9 \times 10^{-60}$ *N*, which is the gravitational force due to their masses. However, electric force between two neutrons is zero. Therefore, neutrons have no charge, though they have mass.

1(a).3. TWO KINDS OF CHARGES

Let us look at some simple facts, which were established from years of efforts and careful experiments :

(*i*) A glass rod rubbed with a piece of silk brought close to a suspended glass rod rubbed with silk repels the latter as shown in Fig. 1(a).1 (a).

(*ii*) The two pieces of silk cloth with which the glass rods were rubbed also repel each other. However, each glass rod attracts the silk piece with which it was rubbed.

(*iii*) Two ebonite/amber rods rubbed with cat's fur repel eachother as shown in Fig. 1(a).1(b). However, each ebonite rod attracts the cat's fur with which it was rubbed.

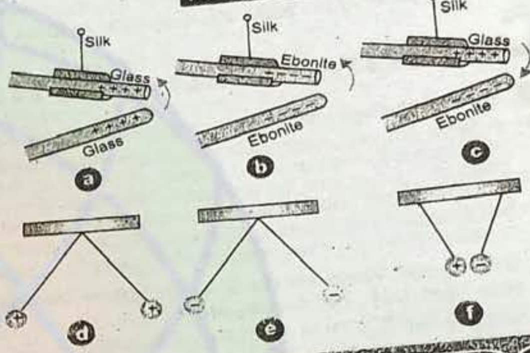
(iv) An ebonite rod rubbed with cat's fur attracts a glass rod rubbed with a piece of silk as shown in Fig. 1(a).1(c). However, the charged glass rod repels the cat's fur.

(v) When a glass rod rubbed with a piece of silk is made to touch two small pith balls (or polystyrene balls) suspended by silk/nylon threads, the balls repel eachother, as shown in Fig. 1(a).1(d).

(vi) Similarly, when an ebonite/amber rod rubbed with cat's fur is made to touch two small pith balls suspended by silk/nylon threads, the balls repel eachother, as shown in Fig. 1(a).1(e).

(vii) However, a pith ball (or polystyrene ball) touched with charged glass rod attracts another pith ball touched with charged ebonite rod, as shown in Fig. 1(a).1(f).

FIGURE 1(a).1



A careful analysis of these facts observed leads us to the following conclusions :

(i) The bodies like glass rods, ebonite/amber rods, silk, fur etc. acquire electric charge on rubbing.

(ii) The pith balls or polystyrene balls acquire electric charge by *actual contact* with a charged body.

(iii) The charge developed on glass rod rubbed with silk is different from the charge developed on ebonite rod rubbed with fur. This is because a charged glass rod repels another charged glass rod, but attracts a charged ebonite rod. Hence, there are two kinds of charges. When a glass rod is rubbed with silk, the rod acquires one kind of charge and the silk acquires second kind of charge. This is true for any pair of objects that are rubbed to be electrified. ***Further, like charges repel each other and unlike charges attract each other.***

(iv) When an electrified glass rod is brought in contact with the silk piece, with which it was rubbed, they no longer attract eachother. They also do not attract other light objects as they did on being electrified. It means the charges acquired on rubbing are lost when the two oppositely charged bodies are brought in contact with eachother. It leads us to the conclusion that ***charges acquired by the objects on rubbing against eachother must be equal and opposite.*** That is why they neutralise or nullify eachother's effect. ***Du Fay was the first to show two kinds of charges.*** An *American scientist **Benjamin Franklin*** named the two kinds of charges as positive and negative. By convention, ***charge acquired by glass rod or cat's fur is called positive. And the charge acquired by ebonite/amber rod or silk cloth is called negative.***

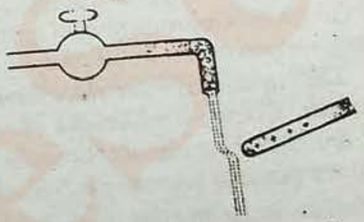
Hence, there are two kinds of charges. *The property which differentiates the two kinds of charges is called the,**polarity of charge.***

If a body possesss an electric charge, it is said to be charged or electrified. *When it has no charge, it is said to be* ***neutral.***

DO YOU KNOW?

- If an electrically charged rod is brought near normal flow of water from a tap, the flow gets slightly diverted towards the rod as shown in Fig. 1(a).2.

FIGURE 1(a).2



- If we cut out long thin strips of white paper, iron them lightly and take them near a T.V. screen or computer monitor, we find that the strips get attracted to the screen, and remain stuck to the screen for a while. This is because the strips acquire electric charge on ironing. Their sticking to the screen is due to electrostatic force of attraction.
- Some cosmetic products contain an organic compound, called **chitin,** which is found in crabs, butterflies and other insects. This is because chitin is positively charged and so it helps cosmetic products stick to skin and human hair, which are usually negatively charged slightly.

Further, *note that only rubbed area of non conducting body gets charged, and this charge does not move to other parts of the body. The charge is static on rubbed portion only.*

CURIOSITY QUESTIONS

Q. 1. What role does electrostatics play in a xerox copying machine ?

Ans. A xerox copying machine is one of the many industrial applications of the forces of attraction and repulsion between charged bodies. Particles of black powder, called **toner** stick to a tiny carrier bead of the machine on account of electrostatic forces. The negatively charged toner particles are attracted from carrier bead to a rotating drum, where a positively charged image of document being copied has formed. A charged sheet of paper then attracts the toner particles from the drum to itself. They are then heat fused in place to produce the photo copy.

Q. 2. When your friend chews a winter green life saver in a dark room, you see a faint flash of blue light from his mouth. How ?

Ans. This display of light is often called sparking. It occurs due to electric discharge of the electrostatic charges produced in chewing the winter green life saver.

1(a).4. CONDUCTORS, INSULATORS AND DIELECTRICS

Most of the substances in nature are divided into two categories, namely, *conductors* and *insulators*.

A substance which can be used to carry or conduct electric charge from one place to the other is called a conductor. Silver is one of the best conductors. Other examples of conductors are copper, iron, aluminium, mercury, coal etc. Earth is a good conductor. Human body is also a good conductor of electricity. The liquid conductors include, salt solutions, acids, alkalis etc.

In metallic conductors, there are very large number of free electrons which act as carriers of charge. Infact, in a metal, the outer (valence) electrons part away from their atoms and are free to roam about in the body of the metal, but they cannot leave the metal under normal circumstances. The free electrons form a kind of *electron gas*, they collide with one another ; and also with the ions ; and move randomly in different directions. In an external electric field, the free electrons drift against the direction of the field. The residual atoms made up of nuclei and the bound electrons remain held in their fixed positions. They constitute the *bound charges* in the conductor as they cannot move. In electrolytic conductors, the charge carriers are both, the positive and negative ions.

The insulators are the materials which cannot conduct electricity, i.e., they are poor conductors of electricity. Common examples of insulators are glass, rubber, plastic, ebonite, mica, wax, paper, wood etc. They are called insulators, because they prevent charge from going to places where it is not desired. Such subtances possess *almost no free electrons.*

Infact, in an insulator, each electron is *attached or bound* to a particular atom and is *not free* to move in the body of the insulator. As each electron stays near its '*parent*' nucleus or within its atom or molecule, and cannot move far away from it, therefore, *an insulator does not possess freely movable charges.* Hence it fails to conduct electricity.

Insulators are also called Dielectrics. Obviously, dielectrics cannot conduct electricity. However, when an external electric field is applied, induced charges appear on the surface of the dielectric. *Hence we may define* ***dielectrics as the insulating materials which transmit electric effects without conducting.***

When some charge is transferred to a conductor, it gets distributed readily over the entire surface of the conductor. In contrast, if some charge is put on an insulator, it stays at the same place.

A nylon or plastic comb gets electrified on combing dry hair or on rubbing. But a metallic rod does not get electrified on rubbing. This is because charges on metal leak through our body to the ground as both are good conductors of electricity.

RETAIN IN MEMORY

When a charged body is brought in contact with the earth, all the excess charge on the body disappears by causing a momentary current to pass to the ground through our body. This process of sharing charges with the earth is called **grounding** or **earthing.** Earthing near the mains supply of a building is done by burying deep into earth, a thick metal plate. The electric wiring in our houses has three wires ; live, neutral and earth. The first two carry

RETAIN IN MEMORY electric current from the power station and the third (earth) is connected to the buried metal plate. Metallic bodies of appliances like T.V., refrigerator, electric iron etc. are connected to earth wire. If a live wire were to touch the metallic body, charge flows to earth without damaging the appliance and without causing injury to us.

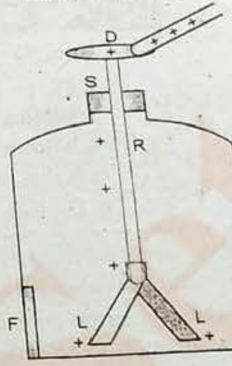
1(a).5. GOLD LEAF ELECTROSCOPE (GLE)

A gold leaf electroscope (GLE) is an instrument which is used for detecting the presence of electric charge and its polarity (*i.e.*, ± sign of charge). The instrument can also be used for measuring potential difference.

The essential parts of a gold leaf electroscope are shown in Fig. 1(a).3. LL are two extremely thin gold foils attached to lower end of a metal rod R fitted in a glass jar G through an insulating stopper S of cork or rubber etc. D is a metal disc at the free end of the metal rod. The sensitivity of the instrument is increased by pasting two tin foils F, F on the inner side of glass jar opposite to the gold leaves.

As the gold leaves are extremely thin conducting foils which have low mass per unit area and are flexible, therefore, they respond very quickly to small electrostatic forces. Thin aluminium foils can also serve the same purpose. When a charged rod is touched with the metal disc D, the same charge is transferred to the gold leaves through the metal rod. The leaves repel eachother and diverge as shown in Fig. 1(a).3. By measuring the divergence of leaves, the amount of charge on the body can be estimated.

FIGURE 1(a).3



1(a).6. ORIGIN OF ELECTRIC CHARGE IN ELECTROSTATICS

It is known that all matter is made up of atoms and/or molecules, the basic unit being an atom. We also know that every atom consists of a central core called the *atomic nucleus,* around which negatively charged electrons revolve in circular orbits. Every atom is electrically neutral, containing as many electrons as the number of protons in the nucleus. *Thus, even though normally, the materials are electrically neutral, they do contain charges, but their charges are exactly balanced.*

The vast amount of charge in an object is usually hidden as the object contains equal amounts of positive charge and negative charge. With such an equality or balance of charge, the object is said to be electrically neutral, i.e., it contains no net charge.

If the positive and negative charges are not in balance, then there is a net charge. ***Thus, an object is charged if it has a charge imbalance or some net charge.*** Hence, to electrify or charge a neutral body, we need to add or remove one kind of charge. When we say that a body is charged, we always refer to ***excess charge or deficit charge.***

In solids, some of the electrons are less tightly bound in the atom. These are the charges, which are transferred from one body to the other.

When we rub two insulating substances against each other, we provide energy to overcome friction between them. This energy is used in removing electrons from one substance and transferring them to the other. The transfer takes place from the material in which electrons are held less tightly (with lower work function) to the material in which electrons are held more tightly (with higher work function), *i.e.,* ***electrons are transferred from the material whose work function is lower to the material whose work function is higher.*** Consequently, the material which loses electrons acquires a positive charge and material which gains electrons acquires an equal negative charge. For example, when we rub a glass rod with silk, electrons are transferred from glass rod to silk. The glass rod becomes positively charged and silk acquires an equal negative charge. Thus, *charging by rubbing is due to actual transfer of electrons.*

The cause of charging is actual transfer of electrons from one material to the other. The insulating material with lower work function loses electrons and becomes positively charged and vice-versa.

Further, as an electron has a mass, howsoever small it may be, therefore *there does occur some change in mass on charging. A positively charged body has lost some electrons and hence its mass reduces slightly. On the other hand, a negatively charged body has gained some electrons and hence its mass increases slightly.*

Note that in rubbing two insulating bodies, the number of electrons that are transferred, is a very small fraction of the total number of electrons in the material bodies. Hence, the charge acquired by friction is a very small fraction ($\approx 10^{-6}$ coulomb) of the total positive and negative charge content of the bodies.

Further, as only the less tightly bound electrons in a material body can be transferred from it to another by rubbing, only under suitable conditions, we have to stick to certain pairs of materials to observe charging on rubbing the bodies.

In Table 1(a). 1, we have listed the pairs of objects which get charged on rubbing against each other. They have been divided into two classes, one acquiring positive charge and the other acquiring negative charge on rubbing.

TABLE 1(a).1 **Objects acquiring two kinds of charges on rubbing**

POSITIVE CHARGE	NEGATIVE CHARGE
1. Glass rod	1. Silk cloth
2. Fur or woolen cloth	2. Ebonite, Amber, Rubber rod
3. Woolen coat	3. Plastic seat
4. Woolen carpet	4. Rubber shoes
5. Nylon or Acetate	5. Cloth
6. Dry hair	6. Comb

Obviously, any two charged objects, in the same column repel each other and any two charged objects from different columns attract each other.

Further, different substances have been arranged in a series, called **Triboelectric Series.** When any two of the substances in series are rubbed together, the one occurring earlier in the series acquires positive charge and the other occurring later in series acquires negative charge. Some of the substances in triboelectric series are : 1. Fur 2. Flannel 3. Wool 4. Glass 5. Paper 6. Cotton 7. Silk 8. Wood 9. Metals 10. Rubber 11. Orlon 12. Polyethylene 13. Teflon 14. Ebonite, etc.

Thus glass acquires a positive charge when rubbed with silk and it acquires a negative charge when rubbed with fur.

1(a).7. CHARGING BY INDUCTION

We know that a body can be charged by putting it in contact with another charged body either directly or by means of a conductor. For example, when a charged ebonite rod is in contact with a pith ball or connected to it by a copper wire, it transfers some of its negative charge to the pith ball. ***This is charging by conduction.***

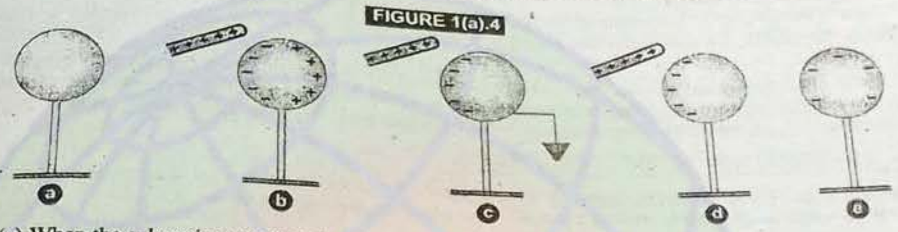
In charging by induction, a charged body A imparts to another body B, some charge of opposite sign without any actual contact between A and B. Obviously, body A shall not lose any charge as it is not in contact with B.

The steps involved in charging a metallic sphere by induction are shown in Fig. 1(a).4.

(*a*) To begin with, a metallic sphere on an insulating stand is uncharged, Fig. 1(a).4(a).

(*b*) When a charged glass rod is brought near the uncharged metallic sphere, free electrons of the sphere are attracted and start piling up at the near end. This end therefore, becomes negatively charged and the farther end of the sphere becomes positively charged due to deficit of electrons, Fig. 1(a).4(b). The redistribution of charge is almost instantaneous and stops as soon as net force on free electrons in the metallic sphere becomes zero.

FIGURE 1(a).4



(c) When the sphere is grounded, *i.e.*, it is connected to earth by a conducting wire, electrons flow from the ground to the sphere and neutralise the positive charge on the farther end of the sphere. The negative charge at the near end of the sphere remains bound there due to attractive force of glass rod, Fig. 1(a).4(c).

(d) When the sphere is disconnected from the ground, the negative charge continues to be held on the near end, Fig. 1(a).4(d).

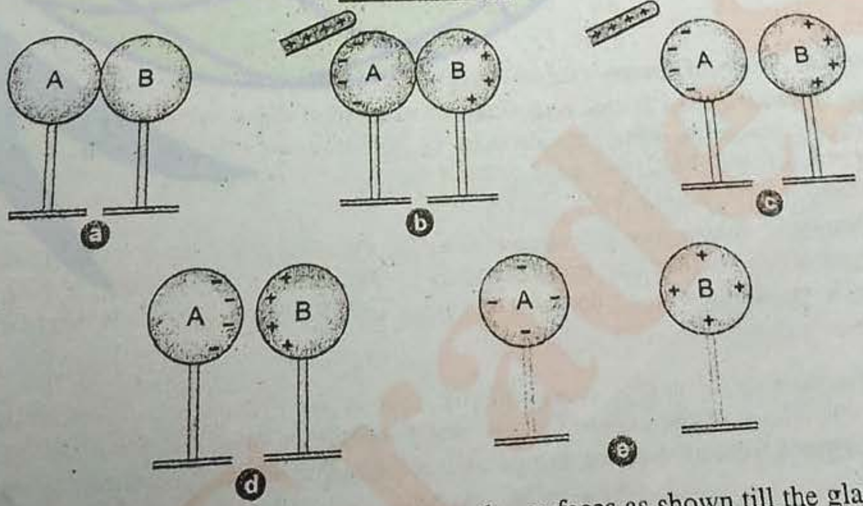
(e) When the glass rod is removed, the negative charge spreads uniformly over the sphere, Fig. 1(a).4(e).

Similar steps are involved when a negatively charged rod is used for charging the sphere positively by induction.

Let us now understand **how we charge two spheres by induction.** Fig. 1(a).5(a) shows two metal spheres A and B supported on insulating stands, held in contact with eachother.

Let a positively charged glass rod be brought near the sphere A. Free electrons in both the spheres are attracted towards the rod. Therefore, left surface of left sphere A has an excess of negative charge and right surface of right sphere B has an excess of positive charge. *Note that all the electrons in the spheres have not accumulated on the left surface of sphere A.* This is because as negative charge starts building up at the left face of A, further electrons are repelled by these. *An equilibrium is reached almost instantly under the action of force of attraction of the rod and the force of repulsion due to the accumulated negative charges.* Fig. 1(a).5(b) shows this equilibrium situation.

FIGURE 1(a).5



Further, the accumulated charges would remain on the surfaces as shown till the glass rod is held near the sphere A. If the rod were removed, the charges would return to their original neutral state in the absence of any outside force.

Separate the spheres A and B by a small distance, while the glass rod is still held near the sphere A. The two spheres carry opposite charges as shown in Fig. 1(a).5(c). They attract each other.

Remove the glass rod. The status of charges on the spheres is shown in Fig. 1(a).5(d).

When the spheres are now separated widely, the charges on them get uniformly distributed as shown in Fig. 1(a).5(e).

This is how two metal spheres get oppositely charged by induction. *Note that in this process of electric induction, the positively charged glass rod does not lose any charge. This is contrary to charging by conduction, i.e., charging by actual contact where the charged glass rod loses some charge.*

1(a).8. QUANTIZATION OF ELECTRIC CHARGE

The quantization of electric charge is the property by virtue of which all free charges are integral multiple of a basic unit of charge of an electron/proton, represented by e.

Thus, charge q of a body is always given by ...(1)

$$\boxed{q = ne}$$

where n is any integer, positive or negative. The basic unit of charge is the charge that an electron or proton carries. By convention, charge on an electron is taken to be negative. Therefore, charge on an electron is written as $(-e)$ and charge on a proton is $(+e)$.

The value of the basic unit of charge or elementary charge is ...(2)

$$\boxed{e = 1{\cdot}6 \times 10^{-19} \text{ coulomb}}$$

It is one of the important constants of nature.

If a body contains n_1 electrons and n_2 protons, the total amount of charge on the body is

$$q = n_2\,(e) + n_1\,(-e) = (n_2 - n_1)\,e$$

As n_1, n_2 are integers, their difference must also be an integer. Thus, the charge on anybody is always an integral multiple of e, and can be increased or decreased also in steps of e.

Thus, any charged body or charged particle can possess charge equal to $\pm 1\,e$, $\pm 2\,e$, $\pm 3\,e$ and so on*, *i.e.*, the possible values of charge are

$$q = \pm e = \pm 1 \times 1{\cdot}6 \times 10^{-19}\,\text{C} = \pm 1{\cdot}6 \times 10^{-19}\,\text{C}$$
$$q = \pm 2\,e = \pm 2 \times 1{\cdot}6 \times 10^{-19}\,\text{C} = \pm 3{\cdot}2 \times 10^{-19}\,\text{C}$$
$$q = \pm 3\,e = \pm 3 \times 1{\cdot}6 \times 10^{-19}\,\text{C} = \pm 4{\cdot}8 \times 10^{-19}\,\text{C}$$

and so on. The values of charge lying in between these values are not possible.

The cause of quantization is that only integral number of electrons can be transferred from one body to another. For example, when one electron is transferred, the charges acquired by the two bodies will be $q = \pm 1e = \pm 1{\cdot}6 \times 10^{-19}$ C. Similarly, when n electrons are transferred, the charges acquired by the two bodies will be $q = \pm ne = \pm n \times 1{\cdot}6 \times 10^{-19}$ C.

The quantization of charge was first suggested by the experimental laws of electrolysis discovered by **Faraday.** It was actually demonstrated experimentally by **Millikan** in 1912. Thus, quantization of charge is an experimentally verified law in all domains of nature. Like charge ; energy and angular momentum are also quantized.

RETAIN IN MEMORY Quantization of charge is meaningful only at the microscopic level, where the charges involved are of the order of a few tens or hundreds of e, *i.e.*, they can be counted. Such charges appear in discrete lumps and quantization of charge cannot be ignored.

---

*Recent discoveries have shown that neutron and proton are made up of **quarks**, which carry charges $\pm\left(\frac{2}{3}e\right)$ and $\pm\left(\frac{1}{3}e\right)$, but these quarks do not have free existence. Therefore, the basic unit of charge which has independent existence is e only.

RETAIN IN MEMORY However, at the *macroscopic level*, we deal with charges of a few microcoulomb. A charge of magnitude 1 μC contains electrons whose number $n = \frac{q}{e} = \frac{1 \times 10^{-6}\,\text{C}}{1{\cdot}6 \times 10^{-19}\,\text{C}} \approx 10^{13}$, which is very large. At this scale, the fact that charge can increase or decrease only in units of e is not visible. The grainy nature of charge is lost and it appears to be continuous. The situation can be compared with the geometrical concepts of points and lines. A dotted line, viewed from a distance, appears continuous to us, but is not continuous in reality. As many points very close to one another normally give an impression of a continuous line, many small charges taken together appear as a continuous charge distribution. Hence at macroscopic level, quantization of charge has no practical consequence, and it can be ignored.

Sample Problem **Is a charge of $5{\cdot}8 \times 10^{-18}$ C possible ?**

Sol. From $q = n\,e$, $n = \frac{q}{e} = \frac{5{\cdot}8 \times 10^{-18}}{1{\cdot}6 \times 10^{-19}} = \mathbf{36{\cdot}25}$

As n is not an integer, this value of charge is not possible.

1(a).9. ADDITIVITY OF CHARGE

Additivity of charge is a property by virtue of which total charge of a system is obtained simply by adding algebraically all the charges present anywhere on the system.

It means charges are scalars like the mass of a body and are added by simple laws of Mathematics. If a system contains n charges $q_1, q_2, q_3, \ldots, q_n$, then the total charge of the system is

$$q = q_1 + q_2 + q_3 + \ldots + q_n.$$

Charge has magnitude only, but no direction, similar to the mass. However, mass of a body is always positive, but charge can be either positive or negative. Therefore, ***proper signs have to be used while adding the charges in a system.*** For example, if a system contains charge $+q, -2q, +3q$ and $+5q$, then the total charge of the system is $= +q - 2q + 3q + 5q = +7q$

1(a).10. CONSERVATION OF CHARGE

Conservation of charge is the property by virtue of which total charge of an isolated system always remains constant or conserved.

Within an isolated system consisting of many charged bodies, charges may get redistributed due to interactions among the bodies, but the total charge of the system shall remain the same.

For example, when we rub two insulating bodies, what one body gains in charge, the other body loses the same amount of charge. Thus, ***it is not possible to create or destroy net charge carried by any isolated system.*** However, charge carrying particles may be created or destroyed in a process. For example, a neutron turns into a proton and an electron. The proton and electron thus created have equal and opposite charges. The total charge is zero before and after the creation. Thus, ***charges can be created or destroyed in equal and unlike pairs only.***

Following examples illustrate the property of conservation of charge.

(*i*) In the phenomenon of **pair production,** a γ ray photon materialises into an electron and a positron having total charge $-e + e = 0$, which is the initial charge on a photon.

$$\gamma = e^- + e^- \qquad \text{(pair production)}$$

(*ii*) In **annhilation of matter,** an electron and a positron annhilate eachother to produce two γ-ray photons with zero charge. Charge is thus conserved.

$$e^- + e^+ = \gamma + \gamma \qquad \text{(annhilation)}$$

(*iii*) In all **radioactive decays,** charge number is always conserved.

For example, in radioactive decay of U-238, the nucleus is transformed into Th-234 with the emission of an alpha particle, which is a helium nucleus, *i.e.*,

$$_{92}U^{238} \longrightarrow {}_{90}Th^{234} + {}_{2}He^{4} \qquad \text{(radioactive decay)}$$

(*iv*) In all **nuclear transformations,** charge number is always conserved. For example :

$$_{7}N^{14} + {}_{2}He^{4} \longrightarrow {}_{8}O^{17} + {}_{1}H^{1}$$

Note that in applying the conservation of charge principle, we must add the charges algebraically, with regard to their signs.

1(a).11. COMPARISON OF CHARGE AND MASS

We are familiar with role of mass in gravitation, and we have just studied some features of electric charge. We can compare the two as shown in Table 1(a). 2.

TABLE 1(a).2. **Comparison of charge and mass**

CHARGE	MASS
1. Electric charge on a body may be positive, negative or zero.	1. Mass of a body is a positive quantity.
2. Charge carried by a body does not depend upon velocity of the body.	2. Mass of a body increases with its velocity as $m = \frac{m_0}{\sqrt{1 - v^2/c^2}}$, where c is velocity of light in vacuum, m is the mass of the body moving with velocity v and m_0 is rest mass of the body.
3. Charge is quantized.	3. The quantization of mass is yet to be established.
4. Electric charge is always conserved.	4. Mass is not conserved as it can be changed into energy and vice-versa.
5. Force between charges can be attractive or repulsive, according as charges are unlike or like charges.	5. The gravitational force between two masses is always attractive.
6. The force between two charges follows inverse square law.	6. The force between two masses also follows inverse square law.
7. Charge cannot exist without mass.	7. Mass can exist without charge.
8. Unit of charge is a derived unit (1 C = 1 As).	8. Unit of mass is a fundamental unit.
9. An accelerated charge emits radiation.	9. Accelerated mass emits no radiation.

1(a).12. COULOMB'S LAW

Coulomb performed several experiments to measure the force between charged bodies. When the linear sizes of charged bodies are much smaller than the distance separating them, the size may be ignored, and the charged bodies may be treated as *point charges.*

According to **Coulomb's law,**

The force of interaction between any two point charges is directly proportional to the product of the charges and inversely proportional to the square of the distance between them.

The force acts always along the line joining the two charges.

Suppose two point charges q_1 and q_2 are separated in vacuum by a distance r.

According to Coulomb's law, $F \propto \frac{|q_1||q_2|}{r^2}$ or $\boxed{F = \frac{k\,|q_1||q_2|}{r^2}}$ ...(1)

where k is **electrostatic force constant.**

The value of electrostatic force constant k depends on the nature of medium separating the charges, and on the system of units.

When the charges are situated in free space (air/vacuum), then in cgs system, $k = 1$.

In SI, $k = 9 \times 10^9 \text{ N } m^2 \text{ C}^{-2}$

We write,

$$\boxed{k = \frac{1}{4\pi\epsilon_0}} \quad ...(2)$$

where ϵ_0 is called ***absolute electrical permittivity of the free space.***

$\therefore$ From (1), the magnitude of force is

$$\boxed{F = \frac{1}{4\pi\epsilon_0} \frac{|q_1||q_2|}{r^2}} \quad ...(3)$$

Units, Dimensions and Value of ϵ_0

From (3), $\epsilon_0 = \frac{1}{4\pi F} \frac{q_1 q_2}{r^2}$

As SI unit of charge is coulomb (C), therefore,

$$\text{Units of } \epsilon_0 = \frac{1}{\text{N}} \frac{\text{C.C}}{\text{m}^2} = \text{C}^2\text{N}^{-1}\text{m}^{-2}$$

$$\text{Dimensions of } \epsilon_0 = \frac{(\text{AT})(\text{AT})}{(\text{MLT}^{-2})(\text{L}^2)} = [\text{M}^{-1}\text{ L}^{-3}\text{ T}^4\text{ A}^2] \quad ...(4)$$

From (2), $k = \frac{1}{4\pi\epsilon_0}$ or $\epsilon_0 = \frac{1}{4\pi k}$

$$\therefore \quad \epsilon_0 = \frac{1}{4 \times 3{\cdot}14 \times 9 \times 10^9}$$

$$\boxed{\epsilon_0 = 8{\cdot}85 \times 10^{-12} \text{ C}^2\text{N}^{-1} \text{ m}^{-2}} \quad ...(5)$$

Note that permittivity is a measure of how an electric field affects and is affected by a medium.

1(a).13. COULOMB'S LAW IN VECTOR FORM

As stated already, according to Coulomb's law, the force of interaction F between any two point charges q_1 and q_2 is directly proportional to the product of the charges, and inversely proportional to the square of the distance (r) between them. *i.e.*

$$F \propto \frac{|q_1||q_2|}{r^2}$$

$$\boxed{F = \frac{k\,|q_1||q_2|}{r^2}}$$

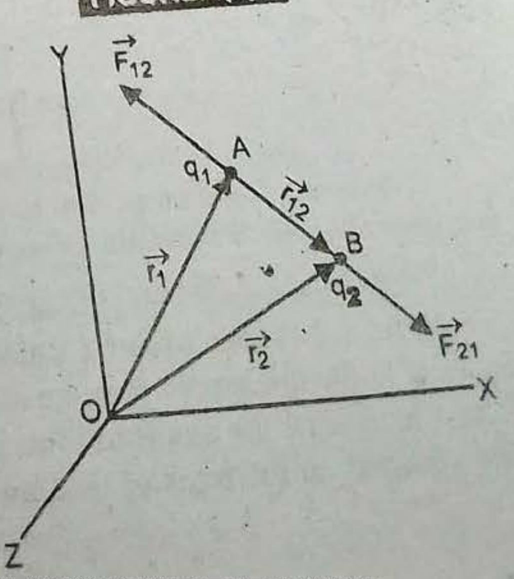
where k is electrostatic force constant.

As force is a vector, it is better to write Coulomb's law in the vector notation. In Fig. 1(*a*).6, let

$\vec{r}_1 = \overrightarrow{OA}$ = position vector of charge q_1

$\vec{r}_2 = \overrightarrow{OB}$ = position vector of charge q_2

FIGURE 1(a).6



$\therefore$ The vector leading from q_1 to q_2 is ...(6)

$$\overrightarrow{AB} = \vec{r}_{12} = \vec{r}_2 - \vec{r}_1 \qquad ...(7)$$

In the same way, vector leading from q_2 to q_1 is

$$\overrightarrow{BA} = \vec{r}_{21} = \vec{r}_1 - \vec{r}_2$$

The magnitude of $\vec{r}_{12}$ is r_{12} and magnitude of $\vec{r}_{21}$ is r_{21}.

As the direction of a vector is specified by a unit vector along the vector, we define

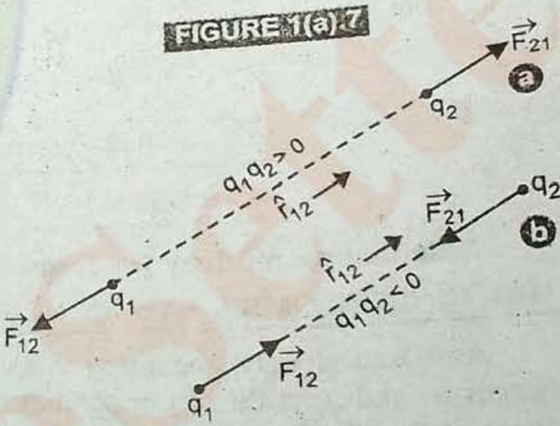
$$\hat{r}_{12} = \frac{\vec{r}_{12}}{r_{12}} \quad \text{and} \quad \hat{r}_{21} = \frac{\vec{r}_{21}}{r_{21}}$$

If $\vec{F}_{12}$ = force on q_1 due to q_2, and $\vec{F}_{21}$ = force on q_2 due to q_1, then as is clear from Fig. 1(a).6, Coulomb's force law between two point charges q_1 and q_2 located at $\vec{r}_1$ and $\vec{r}_2$ in vacuum is expressed

as $$\vec{F}_{21} = \frac{1}{4\pi\epsilon_0}\frac{q_1 q_2}{AB^2}, \text{ along AB}$$

or $$\boxed{\vec{F}_{21} = \frac{1}{4\pi\epsilon_0}\frac{q_1 q_2}{r_{12}^2}\times\hat{r}_{12}} = \frac{1}{4\pi\epsilon_0}\frac{q_1 q_2}{r_{12}^3}\times\vec{r}_{12} = \frac{1}{4\pi\epsilon_0}\frac{q_1 q_2(\vec{r}_2-\vec{r}_1)}{|\vec{r}_2-\vec{r}_1|^3} \qquad ...(8)$$

FIGURE 1(a).7



It should be clearly understood, that eqn. (8) is valid for any sign of q_1 and q_2, whether positive or negative.

If q_1, q_2 are of same sign (either both positive or both negative) ; $q_1 q_2 > 0$; $\vec{F}_{21}$ is along $\vec{r}_{12}$, which denotes repulsion for like charges ; Fig. 1(a).7(a).

If q_1 and q_2 are of opposite sign (*i.e.*, one is positive and other is negative), $q_1 q_2 < 0$; $\vec{F}_{21}$ is along $-\hat{r}_{12}$, which denotes attraction between unlike charges, Fig. 1(a).7(b).

Thus, eqn. (8) takes care of both the cases of like and unlike charges correctly.

The force $\vec{F}_{12}$, on charge q_1 due to charge q_2 is obtained from eqn. (8), by simply interchanging 1 and 2, *i.e.*,

$$\boxed{\vec{F}_{12} = \frac{1}{4\pi\epsilon_0}\frac{q_1 q_2}{r_{12}^2}\times\hat{r}_{21} = -\vec{F}_{21}.} \qquad ...(9)$$

Therefore, force on q_1 due to q_2 is equal and opposite to the force on q_2 due to q_1. Thus, *Coulomb's law obeys Newton's third law of motion.*

Note that eqns. (8) and (9) give us the forces between two charges q_1 and q_2 in vacuum only.

Notes : 1. More about Coulomb's Law. Coulomb's law is universal. The force which binds th electrons to the nucleus to form an atom is calculated from this law. The same law applies to van der wa forces which unite the atoms to form molecules. The three states of matter viz. solids, liquids and gases a also explained on the basis of this law.

2. Coulomb's law has been verified over distances ranging from nuclear dimensions ($\approx 10^{-15}$ m) to macroscopic distances ($\approx 10^{18}$ m). Further, the law is applicable only to point charges. These are the limitations of Coulomb's Law.

3. Coulomb's law of electrostatic force between two charges corresponds to Newton's law of gravitational force between two masses, *i.e.*, $F = \frac{G m_1 m_2}{r^2}$, where G is universal gravitational constant $= 6{\cdot}67 \times 10^{-11}$ Nm^2/kg^2. This value is much smaller compared to the value of electrostatic force constant, $k = 9 \times 10^9$ Nm^2/C^2. That is why electrostatic forces are far more stronger than the gravitational forces. This is evident from the fact that a charged glass rod attracts a piece of paper against the gravitational pull of earth on the paper.

Further, whereas electrostatic force may be attractive or repulsive depending on the sign of charges, gravitational force is always attractive.

Sample Problem **How is force between two charges affected when each charge is doubled and distance between them is also doubled ?**

Sol. As $F \propto \frac{|q_1||q_2|}{r^2}$

$\therefore$ F becomes $\frac{(2)\,(2)}{(2)^2}$ time = 1 time, *i.e.*, **force remains the same.**

1(a).14. UNITS OF CHARGE

The SI unit of charge is coulomb.

We can define unit charge from eqn. (3). Suppose $q_1 = q_2 = q$; $r = 1$ m and $F = 9 \times 10^9$ N

From (3), $9 \times 10^9 = 9 \times 10^9 \, \frac{q\,q}{1^2}$ or $q^2 = 1$ or $q = \pm 1$ (coulomb), Hence,

Unit charge in SI (i.e. one coulomb) is that much charge which when placed in vacuum at a distance of one metre from an equal and similar charge would repel it with a force of 9×10^9 newton.

The cgs unit of charge is **1 electrostatic unit (e.s.u.)** of charge or **stat coulomb.**

It is also called one **franklin** (Fr), in honour of an American scientist Franklin for his contributions to the study of electrostatics.

As charge on an electron is $4{\cdot}8 \times 10^{-10}$ stat coulomb, therefore,

$$1{\cdot}6 \times 10^{-19} \text{ coulomb} = 4{\cdot}8 \times 10^{-10} \text{ stat coulomb} \quad \text{or} \quad 1 \text{ coulomb} = \frac{4{\cdot}8 \times 10^{-10}}{1{\cdot}6 \times 10^{-19}} \text{ stat coulomb}$$

$$\boxed{1 \text{ coulomb} = 3 \times 10^9 \text{ stat coulomb.}} \quad ...(10)$$

Yet another unit of charge is **electromagnetic unit (e.m.u.) of charge**, where

$$\boxed{1 \text{ e.m.u. of charge} = 3 \times 10^{10} \text{ e.s.u. of charge (stat coulomb)} = 10 \text{ coulomb.}}$$

1(a).15. DIELECTRIC CONSTANT OR RELATIVE ELECTRICAL PERMITTIVITY

When the charges are situated in a medium other than free space (vacuum or air), the force between them is given by

$$F_m = \frac{1}{4\pi\epsilon} \times \frac{q_1 q_2}{r^2} \quad ...(11)$$

where ϵ is called ***absolute electrical permittivity of the intervening medium.***

The force betwen the same two charges held the same distance apart in vacuum is

$$F_0 = \frac{1}{4\pi\epsilon_0} \times \frac{q_1 q_2}{r^2} \quad ...(12)$$

Dividing (12) by (11), we get

$$\boxed{\frac{F_0}{F_m} = \frac{\epsilon}{\epsilon_0} = \epsilon_r \text{ or } K} \quad ...(13)$$

where ϵ_r is called **relative electrical permittivity** of the medium. It is also called **dielectric constant** of the medium and is denoted by K.

From (13), we may define

Dielectric constant of a medium is the ratio of absolute electrical permittivity of the medium to the absolute electrical permittivity of free space. Also,

Dielectric constant of a medium may be defined as the ratio of force of interaction between two point charges separated by a certain distance in air/vacuum to the force of attraction/repulsion between the same two point charges, held the same distance apart in the medium.

The value of K depends only on the nature of medium.

For example, for vacuum, $K = 1{\cdot}00000$; for air, $K = 1{\cdot}006$; for hydrogen, $K = 1{\cdot}00026$; for glass, $K = 3$ to 4 ; for mica, $K = 3$ to 6 ; for water, $K = 81$ and so on.

From (13), $\quad \epsilon = \epsilon_0 K$

Using it in (11), $\quad \boxed{F_m = \frac{1}{4\pi\epsilon_0 K} \frac{q_1 q_2}{r^2} = \frac{F_0}{K}}$

Thus, force between two given charges held a given distance apart in water (K = 81) is only 1/81 of the force between them in air/vacuum.

1(a).16. FORCES BETWEEN MULTIPLE CHARGES : PRINCIPLE OF SUPERPOSITION

The mutual electric force between two charges is given by Coulomb's law. However, when we have to calculate the force on a charge due to several stationary charges, we use the principle of superposition in addition to Coulomb's law.

According to **superposition principle,** ***total force on any charge due to a number of other charges at rest is the vector sum of all the forces on that charge due to other charges, taken one at a time. The forces due to individual charges are unaffected by the presence or absence of other charges.***

Suppose charges $q_1, q_2, q_3 \ldots q_n$ are situated at points with position vectors $\vec{r_1}, \vec{r_2}, \vec{r_3}, \ldots \vec{r_n}$ respectively w.r.t. the origin O of the rectangular co-ordinate system XYZ.

In general, total force $\vec{F_0}$ on a test charge q_0 at position $\vec{r_0}$ due to all the n discrete charges can be written as

$$\boxed{\vec{F_0} = \vec{F_{01}} + \vec{F_{02}} + \vec{F_{03}} \ldots + \vec{F_{0n}}} \quad ...(14)$$

The component forces are shown in Fig. 1(a).8.

Here, $\vec{F_{01}}$ = force on q_0 due to q_1,

$\vec{F_{02}}$ = force on q_0 due to q_2 and so on,

$\vec{F_{0n}}$ = force on q_0 due to q_n.

also explained on the basis of

According to Coulomb's law, $\vec{F}_{01} = \frac{1}{4\pi\epsilon_0}\frac{q_0 q_1}{r_{10}^2}\hat{r}_{10}$

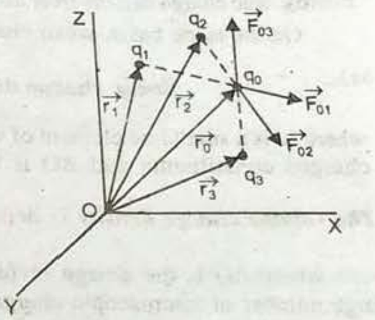
This is the force on q_0 due to q_1, even though other charges are present.

Similarly, force on q_0 due to q_2, even when other charges are present is given by

$$\vec{F}_{02} = \frac{1}{4\pi\epsilon_0}\frac{q_0 q_2}{r_{20}^2}\hat{r}_{20}$$

and so on
$$\vec{F}_{0n} = \frac{1}{4\pi\epsilon_0}\frac{q_0 q_n}{r_{n0}^2}\hat{r}_{n0}$$

FIGURE 1(a).8



Putting these values in eqn. (14), we get total force on charge q_0 as

$$\vec{F}_0 = \frac{1}{4\pi\epsilon_0}\left[\frac{q_0 q_1}{r_{10}^2}\hat{r}_{10} + \frac{q_0 q_2}{r_{20}^2}\hat{r}_{20} + \frac{q_0 q_3}{r_{30}^2}\hat{r}_{30} + \dots + \frac{q_0 q_n}{r_{n0}^2}\hat{r}_{n0}\right]$$

$$\boxed{\vec{F}_0 = \frac{1}{4\pi\epsilon_0}\sum_{i=1}^{i=n}\frac{q_0 q_i}{r_{i0}^2}\hat{r}_{i0}}$$

$$\vec{F}_0 = \frac{q_0}{4\pi\epsilon_0}\sum_{i=1}^{i=n}\frac{q_i}{r_{i0}^3}\vec{r}_{i0}$$

$$\boxed{\vec{F}_0 = \frac{q_0}{4\pi\epsilon_0}\sum_{i=1}^{i=n}\frac{q_i}{|\vec{r}_0 - \vec{r}_i|^3}(\vec{r}_0 - \vec{r}_i)} \quad \dots(15)$$

The direction of net force $\vec{F}_0$ on charge q_0 due to n discrete charges can be determined using *polygon law of vectors.*

RETAIN IN MEMORY We can use superposition principle for computing (*i*) net force (*ii*) net field (*iii*) net flux (*iv*) net potential as well as net potential energy at the observation point P due to any configuration of charges.

1(a).17. CONTINUOUS CHARGE DISTRIBUTION

As charge can exist only as integral multiple of basic charge (e), therefore, charge distribution is always discrete, on account of atomicity of charge. However, it is impractical to work in terms of discrete charges always. For example, on the surface of a charged conductor, we cannot specify the charge distribution in terms of the locations of the microscopic charged constituents. However, we can consider a small area element ΔS on the surface of the conductor. This area element is very small on the macroscopic scale, but big enough to include a very large number of electrons. If ΔQ is the amount of charge on this element, we define **surface charge density** (σ) at the area element by $\sigma = \frac{\Delta Q}{\Delta S}$

We can repeat the process at different points on the surface of the conductor and thus arrive at a continuous function σ, called the surface charge density. *At the microscopic level, charge distribution is **discontinuous**,* as there are discrete charges separated by intervening space, where there is no charge.

Therefore, σ represents *macroscopic surface charge density* which is a smoothed out average of the microscopic charge density over an area element ΔS, which is small macroscopically but large microscopically.

On the same basis, when charge is distributed along a line, straight or curved, we define

$$\textbf{linear charge density, } \lambda = \frac{\Delta Q}{\Delta l}$$

where Δl is a small line element of wire on the macroscopic scale that includes a large number of microscopic charged constituents and ΔQ is the charge contained in that line element. The units of λ are C/m.

The volume charge density is defined in a similar manner as $\rho = \frac{\Delta Q}{\Delta V}$,

where ΔQ is the charge included in the macroscopically small volume element ΔV that includes a large number of microscopic charged constituents. The units of ρ are C/m^3.

Note that the notion of continuous charge distribution is similar to the continuous mass distribution in mechanics. For example, when we talk of density of a liquid, we are referring to its macroscopic density treating it as a continuous fluid and ignoring its discrete molecular constitution.

1(a).18. FORCE DUE TO CONTINUOUS DISTRIBUTION OF CHARGES

The force due to a continuous charge distribution can be obtained in almost the same way as for a system of discrete charges.

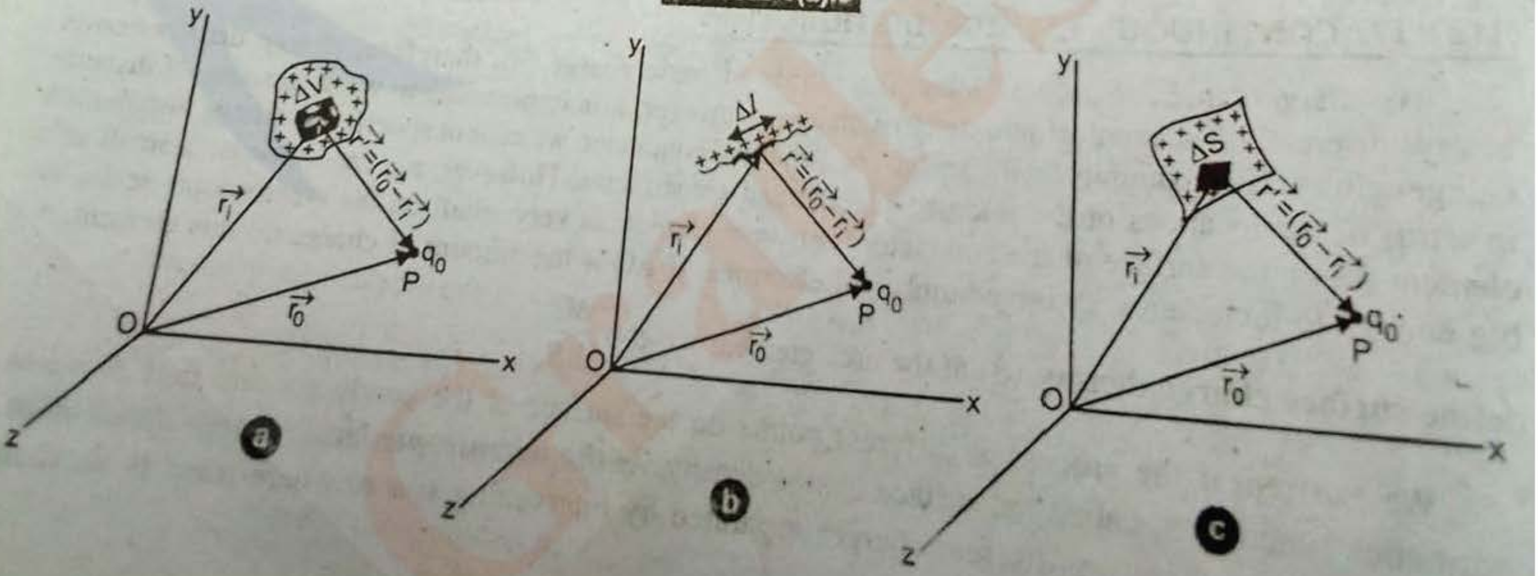
Suppose a continuous charge distribution in space has a volume charge density ρ. With respect to any suitably chosen origin O, let the position vector of any point in the charge distribution be $\vec{r_i}$. The volume charge density ρ is a function of $\vec{r_i}$, *i.e.*, it may vary from point to point. Divide the charge distribution into small volume elements of size ΔV. Therefore, charge in this volume element is $\Delta Q = \rho \cdot \Delta V$

Consider any general point P inside or outside the charge distribution with position vector $\overrightarrow{OP} = \vec{r_0}$. Using Coulomb's law, force due to charge element ΔQ on a small test charge q_0 at P is

$$d\vec{F} = \frac{1}{4\pi\epsilon_0}\frac{q_0(\Delta Q)}{r'^2}\hat{r'} = \frac{q_0}{4\pi\epsilon_0}\frac{\rho\Delta V}{r'^2}\hat{r'}$$

where r' is the distance between the charge element and point P ; and $\hat{r'}$ is unit vector directed from charge element to the point P. As is clear from Fig. 1(a).9(a), $\vec{r'} = (\vec{r_0} - \vec{r_i})$

FIGURE 1(a).9



By the superposition principle, total force due to entire volume charge distribution is obtained by summing over the forces due to different volume elements.

$$\vec{F} = \frac{q_0}{4\pi\epsilon_0} \sum_{\text{all}\,\Delta V} \frac{\rho\,\Delta V}{r'^2}\,\hat{r}' \qquad \text{...(16)}$$

When $\Delta V \rightarrow 0$, the sum becomes an integral and total force can be written as

$$\boxed{\vec{F} = \frac{q_0}{4\pi\epsilon_0} \int_V \frac{\rho\,\Delta V}{r'^2}\,\hat{r}'} \qquad \text{...(17)}$$

Proceeding as above, we can write total force due to *continuous line distribution of charge* as shown in Fig. 1(a).9(b) as

$$\boxed{\vec{F} = \frac{q_0}{4\pi\epsilon_0} \int_L \frac{\lambda\,\Delta l}{r'^2}\,\hat{r}'} \qquad \text{...(18)}$$

And total force due to *continuous surface distribution of charge* as shown in Fig. 1(a).9(c) as

$$\boxed{\vec{F} = \frac{q_0}{4\pi\epsilon_0} \int_S \frac{\sigma\,ds}{r'^2}\,\hat{r}'} \qquad \text{...(19)}$$

SOLVED EXAMPLES

TYPE A EXAMPLES BASED ON QUANTIZATION OF CHARGE

Formula used.	$q = \pm ne$
Units used.	q and e are in coulomb, n is a number
Standard value.	$e = 1{\cdot}6 \times 10^{-19}$ coulomb

Example 1 **Which is bigger, a coulomb or charge on an electron ? How many electronic charges form one coulomb of charge ?** **(Pb. Board 2011)**

Solution. A coulomb of charge is bigger than the charge on an electron.

Magnitude of charge on one electron, $e = 1{\cdot}6 \times 10^{-19}$ coulomb

Number of electronic charges in one coulomb, $n = \frac{q}{e} = \frac{1}{1{\cdot}6 \times 10^{-19}} = 0{\cdot}625 \times 10^{19}$

Example 2 **How much positive and negative charge is there in a cup of water ?**

NCERT Solved Example

Solution. Suppose the cup contains 250 cc of water (H_2O).

Mass of 250 cm^3 of water = 250 g.

Molecular weight of water = 2 + 16 = 18

Number of molecules in 18 g of water = $6{\cdot}023 \times 10^{23}$

Number of molecules in 250 g of water $= \frac{6{\cdot}023 \times 10^{23} \times 250}{18}$

As each molecule of water contains 10 electrons, therefore, total number of electrons,

$$n = \frac{10 \times 6.023 \times 10^{23} \times 250}{18} = 8.365 \times 10^{25}$$

As $q = ne$, therefore, $q = 8.365 \times 10^{25} \times 1.6 \times 10^{-19}\ C = \mathbf{1.338 \times 10^7\ C}$

Example 3 **If a body gives out 10^9 electrons every second, how much time is required to get a total charge of 1 C from it ?** **NCERT Solved Example**

Solution. Here, $n = 10^9$ electrons/sec

Charge given/sec, $q = ne = 10^9 \times 1.6 \times 10^{-19}\ C = 1.6 \times 10^{-10}\ C$

Total charge, $Q = 1\ C$

$$\therefore \text{ Time required} = \frac{Q}{q} = \frac{1}{1.6 \times 10^{-10}} \text{ sec} = 6.25 \times 10^9\ s = \frac{6.25 \times 10^9}{3600 \times 24 \times 365} \text{ year} = \mathbf{198.18 \text{ year}}$$

Example 4 **A metal sphere has a charge of $-6.5\ \mu C$. When 5×10^{13} electrons are removed from the sphere, what would be the net charge on it?**

Solution. Here, $q_1 = -6.5\ \mu C$, and

$$q_2 = ne = 5 \times 10^{13}\ (1.6 \times 10^{-19})\ C$$
$$= 8.0 \times 10^{-6}\ C = 8.0\ \mu C$$

As electrons are removed from the sphere, q_2 is positive. Therefore, net charge on the sphere,

$$q = q_1 + q_2 = -6.5\ \mu C + 8.0\ \mu C = \mathbf{1.5\ \mu C}$$

Example 5 **Two bodies A and B carry charges $-3.00\ \mu C$ and $-0.44\ \mu C$. How many electrons should be transferred from A to B so that they acquire equal charges?**

Solution. Here, $q_1 = -3.00\ \mu C$ and $q_2 = -0.44\ \mu C$

Let n electrons be transferred from A to B, when A and B would carry same charge.

$\therefore$ Charge on A = Charge on B

$$-3.00 + ne = -0.44 - ne$$
$$2\,ne = 3.00 - 0.44 = 2.56\ (\mu C)$$
$$n = \frac{2.56}{2e}$$

Taking $e = 1.6 \times 10^{-19}\ C = 1.6 \times 10^{-13}\ \mu C$

$$n = \frac{2.56}{2 \times 1.6 \times 10^{-13}} = 0.8 \times 10^{13} = \mathbf{8 \times 10^{12}}$$

TYPE B EXAMPLES BASED ON COULOMB'S LAW

Formulae used. $F_0 = \frac{1}{4\pi\epsilon_0} \frac{|q_1||q_2|}{r^2}$; $F_m = \frac{1}{4\pi\epsilon} \frac{|q_1||q_2|}{r^2} = \frac{1}{4\pi\epsilon_0 \epsilon_r} \frac{|q_1||q_2|}{r^2}$

Units used. q_1, q_2 are in coulomb, F in newton and r in metre.

Standard Values. $\frac{1}{4\pi\epsilon_0} = 9 \times 10^9\ Nm^2\ C^{-2}$

$$\epsilon_0 = 8.85 \times 10^{-12}\ C^2 N^{-1} m^{-2}$$

Example 6 **Two charged particles having charge $2\cdot0 \times 10^{-8}$ C each are joined by an insulating string of length 1 m and the system is kept on a smooth horizontal table. Find the tension in the string.**

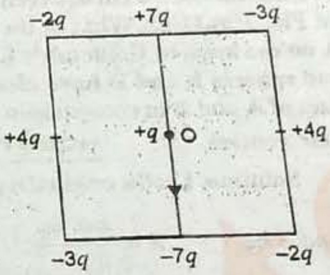
Solution. Here $q_1 = q_2 = 2 \times 10^{-8}$ C, $r = 1$ m

Tension in the string is the force of repulsion (F) between the two charges.

$\therefore$ According to Coulomb's law, $F = \dfrac{q_1\, q_2}{4\pi \epsilon_0\, r^2} = \dfrac{9\times10^9\,(2\times10^{-8})\,(2\times10^{-8})}{1^2} = 3\cdot6 \times 10^{-6}$ N

Example 7 **A particle carrying charge $+q$ is held at the centre of a square of each side one metre. It is surrounded by eight charges arranged on the square as shown in Fig. 1(a).10. If $q = 2\ \mu$C, what is the net force on the particle?**

FIGURE 1(a).10



Solution. As is clear from Fig. 1(a).10, forces on the particle at O due to $(-2q, -2q)$; $(-3q, -3q)$ and $(+4q, +4q)$ are equal and opposite. They cancel out in pairs. However, forces due to $+7q$ and $-7q$ add up. Therefore, net force on the particle at O is

$$F = \frac{1}{4\pi\epsilon_0} \times \frac{(7q)(q) + 7q(q)}{(1/2)^2}$$

$$= \frac{9\times10^9 \times 14\,(2\times10^{-6})^2}{1/4} = 36 \times 14 \times 4 \times 10^{-3}\ \text{N}$$

$$= 2\cdot016\ \text{N}$$

Example 8 **Coulomb's law for electrostatic force between two point charges and Newton's law for gravitational force between two stationary point masses, both have inverse square dependence on the distance between the charges/masses (*a*) compare the strength of these forces by determining the ratio of their magnitudes (*i*) for an electron and a proton (*ii*) for two protons (*b*) estimate the accelerations for electron and proton due to electrical force of their mutual attraction when they are 1 Å apart.**

NCERT Solved Example

Solution. (*a*) (*i*) For an electron and proton

$$|F_e| = \frac{1}{4\pi\epsilon_0}\,\frac{e\times e}{r^2}\ ;\quad |F_g| = \frac{G\,m_e . m_p}{r^2}$$

$$\frac{|F_e|}{|F_g|} = \frac{1}{4\pi\epsilon_0}\,\frac{e^2}{G\,m_e\,m_p} = \frac{9\times10^9\,(1\cdot6\times10^{-19})^2}{6\cdot67\times10^{-11}\times9\times10^{-31}\times1\cdot66\times10^{-27}} = 2\cdot3 \times 10^{39}$$

(*ii*) Similarly, for two protons,

$$\frac{|F_e|}{|F_g|} = \frac{1}{4\pi\epsilon_0}\,\frac{e^2}{G.m_p\,m_p} = \frac{9\times10^9\,(1\cdot6\times10^{-19})^2}{6\cdot67\times10^{-11}\times(1\cdot66\times10^{-27})^2} = 1\cdot3 \times 10^{36}.$$

(*b*) Force of mutual attraction between an electron and a proton,

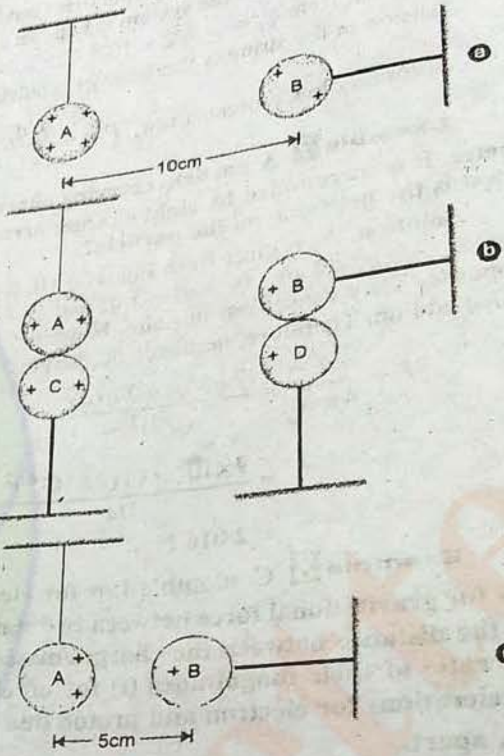
$$F = \frac{1}{4\pi\epsilon_0}\,\frac{e^2}{r^2} = \frac{9\times10^9\,(1\cdot6\times10^{-19})^2}{(10^{-10})^2} = 2\cdot3 \times 10^{-8}\ \text{N}$$

$$\text{Acceleration of electron} = \frac{F}{m_e} = \frac{2\cdot3\times10^{-8}}{9\times10^{-31}} = 2\cdot5 \times 10^{22}\ \text{m/s}^2$$

$$\text{Acceleration of proton} = \frac{F}{m_p} = \frac{2\cdot3\times10^{-8}}{1\cdot66\times10^{-27}} = 1\cdot3 \times 10^{19}\ \text{m/s}^2$$

Example 9 A charged metallic sphere A is suspended by a nylon thread. Another charged metallic sphere B carried by an insulating handle is brought close to A such that the distance between their centres is 10 cm as shown in Fig. 1(a).11(a). The resulting repulsion of A is noted (for example, by shining a beam of light and measuring the deflection of its shadow on a calibrated screen). Spheres A and B are touched by uncharged spheres C and D respectively, as shown in Fig. 1(a).11(b). C and D are then removed and B is brought closer to A to a distance of 5·0 cm between their centres, as shown in Fig. 1(a).11(c). What is the expected repulsion of A on the basis of Coulomb's Law ? Spheres A and C and spheres B and D have identical sizes. Ignore the sizes of A and B in comparison to separation between their centres. **NCERT Solved Example**

FIGURE 1(a).11



Solution. Let the original repulsive force between A and B be $F = \frac{k\,q_1\,q_2}{r^2}$

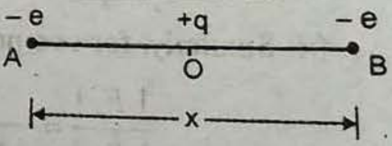
As A and C have same size, charges are shared equally. Again, as B and D have same size, their charges are also shared equally.

As charges on A and B are halved, and distance between them is also halved from 10 cm to 5 cm,

therefore, $F' = \frac{k\,(q_1/2)\,(q_2/2)}{(r/2)^2} = \frac{k\,q_1\,q_2}{r^2} = F$

Example 10 **Two electrons and a positive charge q are held along a straight line. At what position and for what value of q will the system be in equilibrium ? Check whether it is stable, unstable or neutral equilibrium.**

FIGURE 1(a).12



Solution. Let two electrons of charges – e each be held at A and B. The third charge + q must be placed at the centre O of AB. The forces on + q, due to two electrons being equal and opposite, cancel eachother and it is in equilibrium.

For the charge (– e) at A to be in equilibrium, Fig. 1(a).12, force on charge at A due to – e charge at B + force on charge at A due to + q charge at O = Zero

$$\frac{1}{4\pi\epsilon_0}\frac{(-e)(-e)}{x^2} + \frac{1}{4\pi\epsilon_0}\frac{q(-e)}{(x/2)^2} = 0$$

or
$$\frac{1}{4\pi\epsilon_0}\frac{e^2}{x^2} = \frac{1}{4\pi\epsilon_0}\frac{q(e)\times 4}{x^2}$$

or
$$e = 4\,q \quad \text{or} \quad q = e/4$$

If charge at O is moved slightly towards A, it would not return to O on its own and shall continue to move towards A. Hence ***equilibrium is unstable.***

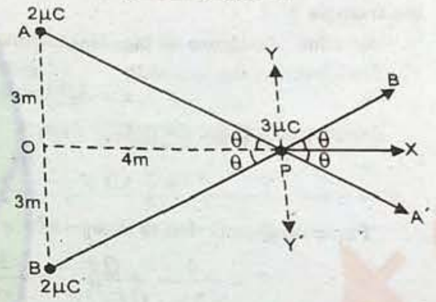
TYPE C EXAMPLES BASED ON SUPERPOSITION PRINCIPLE

Formula used. $\vec{F_0} = \vec{F_{01}} + \vec{F_{02}} + \vec{F_{03}} + \ldots\ldots$

Units used. Force is in newton, when charges are in coulomb and distance is in metre.

Example 11 **Two equal positive charges, each of 2 μC interact with a third positive charge of 3 μC situated as shown in Fig. 1(a).13. Calculate the magnitude and direction of the force on the 3 μC charge.**

FIGURE 1(a).13



Solution. In Fig. 1(a).14,

$$OA = OB = 3\text{ m},\ OP = 4\text{ m}$$

$$\therefore \quad AP = BP = \sqrt{3^2 + 4^2} = 5\text{ m}$$

According to Coulomb's law,

Force on charge at P due to charge at A

$$F_1 = \frac{1}{4\pi\epsilon_0}\frac{q_1 q_2}{AP^2}$$

$$F_1 = \frac{9\times10^9\times(2\times10^{-6})\times(3\times10^{-6})}{5^2} = \frac{54}{25}\times10^{-3}\,N = 2{\cdot}16\times10^{-3}\text{ N}$$

$F_1 = 2{\cdot}16 \times 10^{-3}$ N, along PA' opposite to PA. It has two rectangular components $F_1 \cos\theta$ along PX and $F_1 \sin\theta$ along PY'. Similarly, force on charge at P due to charge at B, $F_2 = F_1$ (in magnitude). It is along PB' opposite to PB. It also has two rectangular components : $F_2 \cos\theta$ along PX and $F_2 \sin\theta$ along PY.

The components along PY and PY' cancel. The components along PX add up.

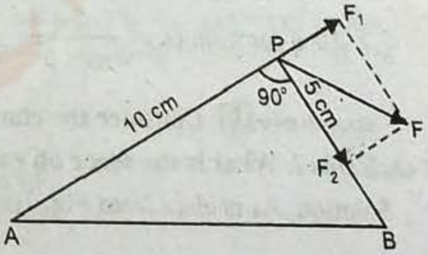
Total force on 3 μC charge is $F = 2\,F_1 \cos\theta = 2\times2{\cdot}16\times10^{-3}\times\frac{4}{5} = \mathbf{3{\cdot}5 \times 10^{-3}}$ ***N*, along *PX*.**

Example 12 **Find the magnitude of the resultant force on a charge of 1 μC held at P due to two charges of + 2 × 10^{-8} C and − 10^{-8} C at *A* and *B* respectively.**

Given *AP* = 10 cm and *BP* = 5 cm.

∠*APB* = 90°, Fig. 1(a).14.

FIGURE 1(a).14



Solution. Here, F = ?, Charge at P, $q = 1\ \mu C = 10^{-6}$ C

Charge at A, $q_1 = +2\times10^{-8}$ C

Charge at B, $q_2 = -10^{-8}$ C

AP = 10 cm = 0·1 m, BP = 5 cm = 0·05 m

∠APB = 90°

Force at P due to q_1 charge at A, $F_1 = \frac{1}{4\pi\epsilon_0}\frac{q_1 q}{AP^2}$, along AP produced

$$= \frac{9\times10^9\times2\times10^{-8}\times10^{-6}}{(0{\cdot}1)^2} = 18\times10^{-3}\text{ N}$$

Force at P due to q_2 charge at B, $F_2 = \frac{1}{4\pi\epsilon_0}\frac{q_2 q}{BP^2}$, along PB

$$= \frac{9\times10^9\times10^{-8}\times10^{-6}}{(0{\cdot}05)^2} = 36\times10^{-3}\text{ N}$$

As angle between $\vec{F_1}$ and $\vec{F_2}$ is 90°,

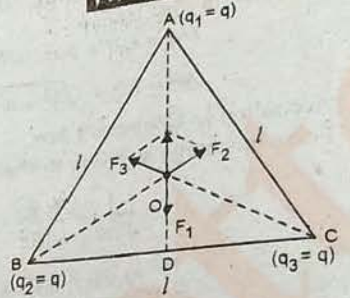
$\therefore$ Resultant force, $F = \sqrt{F_1^2 + F_2^2}$

$$F = \sqrt{(18\times10^{-3})^2 + (36\times10^{-3})^2} = 18 \times 10^{-3} \times 2{\cdot}236 = 4{\cdot}0 \times 10^{-2}\ \text{N}$$

Example 13 **Consider three charges q_1, q_2, q_3 each equal to q at the vertices of an equilateral triangle of side l. What is the force on a charge Q (with the same sign as q) placed at the centroid of the triangle ?**

NCERT Solved Example

FIGURE 1(a).15



Solution. As shown in Fig. 1(a).15, draw AD ⊥ BC.

$$\therefore \quad AD = AB\cos 30° = \frac{l\sqrt{3}}{2}$$

Distance AO of the centroid O from A

$$= \frac{2}{3}AD = \frac{2}{3}\frac{l\sqrt{3}}{2} = \frac{l}{\sqrt{3}}$$

$\therefore$ Force on Q at O due to charge $q_1 = q$ at A

$$F_1 = \frac{1}{4\pi\epsilon_0}\frac{Qq}{(l/\sqrt{3})^2} = \frac{3Qq}{4\pi\epsilon_0 l^2}, \text{ along AO}$$

Similarly, force on Q due to charge $q_2 = q$ at B

$$F_2 = \frac{3Qq}{4\pi\epsilon_0 l^2} \text{ along BO}$$

and force on Q due to charge $q_3 = q$ at C

$$F_3 = \frac{3Qq}{4\pi\epsilon_0 l^2}, \text{ along CO}$$

Angle between forces F_2 and $F_3 = 120°$

By parallelogram law, resultant of F_2 and $F_3 = \dfrac{3Qq}{4\pi\epsilon_0 l^2}$ along OA

$$\therefore \text{Total force on } Q = \frac{3Qq}{4\pi\epsilon_0 l^2} - \frac{3Qq}{4\pi\epsilon_0 l^2} = 0$$

Example 14 **Consider the charges q, q and $-q$ placed at the vertices of an equilateral triangle of each side l. What is the force on each charge ?**

NCERT Solved Example

Solution. As is clear from Fig. 1(*a*).16, force on $q_1 = q$ at A

$$\vec{F_1} = \vec{F_{12}} + \vec{F_{13}} = F\,\hat{r_1} \quad \text{where } F = \frac{qq}{4\pi\epsilon_0 l^2}$$

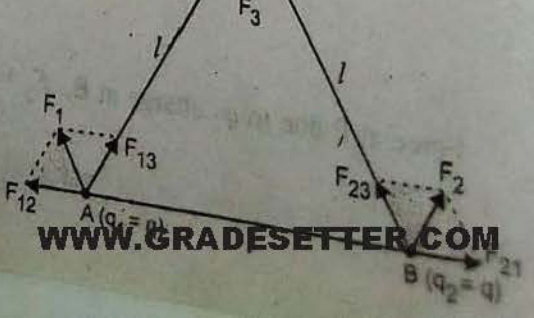
and $\hat{r_1}$ = unit vector along BC

Force on ($q_2 = q$) at B, $\vec{F_2} = \vec{F_{21}} + \vec{F_{23}} = F\,\hat{r_2}$,

where $\hat{r_2}$ = unit vector along AC

Force on $q_3 = -q$ at C

FIGURE 1(a).16



$$\vec{F_3} = \vec{F}_{31} + \vec{F}_{32} = [\sqrt{F_1^2 + F_2^2 + 2F_1F_2\cos 60^\circ}\,]\,\hat{n} = \sqrt{3}\,F\,\hat{n}$$

where $\hat{n}$ = unit vector along the direction bisecting ∠BCA.

We can show that $\vec{F}_1 + \vec{F}_2 + \vec{F}_3 = 0$

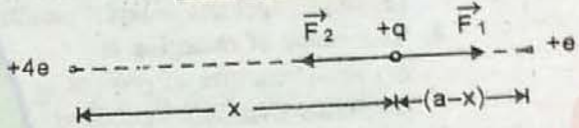
TYPE D TYPICAL EXAMPLES

Example 15 **Two fixed point charges + 4e and +e units are separated by a distance a. Where should the third point charge be placed for it to be in equilibrium ?** **(Chhatisgarh Board 2012)**

Solution. Let a point charge q be held at a distance x from the charge $+4e$, Fig. 1(a).17.

∴ Distance of q from charge $+e = (a-x)$

FIGURE 1(a).17



Force on this charge exerted by the charge $+4e$ is

$$F_1 = \frac{q(4e)}{4\pi\epsilon_0 x^2},\ \textit{directed away from } (4e)$$

Force on this charge exerted by the charge $+e$

$$F_2 = \frac{q(e)}{4\pi\epsilon_0 (a-x)^2},\ \textit{directed away from } (e)$$

For the charge q to be in equilibrium $F_1 = F_2$

i.e. $$\frac{q(4e)}{4\pi\epsilon_0 x^2} = \frac{q(e)}{4\pi\epsilon_0 (a-x)^2} \quad \text{or} \quad \frac{4}{x^2} = \frac{1}{(a-x)^2}$$

or $$\frac{2}{x} = \frac{1}{a-x} \quad \text{or} \quad x = 2a - 2x$$

∴ $$3x = 2a \quad \text{or} \quad x = 2a/3$$

Hence the charge q should be held at a distance $2a/3$ from charge $(+4e)$.

Example 16 **Two pieces of copper, each weighing 0·01 kg are placed at a distance of 0·1 m from each other. One electron from per 1000 atoms of one piece is transferred to other piece of copper. What will be the coulomb force between two pieces after the transfer of electrons ? Atomic weight of copper is 63·5 g/mole. Avogadro's number = 6×10^{23} /gram mole.**

Solution. Mass of each piece of copper = 0·01 kg = 10 g

$$\text{Number of atoms in each piece of copper} = \frac{6\times10^{23}\times10}{63{\cdot}5} = 9{\cdot}45\times10^{22}$$

$$\text{Number of electrons transferred} = \frac{1}{1000}\times9{\cdot}45\times10^{22}$$

$$n = 9{\cdot}45\times10^{19}$$

∴ charges on the each piece after transfer of electrons,

$$q_1 = q_2 = \pm ne = \pm 9{\cdot}45\times10^{19}\times1{\cdot}6\times10^{-19} = \pm 15{\cdot}12\ \text{C}$$

$$r = 0{\cdot}1\ \text{m}$$

$$F = \frac{1}{4\pi\epsilon_0}\frac{q_1 q_2}{r^2} = 9\times10^9\,\frac{(15{\cdot}12)^2}{(0{\cdot}1)^2} = 2{\cdot}06\times10^{14}\ \text{N}$$

TEST YOUR GRIP

I. MULTIPLE CHOICE QUESTIONS

1. 1 stat-Coulomb = ... Coulomb
(a) 3×10^9 (b) 3×10^{-9} (c) $\frac{1}{3}\times 10^9$ (d) $\frac{1}{3}\times 10^{-9}$ **(Bihar Board 2012)**

2. Which of the following is not an insulator ?
(a) glass (b) rubber (c) ebonite (d) human body

3. An object is charged when it has a charge imbalance, which means the
(a) object contains no electrons (b) object contains no protons
(c) object contains equal number of electrons and protons
(d) object contains unequal number of electrons and protons

4. The cause of charging is
(a) actual transfer of protons (b) actual transfer of electrons
(c) actual transfer of neutrons (d) none of the above

5. When a plastic comb is passed through dry hair, the charge acquired by the comb is
(a) always negative (b) always positive (c) sometimes negative (d) none of the above

6. Out of glass (rod) and silk (cloth), work function of glass is
(a) smaller (b) larger (c) equal (d) none of the above

7. The cause of quantization of electric charge is
(a) transfer of electrons (b) transfer of protons
(c) transfer of integral number of electrons (d) none of the above **(Jharkhand Board 2012)**

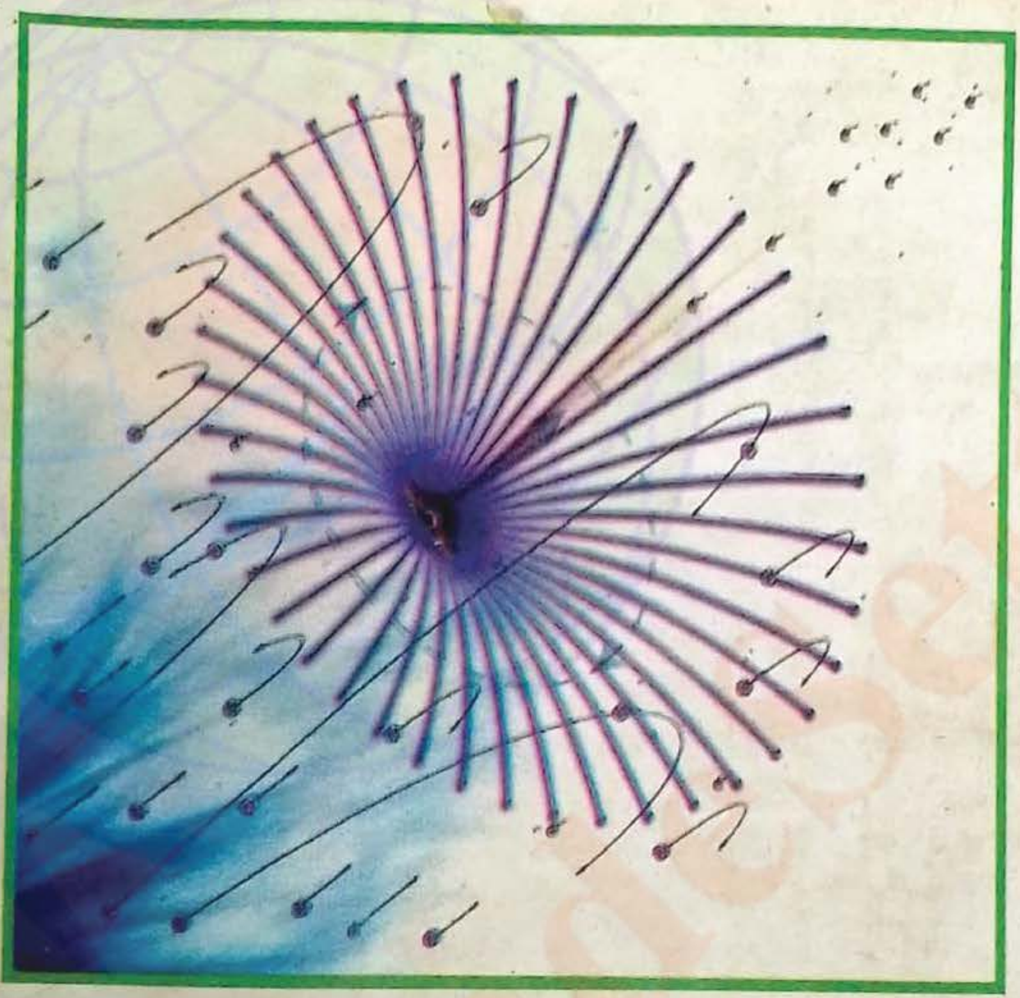
8. What is not true ?
(a) It is not possible to create or destroy net charge carried by any isolated system
(b) Charges can be created or destroyed in equal and unlike pairs only
(c) Proper signs have to be used while adding the charges in a system
(d) Excess of electrons over protons in a body is responsible for positive charge of the body.

9. Charge on a body which carries 200 excess electrons is
(a) $-3{\cdot}2 \times 10^{-18}$ C (b) $3{\cdot}2 \times 10^{-18}$ C (c) $-3{\cdot}2 \times 10^{-17}$ C (d) $3{\cdot}2 \times 10^{-17}$ C

10. The value of absolute electrical permittivity of free space is
(a) 9×10^9 Nm^2 C^{-2} (b) 9×10^{-9} Nm^2 C^{-2}
(c) $8{\cdot}85 \times 10^{-12}$ C^2 N^{-1} m^{-2} (d) $8{\cdot}85 \times 10^{-12}$ C^2 Nm^{-2}

II. FILL IN THE BLANKS

1. Lightning is a common example of............ .
2. Value of charge on a body which carries 10 excess electrons is............ .
3. Like charges............each other and unlike charges............eachother.
4. The charges acquired by the objects on rubbing against eachother must be............ and............ .
5. ....was the first to show............kinds of charges.
6. Insulators are also called............ .
7. The cause of charging is............of electrons from............to............ .
8. Electrons are transferred from the material whose............is............to the material whose............ is............ .
9. Charges can be created or destroyed in............and............pairs only.
10. The value of electrostatic force constant in free space is............ .



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