2.1 Introduction :

The importance of oxygen to the body is the same as the importance of electric power to technology. Electricity is called the "Mother of Technology", where "Electric Charge" is the foundation of electricity. The most important property of electric charge is that it can be transferred from one object to another. You know that when two suitable objects are rubbed against each other, electric charge is transferred on both of them. For example, a glass rod becomes positively charged by losing electrons when it is rubbed with silk, while the silk becomes negatively charged by getting electrons in this case.

While wearing or taking off a shirt, t–shirt or sweater in a dry environment (mostly in winter) you might have heard a cracking sound with/without a spark.

Sparkling sparks with a crackling sound is experienced while covering a woolen blanket on a winter night. Everybody has experienced unnoticing felt a shock while holding the metal handle of the door of the house, opening the door of the car or holding the metal rod in the bus. Lightning flashes in the sky with the thunder of the clouds. All these happen because of transfer of electricity due to any reason anyhow. Here the electric charge that is fixed on the object is called static charges and the study of their effects is called static electricity.

When electric charges are made to move by applying some force, the movement of charges is called electric current and the study of effects produced by an electric current is called current electricity.

2.2 Electric Charge :

You know that every substance is made up of atoms or molecules. Each atom is made up of electrons moving in fixed orbits around its nucleus. There are positively charged protons and neutral neutrons inside the nucleus. Thus, every substance is made up of electrons, protons and neutrons, called Fundamental Particles. Here, the mass of an electron is $M_e = 9.1 \times 10^{-31}$ kg, the mass of a proton and a neutron are considéred to be nearly the same, i.e. $M_p \cong M_n = 1.6 \times 10^{-27}$ kg.

As you know about Newton's law of gravitation (Every particle/body in the universe attracts every other particle/body with a force whose magnitude is directly proportional to the product of their masses and inversely proportional to the square of the distance between them, $Fg = G\dfrac{m_1 m_2}{R^2}$. According to this, when two electrons are 1 cm apart, they exert a gravitational force of 5.5×10^{-67} N on each other. However, at the same distance, a repulsive force called electric force of $Fe = 2.24 \times 10^{-24}$ N exists between two electrons. Electric force is 10^{43} times greater than the gravitational force. Thus, electric force is very strong. Even when two protons are placed at a distance of (apart from each other) 1 cm, an electric repulsive force of an equal value exists. However, the electric force of attraction between a proton and an electron at a distance of 1 cm seems to be of equal value. Thus, just as mass is the main cause of gravitational force, the property of particles due to which an electric force exists between them is called the 'electric charge' of the particle. The force acting between two like charges is repulsive and it is attractive between two, unlike charges.

From the above discussion, it is clear that the magnitude of the charge on an electron and a proton is the same but they are of the opposite type. Conventionally charge of an electron is considered negative and that of a proton is positive. However, if the sign convention of electronic charge (on proton and electron) is changed, it makes no difference whatsoever to the field of science and technology!! And, the value of this charge is $e = 1.6 \times 10^{-19}$ C. The SI unit of electric charge is coulomb, abbreviated as C.

Only electrons are transferred during any chemical process or when a charge is transferred. Thus, the substance which receives electrons becomes negatively charged and the substance which loses electrons becomes positively charged. In general, every object is neutral.

Since the charge on an electron is $e = 1.6 \times 10^{-19}$ C, the value of 1 Coulomb charge or number of electrons in 1 coulomb (1C) electric charge,

$$n = \frac{1}{e} = \frac{1}{1.6 \times 10^{-19}} = 6.25 \times 10^{18} \text{ electrons ... (1)}$$

2.2.1 Quantization of Electric Charge :

Experiments show that the magnitude of an electric charge is always an integer multiple of the fundamental charge (charge of an electron or proton). The unit of charge is Coulomb. Thus,

$Q = ne \quad$ where $n = 1, 2, 3, ... (n \in N)$. ... (2)

This is known as the quantization of electric charge.

The value of the basic unit of charge or elementary charge is

$$e = 1.6 \times 10^{-19} \text{ coulomb}$$

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 $\pm 1\, e, \pm 2\, e, \pm 3e$ and so on.

i.e., the possible values of charge are

$$q = \pm e = \pm 1 \times 1.6 \times 10^{-19}\text{C} = \pm 1.6 \times 10^{-19}\text{ C}$$

$$q = +2e = \pm 2 \times 1.6 \times 10^{-19}\text{C} = \pm 3.2 \times 10^{-19}\text{C}$$

$$q = \pm 3e = \pm 3 \times 1.6 \times 10^{-19}\text{C} = \pm 4.8 \times 10^{-19}\text{C}$$

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, on rubbing. For example, when one electron is transferred, the charges acquired by the two bodies will be $q = 1\,e = \pm 1.6 \times 10^{-19}$ C. Similarly, when n electrons are transferred, the charge acquired by the two bodies will be $q = \pm ne = \pm n \times 1.6 \times 10^{-19}$ C.

2.2.2 Conservation of Electric Charge :

The system in which an electric charge can neither enter from outside nor escape from inside is called an electrically isolated system, The algebraic sum of the electric charges (total electric charge) in an electrically isolated system always remains constant, irrespective of any process that takes place in the system. For example, let a system of zero total charge. Suddenly, a positive charge is generated in this system. Since the algebraic sum of charge is to be constant (here, zero), the charge before and after the process should remain the same. When a positive charge is generated in a process, a negative charge should also be generated in the process, so that the total charge remains zero. Thus, this rule of keeping the total charge constant is called the conversation of charges. For example, by rubbing a glass rod with a piece of silk cloth (these two objects are basically neutral so their total charge is zero), the glass rod becomes positively charged and the silk cloth becomes negatively charged. Thus, the total sum of the electric charges on them remains zero. In other words, only those processes are possible, in an isolated system, in which the electric charge is conserved.

2.2.3 Charging – by Friction or Induction :

As we have just seen, rubbing the glass rod with a silk cloth, both are electrically charged; glass rod is positively charged and silk cloth is negatively charged. The charging means generating (placing) electricity on any object. Take a comb and apply it to dry hair. When a comb is applied to dry hair and then kept closer to a tiny piece of paper, it will attract the paper. This is so because the piece of paper and the comb both possess opposite kinds of electric charges. Thus, an electric charge can be generated by rubbing an object and the object can be charged.

Similarly, the friction between the metallic body of a moving truck and the atmospheric air causes the body to be charged. This electric charge can also spark, which can be very dangerous for its petrol tank, to the combustible goods (such as clothes, grain, oil, etc.) and other vehicles running around such as petrol tankers. So often a chain of iron attached to the body of the truck is kept sliding on the road so that the electric charge generated/accumulated on the vehicle body passes to the ground. The vehicle tires are made by adding carbon to the rubber so that the generated electricity flows directly into the ground.

There is another way to charge an object other than friction and that is induction. Suppose a metal sphere is somehow positively charged (+Q) and placed on an insulating stand. When the similar but the electrically neutral metal sphere is made to touch the first sphere or both spheres are connected with a conducting wire, the positive charge of the first sphere is equalized by the electrons on the second sphere. Since both the spheres are identical, the second sphere loses Q/2 negative charge and becomes Q/2 positively charged. The charge on the first sphere is also Q/2. Thus, a neutral sphere is also electrically charged when it comes in contact with a charged sphere.

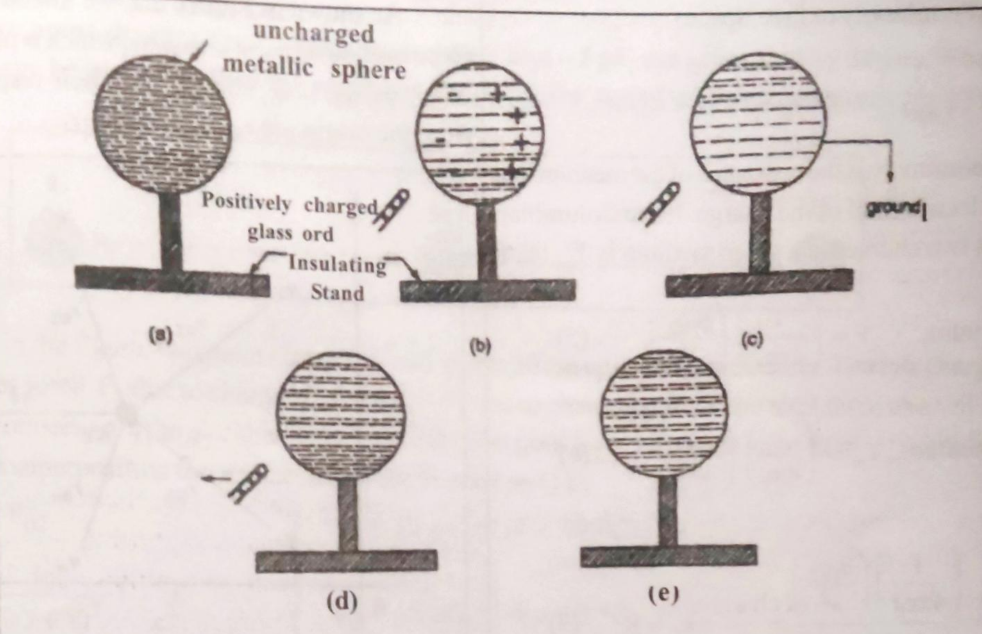


Fig. 2.1 : Electric Induction in the Isolated Metallic Spheres

An electrically neutral metal sphere is placed on the insulating stand (**Figure–2.1**). A glass rod is positively charged by rubbing with silk. When this rod is kept closer to the sphere, electrons of the sphere are attracted towards the part of the surface where the positively charged glass rod is kept closer. The positive charge is exposed on the back surface of the sphere. As soon as the rear surface of the sphere is grounded with conducting wire, the electrons from the ground rush to the surface of the sphere and the positive charge become electrically neutral on receiving these electrons. The negative charge still remains on the surface towards the rod (Fig –2.1c and d). Now removing the rod from the sphere, the remaining negative charge on the sphere is evenly distributed over the sphere (Fig 2.1–e). Thus, the sphere can be charged without bringing into direct contact with the charged glass rod. This method is called "Induction".

Here, it is interesting that the glass rod does not lose any electric charge and the sphere gets charged. While in the direct contact method, discussed above, the second sphere receives the same charge as the charged sphere loses. This is the main difference between charging an object using the direct contact method and the induction method.

2.2.4 Coulomb's Law :

French scientist Charles Coulomb conducted many experiments to find the force between two electric charges and deduced that "The electric force (Couloumbian force) between two stationary point charges is directly proportional to the product of their charges and inversely proportional to the square of the distance between them." This is Coulomb's law. This force is along the line of joining the two charges.

Let two stationary point charges q_1 and q_2 are separated by a distance r. The coulombian electric force between them,

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

$$\therefore \quad F = k\frac{q_1 q_2}{r^2} \qquad \text{... (3)}$$

When there is vacuum or air medium between the charges, the electric force constant or coulomb's constant $k = 8.9875 \times 10^9 \approx 9 \times 10^9\ \text{Nm}^2\text{C}^{-2}$ in SI system. In CGS system, $k = 1$ dyne cm C^2.

Coulomb's law is a basic law of nature. This is true only for static point (electric) charges. However, this rule can also be applied to large charged objects, if the distance between them is much larger than their size.

Here, Coulomb's constant, $k = \left(\frac{1}{4\pi\varepsilon_0}\right)$ ... (4)

Where, Permittivity of Free Space,

$$\varepsilon_0 = \left(\frac{1}{4\pi k}\right) = 8.854 \times 10^{-12}\ C^2/Nm^2.$$

Here, Permittivity is the resistance of the medium that impedes the electric field of the charge. If the Columbian force between two charges in a given medium is F_m then,

In a vacuum, $$F = \left(\frac{1}{4\pi\varepsilon_0}\right)\left(\frac{q_1 q_2}{r^2}\right) \quad \text{... (5)}$$

In the medium, $$F_m = \left(\frac{1}{4\pi\varepsilon}\right)\left(\frac{q_1 q_2}{r^2}\right) \quad \text{... (6)}$$

$$\therefore \frac{F}{F_m} = \frac{\left(\frac{1}{4\pi\varepsilon_0}\right)\left(\frac{q_1 q_2}{r^2}\right)}{\left(\frac{1}{4\pi\varepsilon}\right)\left(\frac{q_1 q_2}{r^2}\right)} = \frac{\varepsilon}{\varepsilon_0} = \varepsilon_r = K \quad \text{... (7)}$$

Where, ε_r = Relative Permittivity of medium or dielectric constant (K).

$$\varepsilon_r = \frac{\text{Permittivity of medium } (\varepsilon)}{\text{Permittivity of Free Space or Vacuum } (\varepsilon_0)} = K$$

Since the relative permeability of the medium (ε_r), is always greater than one, the Columbian force (F_m) in a given medium is less than the force exerted in a vacuum (F). Thus, $\varepsilon_r > 1 \Rightarrow F_m < F$.

2.2.5 Force between Charges – The Superposition Principle :

Coulomb's law can be used to obtain the electric (Coulombian) force acting between two electric charges. But, if more than two electric charges are present, the net electric force acting on any one of them can be obtained by superposition in addition to Coulomb's law. The net electric force between them can be obtained by summing the individual forces exerted between each pair of electric charges. This is called the superposition principle.

As shown in **Figure 2.2**, we intend to find the total force exerted on a test charge q_0 which is placed in the field of $q_1, q_2, q_3, \ldots q_n$ charges and their respective distances from the origin are $r_{01}, r_{02}, r_{03}, \ldots r_{0n}$.

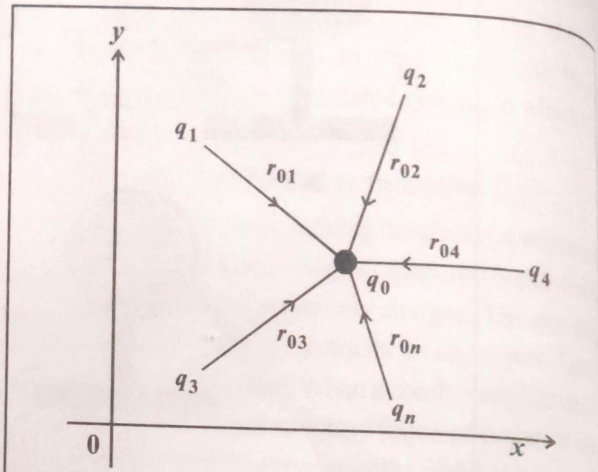


Fig. 2.2 : Electric Force Experienced by a Test Charge in the Electric Field of Two or More Charges.

Here, the force acting between q_0 and

$$q_1 = F_1 = k\frac{q_0 q_1}{r_{01}^2} \quad \text{... (8)}$$

Similarly, the force exerted between q_0 and q_2 will be $F_2 = k\frac{q_0 q_2}{r_{02}^2}$ and the force exerted between q_0 and q_3 will be $F_3 = k\frac{q_0 q_3}{r_{03}^2}$

Therefore, the total net force exerted on the test charge is obtained by summing each of those forces.

$$\therefore F = F_1 + F_2 + F_3 + \ldots + F_n; \quad n = 1, 2, 3, \ldots$$

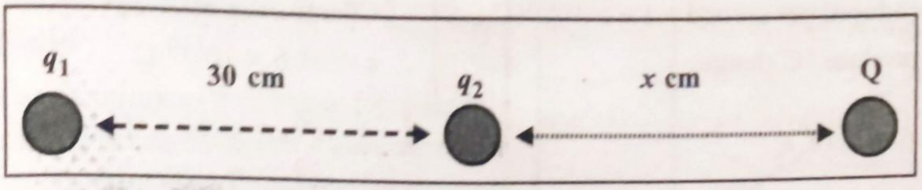
$$\therefore F = k\frac{q_0 q_1}{r_{01}^2} + k\frac{q_0 q_2}{r_{02}^2} + k\frac{q_0 q_3}{r_{03}^2} + \ldots + k\frac{q_0 q_n}{r_{0n}^2}$$

$$\therefore F = k q_0 \sum_{i=1}^{n} \frac{q_i}{r_{0i}^2} \quad \text{... (9)}$$

2.2.6 Illustrations :

Example-1 : Two point charges having magnitude 10 μC and – 5 μC are separated by 30 cm. Where should a third point charge be placed so that the resultant electric force acting on it becomes zero ?

Solution :



As shown in the figure, two point charges q_1 and q_2 are 30 cm apart from each other. The test charge Q, in their field, experiences force F_1 due to charge q_1 and force F_2 due to charge q_2. Also, the total force exerted on Q will be zero on the line connecting q_1 to q_2 either in the right direction from q_2 or x distance apart from q_1 in the left direction. According to the superposition theory, the total force exerted on Q is,

$$F = F_{01} + F_{02}$$

$$\therefore \quad 0 = \frac{kq_1}{(0.3+x)^2} + \frac{kq_2}{x^2}$$

$$\therefore \quad \frac{q_1}{(0.3+x)^2} + \frac{q_2}{x^2} = 0$$

$$\therefore \quad \frac{10 \times 10^{-6}}{(0.3+x)^2} + \frac{-5 \times 10^{-6}}{x^2} = 0$$

$$q_1 = 10\ \mu C = 10 \times 10^{-6} C$$

$$q_2 = -5\ \mu C = -5 \times 10^{-6} C$$

$$r_{01} = 30\text{ cm} = 30 \times 10^{-2} \text{m} = 0.3\text{ m}$$
$$= 0.3 + x$$

$$r_{02} = x\ m$$

$$\therefore \quad 10x^2 - 5(0.3+x)^2 = 0$$

$$\therefore \quad 2x^2 - (0.3+x)^2 = 0$$

$$\therefore \quad 2x^2 - (0.09 + 0.6\,x + x^2) = 0$$

$$\therefore \quad x^2 - 0.6x - 0.09 = 0$$

This is a $ax^2 + bx + c = 0$ type quadratic equation with the solutions $x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$ where $a = 1$, $b = 0.6$ and $c = -0.09$.

$$\therefore \quad x = \frac{0.6 \pm \sqrt{0.36 - 4\,(1)\,(-0.09)}}{2(1)} = \frac{0.6 \pm \sqrt{0.72}}{2} = \frac{0.6 \pm 0.85}{2}$$

$$= 0.725\text{ m અને } -0.125\text{ m} = 72.5\text{ cm and } -12.50\text{ cm}$$

Thus, electric force exerted by q_1 = **10 μC** and q_2 **= – 5 μC charges** upon a charge Q will be zero at a distance of 72.5 cm to the right side from q_2 and 12.5 cm to the left side from q_1.

Example-2 : Calculate the total electric charge on an object that has 20 extra electrons.

Solution :

Number of electrons, $n = 20$,

Charge of an electrone $e = -1.6 \times 10^{-19}$C

The total electrical charge of 20 electrons

$q = ne = (20)(-1.6 \times 10^{-19}) = -3.2 \times 10^{-18}$C

Example-3 : An object emits 10^9 electrons per second. So how long will it take to emit 1 C charge ?

Solution :

Number of electrons, $n = 10^9$ electron/seco

Charge of an electron

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

$q = ne = (10^9)(1.6 \times 10^{-19}) = 1.6 \times 10^{-10}$ C/s

Electric charge produced per second $= 1.6 \times 10^{-10}$ C

Time required to produce 1C charge

$$t = \frac{1}{1.6 \times 10^{-10}} = 6.25 \times 10^9 \text{ s}$$

$$= \frac{6.25 \times 10^9 \text{ s}}{3.154 \times 10^7} = 198.16 \text{ years}$$

Example-4 : The electric force between two positive ions of equal magnitude at a distance of 5Å from each o is 3.7×10^{-9} N. How many electrons would have been removed from each atom ?

Solution :

Force, $F = 3.7 \times 10^{-9}$ N

Distance, $r = 5$ A° $= 5 \times 10^{-10}$ m

No. of electrons, $n = ?$

Coulombian constant,

$k = 8.8975 \times 10^9$ Nm^{2}C^{-2}

Charge of an electron,

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

Let $q_1 = q_2 = Q$

Electric force, $F = k\dfrac{q_1 q_2}{r^2} = k\dfrac{Q^2}{r^2} \Rightarrow \therefore\ Q = r\sqrt{F/k}$

$$Q = (5 \times 10^{-10})\sqrt{\frac{3.7 \times 10^{-9}}{8.8975 \times 10^9}}$$

$$\therefore\ Q = (5 \times 10^{-10})(0.6449 \times 10^{-9}) = 3.22 \times 10^{-19}\text{C}$$

No. of electrons, $n = \dfrac{Q}{e} = \dfrac{3.22 \times 10^{-19}\text{ C}}{1.6 \times 10^{-19}} = 2.01 \approx 2$ electrons

Example- 5 : Find the ratio of gravitational force to electrostatic force between the protons in the nucleu an atom and the electrons revolving around it in an orbit of average r radius. Mass of a proton and electron are $m_p = 1.67 \times 10^{-27}$ kg and $m_e = 9.11 \times 10^{-31}$ kg respectively. The fundamental charge of pro and electron is 1.6×10^{-19} C. Gravitational constant $G = 6.67 \times 10^{-11}$ Nm^2 / kg^{-2} and Coulombian const $k = 8.9875 \times 10^9$ Nm^2 C^{-2}.

Solution :

Between proton and electron, the Gravitational force is $F_G = G\dfrac{m_e m_p}{r^2}$ and Electrostatic force is $F_e = k\dfrac{q_e q_p}{r^2}$

Their ratio is $\dfrac{F_e}{F_G} = \dfrac{kq_e q_p / r^2}{Gm_e m_p / r^2} = \dfrac{kq_e q_p}{Gm_e m_p} = \dfrac{kq_e q_p}{Gm_e m_p}$

$$= \frac{(8.8975 \times 10^9)(1.6 \times 10^{-19})^2}{(6.67 \times 10^{-11})(9.11 \times 10^{-31})(1.67 \times 10^{-27})} = \frac{8.8975 \times 1.6 \times 1.6}{6.67 \times 9.11 \times 1.67} \times 10^{9-38+11+31+27}$$

$$= \frac{22.7776}{101.4754} \times 10^{40} = 0.2245 \times 10^{40} = 2.245 \times 10^{39}$$

This shows that electrostatic forces are ~ 2.25×10^{39} times higher than gravitational forces.

2.3 Electric Field :

Coulomb's law determines the electric force acting between (two electrically) charged objects. However, if the number of charged objects (or electric charges) is large and the charge on each is different then this calculation becomes very complex and tedious.

Suppose a charge (or set of charges) Q is at a certain point in space. The test charge q_0, placed at r distance, will experience electric force according to coulomb's law. What remains there around Q if q_0 is removed ? One can smell the blooming flowers when a garden is nearby. One feels heat up to a certain distance around the fire. So, everything shows their effect in the nearest area. Similarly, Electric charge also produces its own effect in its immediate vicinity in space. This effect is felt more near the charge and gradually reduced with distance. Thus the electric field depends only on the distance from a given charge. This effect of an electric charge felt in the vicinity of space is called the (intensity of) electric field. The SI unit of (intensity of) electric field is newton/coulomb (N/C). The calculation of the force between electric charges has become quite easy due to electric field concept.

2.3.1 Electric Field (Intensity) of a Point Charge :

As shown in **Figure 2.3**, let a point electric charge Q be placed at the origin O of the axes. Now a positive test charge $+q_0$ is placed at the point P at a distance r in the vicinity of it. Charge Q will exert a repulsive force on it in the direction of O to P. Position of Q should not be changed due to q_0. Test charge experiences an electric force that depends only upon the electric field (intensity) of Q at the r distance away from it. The test charge q_0 is very small ($q_0 \to 0$), the otherwise electric field of q_0 may react with that of Q. Therefore we cannot find electric field of charge Q. Also note that q_0 cannot be less than the elementary charge of an electron (or proton) ($= 1.6 \times 10^{-19}$ C). Thus, by placing a positive charge q_0 at point P at a distance r from Q, it experiences an electric force in the electric field of Q. This is simply called the electric field of Q.

$$\text{Electric field, } E = \frac{F}{q_0} \quad \text{.... (10)}$$

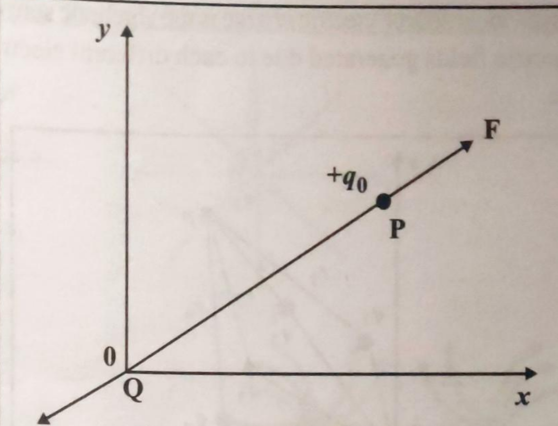


Fig 2.3 : Electric field intensity due to a point charge

The SI unit of an electric field is newton/coulomb (N/C). At a given point, if the test charge does not experience electric force, then the electric field of the charge somewhere near that point can be said to be zero.

In equation (9), F is the electrical force acting between Q and q_0

$$E = \frac{kQ}{r^2} = \left(\frac{1}{4\pi\varepsilon_0}\right)\frac{Q}{r^2} \quad \text{... (11)}$$

Where r distance is the distance between charge Q and point P where the electric field is to be measured.

It was Faraday who first conceptualized the electric field. The charge (or a set of charges) that produces an electric field is called the source charge and the charge used to measure the electric field is called the test charge. Taking $q_0 = 1$ C in equation (10), E = F occurs. From this, the electric field can be defined as follows.

The force experienced by a unit positive charge at a distance r from a charge Q (or a system of charges) is called electric field (or electric field intensity) E at that point.

2.3.2 Electric Field Due to System of Charges :

One can calculate the net electric force acting on a charge using the superposition principle. In the same way, the total electric field produced by a set of electric charges can also be found. Look at Figure 2.4.

We can to find out the net electric field generated by the set of the source charges $q_1, q_2, q_3, ..., q_n$ at respectively $r_1, r_2, r_3, ... r_n$ distance away from the test charge placed at point P. Thus the resultant electric field at point P due to each individual source electric charge is the algebraic sum of the electric fields generated due to each different electric charge.

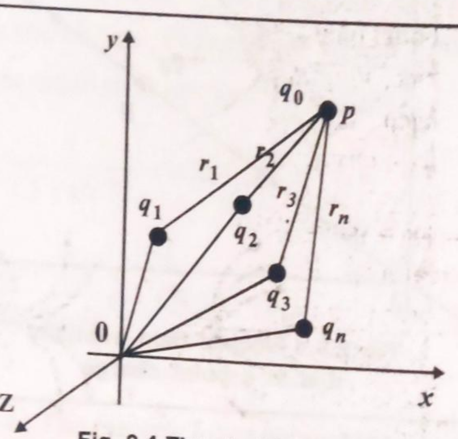


Fig. 2.4 The electric field of a set of charges

$$E_1 = \frac{kq_1}{r_1^2},\ E_2 = \frac{kq_2}{r_2^2},\ E_3 = \frac{kq_3}{r_3^2},\ E_4 = \frac{kq_4}{r_4^2} \ .... \ E_n = \frac{kq_n}{r_n^2}$$

According to the superposition principle,

$$E = E_1 + E_2 + E_3 + ... + E_n = k\left[\frac{q_1}{r_1^2} + \frac{q_2}{r_2^2} + \frac{q_3}{r_3^2} + ... + \frac{q_n}{r_n^2}\right]$$

$$\therefore \quad E = k\sum_{i=1}^{n} \frac{q_i}{r_i^2} \qquad ... (12)$$

Once having obtained the information about the electric field around (due to) a test charge (or a set of charges), the total force exerted on the test charge at a given point can be obtained by F = qE formula. The electric field is a vector quantity and it is in the direction of the force exerted on the electric charge.

2.3.3 Electric Field Lines :

It was Michael Faraday who explained the concept of electric field lines. Faraday named these electric field lines as "electric force lines". The geometric representation of electric field is called electric field lines.

Since electric field is a vector quantity, it has both magnitude and direction. In **Figure 2.5 (a)** electric field due to a positive charge is shown as a vector. Here, using vector $\overrightarrow{AB}$ electric field of $+q$ positive charge is represented. The directions of $\overrightarrow{AB}$ and $\overrightarrow{CD}$ indicate the direction of the electric field at points A and C respectively. $\overrightarrow{AB}$ and $\overrightarrow{CD}$ are in the same direction. The direction of the electric field changes at different points P, Q, R and S. The $\overrightarrow{CD}$ shorter than $\overrightarrow{AB}$ and this indicates that electric field decreases as it moves away from the electric charge. Connecting vectors like $\overrightarrow{AB}$ and $\overrightarrow{CD}$, on the same line gives the electric field line in that direction. Connecting vectors on the same line give a field of electricity in one direction. The electric field lines of the $+q$ charge obtained by this way are shown in **Figure 2.5 (b).**

Michael Faraday, explained the concept of electric field lines. Faraday named these electric field lines "electric lines". The geometric representation of an electric field is called electric field lines.

From **Figure–2.5**, it is clear that the electric field of point $+q$ charge is in the radial direction away from that electric charge and, similarly, the electric field of $-q$ charge is inward in the radial direction, as shown in **Figure–2.5 (c)**. The electric field always exits (starts from) $+q$ and hangs on (ends at) $-q$ as shown in **Figure 2.5 (d).** The electric field of two positive charges is due to repulsion between them, as shown in **Figure 2.5 (e).**

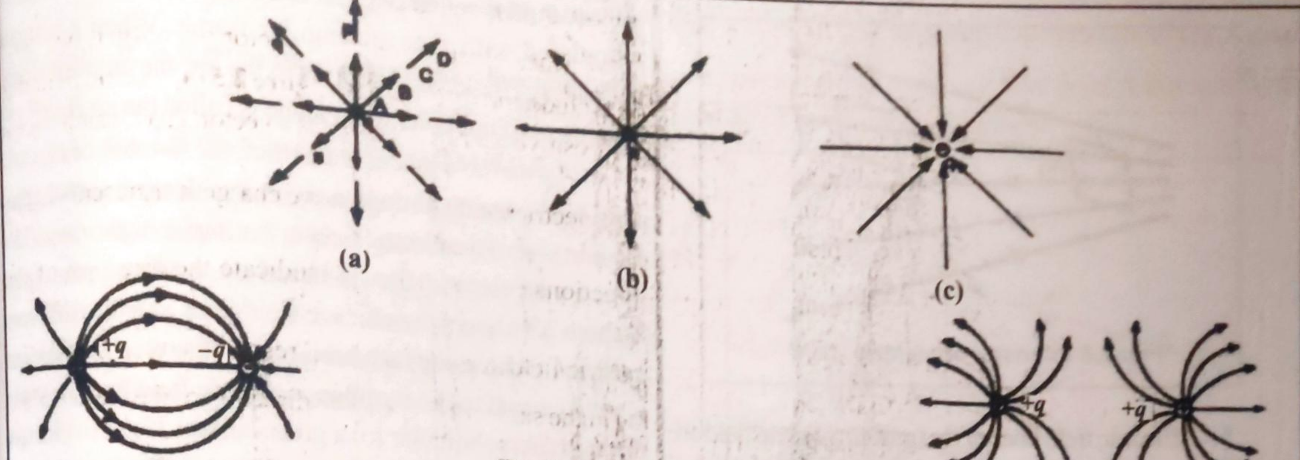


Fig. 2.5 Electric Field Lines

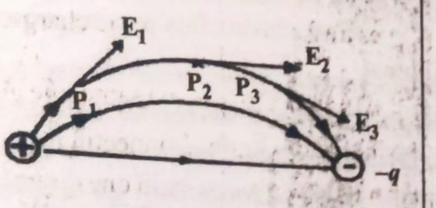


Fig. 2.6 Electric field lines in electric fields of +q and –q charges.

As shown in **Figure–2.6**, electric field lines in the electric field due to $+q$ and $-q$ charges are drawn. An electric field line represents the direction of the force exerted on a single positive charge at a fixed point on it. At point P_1 the force is exerted in the direction of the tangent (in the direction of $\vec{E_1}$). Similarly, at the point P_2, the force is in the direction of $\vec{E_2}$, and so on. In fact, when a positive charge is released into an electric field, the electric field line indicates the direction in which it moves under electric force. Thus, an electric field line is a curve drawn in an electric field, in such a way that the tangent to the curve at any point is in the direction of the net electric field at that point.

- **Characteristics of Electric Field Lines :**

1. Electric field lines start from positive charges and end at negative charges.
2. The tangent drawn at any point on the electric field lines indicates the direction of the electric field at that point.
3. Two electric field lines never cross (intersect) each other. As shown in **Figure–2.7**, if two electric field lines intersect each other at any point, then $+q$ charge at that point experiences the force in both $\vec{E_1}$ and $\vec{E_2}$ directions, which is not possible. i.e. at the intersection point of two electric field lines, two tangents can be drawn which indicate two directions of electric field and this is impossible.

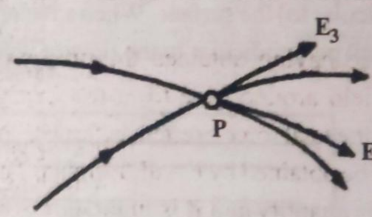


Fig. 2.7

4. The distance between the electric field lines indicates the intensity of the electric field in that area. The closely (Densely) arranged electric field lines indicates a strong (high) electric field (intensity) and vice versa. Spaciously arranged (scattered) electric field lines indicates weak (poor) electric field (intensity) and vice versa. As per **Figure 2.8**, the number of electric field lines passing through a plane A_1 is higher than those through a plane A_2. Therefore, (the intensity of) the electric field is higher in A_1 than that in A_2.

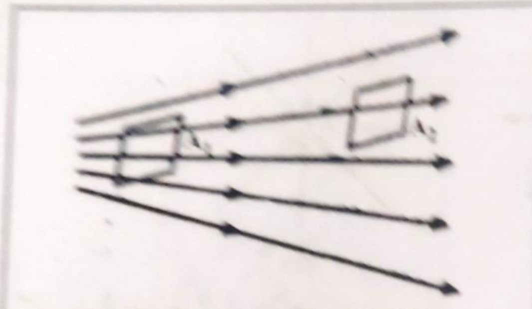


Fig. 2.8 Intensity of electric field

5. Electric field lines of the uniform electric field are mutually parallel and equidistant.
6. Electric field lines are imaginary, but electric field is reality.
7. Electric Field lines are always perpendicular to the conducting surface– in both cases, leaving the electric charge or entering the electric charge. This is the reason why the electric field in the direction parallel to the conducting surface is zero. That is, electric force does not exist parallel to the conducting surface.
8. Electric field lines do not form closed paths.

2.3.4 Electric Flux :

Flux is the amount of matter passing through (perpendicular to) the surface. When a rectangular frame of wire is kept perpendicular to the flow of water, the amount of water passing through it is called the 'flux' of w associated with that rectangular frame. When a sim paper–fan (flickering) rotates in the air, the amount of passing perpendicular to its plane is called the air flux.

As we have discussed earlier, the number of elec field lines passing through a given area determines whe the intensity of the electric field in that area is high or low. T concept of electric flux is based on the same princip **Figure 2.9** shows the electric field lines and the differe surfaces (whose surface area is A). The electric flux i quantity equal to the number of electric field lines passi through (perpendicular to) a given surface area. An elect field is the number of field lines passing perpendicular to t surface of a unit area. So the number of field lines having area A is equal to EA.

Thus, electric flux passing perpendicular to surface area A

$$\varphi = \vec{E} \cdot \vec{A} \quad .... (13)$$

$$\therefore \varphi = EA \cos\theta \quad .... (14)$$

Let a surface S_2 is kept slanting to electric field a shown in **Figure 2.9.** The electric flux passing perpendicul to S_2 is $\varphi = EA \cos\theta$ where θ is the angle formed betwe the electric field $\vec{E}$ and the surface $\vec{S}$. Actually, angle θ i formed between the normal to the surface and the electri field E.

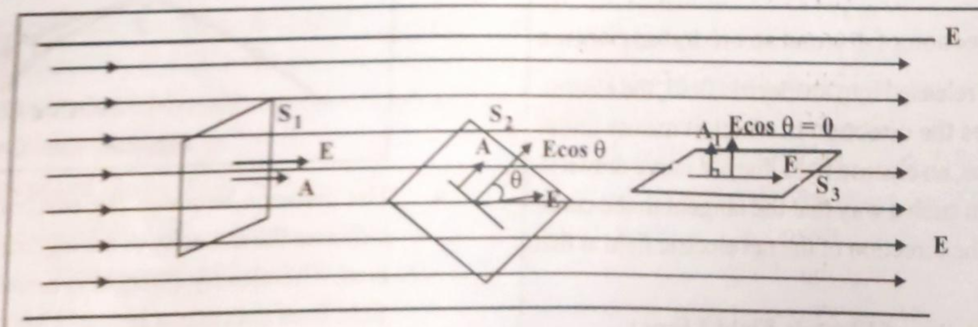


Fig. 2.9 : Electric Flux Passing Through Different Surfaces

Consider the third single surface S_3 placed in the direction parallel to the electric field $\vec{E}$ in **Figure 2.9.** Here the angle between the direction perpendicular to S_3 and $\vec{E}$ is $= 90^o$ so the electric flux associated with the surface is

$$\varphi = EA \cos\theta = EA \cos 90^o = EA(0) = 0$$

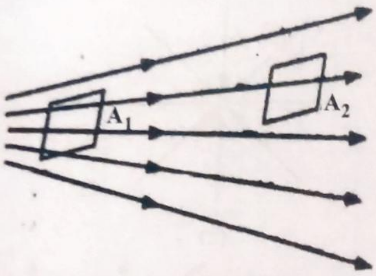


Fig. 2.8 Intensity of electric field

5. Electric field lines of the uniform electric field are mutually parallel and equidistant.
6. Electric field lines are imaginary, but electric field is reality.
7. Electric Field lines are always perpendicular to the conducting surface– in both cases, leaving the electric charge or entering the electric charge. This is the reason why the electric field in the direction parallel to the conducting surface is zero. That is, electric force does not exist parallel to the conducting surface.
8. Electric field lines do not form closed paths.

2.3.4 Electric Flux :

Flux is the amount of matter passing through (perpendicular to) the surface. When a rectangular frame of wire is kept perpendicular to the flow of water, the amount of water passing through it is called the 'flux' of wa associated with that rectangular frame. When a simp paper–fan (flickering) rotates in the air, the amount of a passing perpendicular to its plane is called the air flux.

As we have discussed earlier, the number of elec field lines passing through a given area determines wheth the intensity of the electric field in that area is high or low. T concept of electric flux is based on the same princip **Figure 2.9** shows the electric field lines and the differe surfaces (whose surface area is A). The electric flux is quantity equal to the number of electric field lines passin through (perpendicular to) a given surface area. An electr field is the number of field lines passing perpendicular to th surface of a unit area. So the number of field lines having a area A is equal to EA.

Thus, electric flux passing perpendicular to surface o area A

$$\varphi = \vec{E} \cdot \vec{A} \qquad \text{.... (13)}$$

$$\therefore \varphi = EA \cos\theta \qquad \text{.... (14)}$$

Let a surface S_2 is kept slanting to electric field a shown in **Figure 2.9.** The electric flux passing perpendicula to S_2 is $\varphi = EA\ \cos\theta$ where θ is the angle formed betwee the electric field $\vec{E}$ and the surface $\vec{S}$. Actually, angle θ is formed between the normal to the surface and the electri field E.

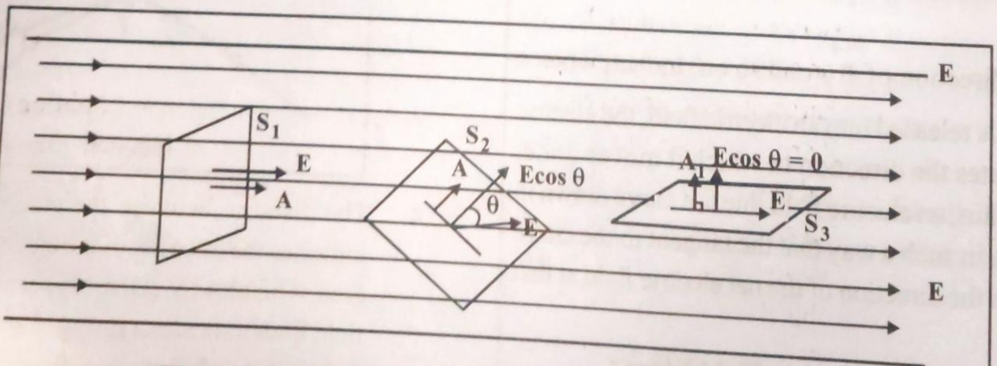


Fig. 2.9 : Electric Flux Passing Through Different Surfaces

Consider the third single surface S_3 placed in the direction parallel to the electric field $\vec{E}$ in **Figure 2.9.** Here, the angle between the direction perpendicular to S_3 and $\vec{E}$ is $= 90^o$ so the electric flux associated with the surface is,

$$\varphi = EA\cos\theta = EA\cos 90^o = EA(0) = 0$$

Similarly, the angle between the direction perpendicular to S_1 and $\vec{E}$ is = 0° so the electric flux associated with S_1 is,

$$\varphi = EA \cos \theta = EA \cos 0° = EA (1) = EA$$

This is denoted by Equation (13). Thus, placing any surface in an electric field, if the angle between the normal to the surface and the electric field is θ, then the flux (i.e. the number of suspended electric lines from that surface) associated with that surface, can be equated to $\phi = EA \cos \theta$. Electrical flux is a scalar quantity and its SI unit is V_m or Nm^2/C.

If the flux associated with a surface is zero means the number of electric field lines passing through that surface is zero, i.e. the electric field line does not pass through that surface.

When a rectangular wire–frame is kept slanting in the water flow, the water flowing through it is less than the same frame is kept perpendicular in the water flow. Because when the frame is kept parallel to the water flow, no water passes through it. Similarly, when a paper–fan is kept perpendicular to (in front of flowing) wind/air flow, it rotates fast. When it is tilted it slowed down, and when it is in the direction of the wind, it almost stops rotating. Thus, the concept of flux is very useful for understanding many laws and their applications in electronics.

2.4 Electric Potential :

So far we have only discussed static electricity. We have also observed that when an electric charge is placed in the electric field of another charge, it experiences electric force F. Now, if the electric charge is able to move due to this force, it will start moving and in such a motion, the work is said to be done by this force. If an object moves under the effect of a force, it is said that work is done on it by that force. The work done on any object is stored in that object in the form of its potential energy. This position indicates the amount of force exerted on the force at that point or the amount of energy in that force at that point.

2.4.1 Work done on a Charge in Electric Field

As shown in **Figure 2.10**, an electric field exists in the vicinity of an axis due to an electric charge Q placed at origin O. Suppose a unit of positive charge (q = +1C) is to be moved from point A to point B, where, the distances $\overline{OA} = r_A$, $\overline{OB} = r_B$ and $\overline{AB} = r$. The work done upon a unit positive charge to move it from point A to point B is the product of force and displacement.

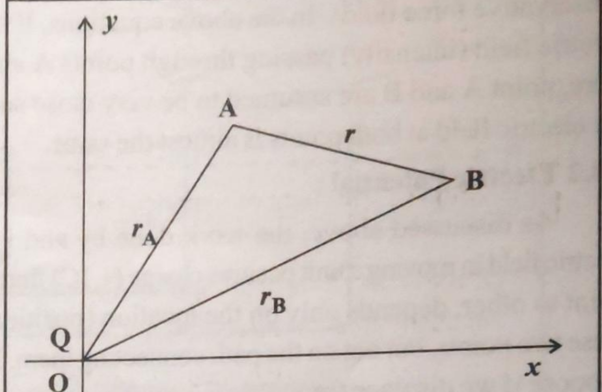


Fig. 2.10 : Work done on electric charge on different paths

$$W_{AB} = k\frac{q_1 q_2}{r^2} r \qquad \text{... (15)}$$

The electric force is applied to charge $q = q_2 = +1$ C by electric charge $q_1 = Q$

$$\therefore \quad W_{AB} = k\frac{Q(1)}{r^2} r = Er$$

$$\therefore \quad W_{AB} = k\frac{Q}{r} = Er \qquad \text{... (16)}$$

If the charge displacement is in the opposite direction to the electric force,

$$W_{AB} = -k\frac{Q}{r} = -Er \qquad \text{... (17)}$$

A negative sign is taken in **Equation (17)** when the work is required to be done upon the charge for the displacement against the electric field by the external force. The above equation is for work done on a unit positive charge. If the charge is $+q$ then the work to be done is

$$W_{AB} = -qEr \qquad \text{.... (18)}$$

One thing to keep in mind here is that whichever path is taken from A to B, the magnitude of work done is the same as **Equation (16)** or **Equation (17).** That is, the magnitude of work depends on the two endpoints only. Also, the work to be done from A to B is the same as the work to be done from B to an irrespective of the path between (joining) them.

$$W_{AB} = -W_{BA}$$

Thus, the total work done by going from A to B and returning from B to A is zero, irrespective of any path chosen. Such a force field is called a conservative force field. Gravitational force field and electric force field are both such conservative force fields. In the above equations, E is the electric field (intensity) passing through points A and B. Here, point A and B are assumed to be very close so that the electric field at both points is almost the same.

2.4.2 Electric Potential :

As discussed above, the work done by and in the electric field in moving a unit positive charge (+ 1C) from one point to other, depends only on the location (position) of these two points, but not on the path connecting them. Now suppose if we displace (move) a unit positive charge first from point A to B, then from point A to C, then from A to D ...etc. in the electric field, then the work done by the electric field will be obtained as...

$$W_{AB} = Er_{AB} \qquad W_{AC} = Er_{AC}$$
$$W_{AD} = Er_{AD} \qquad \text{... etc.}$$

Here if point A is taken as a reference point then the above–mentioned work depends on the location (position) of that point (B, C, D, ...) only. For the sake of simplicity, taking such a reference point at infinite distances from the source of the electric field, is the work required to bring the unit positive electric charge from that point to a point in the field is given by,

$$W_{\infty B} = Er_B \qquad \text{... (19–A)}$$

If the electric charge is shifted in the opposite direction to the electric force, the work done upon it is,

$$W'_{\infty B} = Er_B \qquad \text{... (19–B)}$$

Such a position–based work is called "electric potential" at that point. **"Work required to be done against the electric field in bringing a unit positive charge from infinity to the given point in the electric field of a charge (or of a group of charges) is called electric potential at that point."**

Electric potential is denoted by V. Thus, the electric potential at a point A

$$V_E = -E \cdot r$$

$$\therefore \quad V_A = -k\frac{Q}{r^2} \cdot r$$

$$\therefore \quad V_A = -k\frac{Q}{r} \qquad \text{... (20)}$$

$$\therefore \quad \text{Electric potential} = \frac{\text{The work done on cha}}{\text{Electric charge}}$$

$$\therefore \quad V_A = -\frac{W}{q_0} \qquad \text{... (21)}$$

The unit of Electric potential :

$$V_A = \frac{\text{Joule (J)}}{\text{Coulomb (c)}} = \text{Volt (V)}$$

One thing to keep in mind is that the potential at poi A is not important. But only the potential difference (P between the given points A and B matters, which are follows.

$$V_B - V_A = -k\frac{Q}{r_{AB}} = -\frac{W_{AB}}{q_0} \qquad \text{.... (22)}$$

When two charged objects are brought into conta with each other, the charge will be transmitted from on object at higher potential to another object at lower potenti This conduction will take place until the potentials of the tw objects are equal.

As stated earlier, a point is taken as a reference. Th potentials of the rest of the points are calculated by taking th potential of the earth's surface to be zero.

2.4.3 Potential due to a Point Charge :

As discussed earlier in **Equation (22),** the potenti difference between two points is given by,

$$V_A - V_B = E \cdot r$$

Here the electric field generated due to electric charg is assumed to be uniform. If the electric field due to a poi charge is taken, then it is different at different points as show in **Figure 2.5 (b)** or **Figure 2.5 (c)**. In such a nonunifor electric field, the potentials at different points are als unequal. **Figure 2.11** shows the electric field of such a singl point charge +Q at the different points at different distance In order to calculate electric potential (V) at point A at distance r_A from the positive charge +Q, the work done o the test charge q, when it is brought from an infinite distanc to the electric field of charge +Q, is calculated. The distanc between point A and any point of infinite distance is ver large. Since the potential at this distance is nonuniform, the total distance is divided into micro–segments AB, BC, CD ... etc. Now, the work done on each segment is obtained by considering the electric field in each segment almost equal. The total work done is obtained by summing all such works done on each segment.

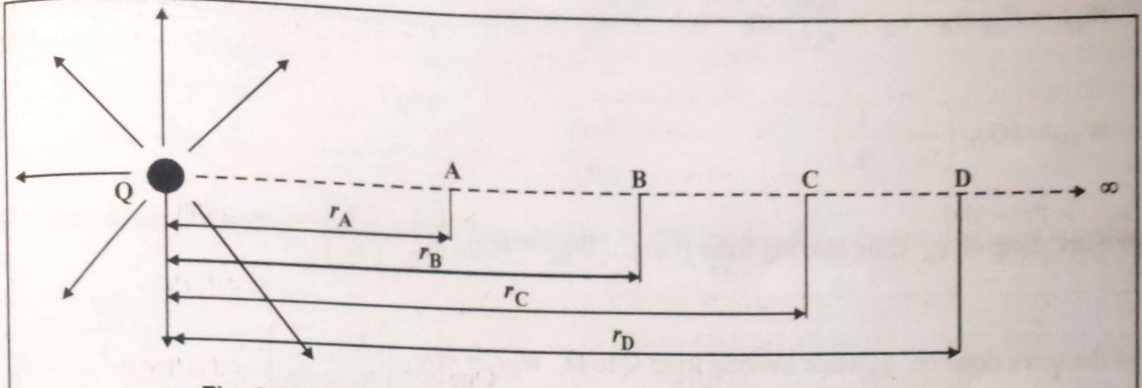


Fig. 2.11 : Electric Field of a Point Charge at Different Distances

The force exerted on charge due to +Q charge at point A = $F_A = k \dfrac{Qq_0}{r_A^2}$

The force exerted on cherge due to +Q charge at point B = $F_B = k \dfrac{Qq_0}{r_B^2}$

The average force exerted during the transition from point A to point B = $F_{AB} = \dfrac{F_A + F_B}{2}$

$$= \frac{1}{2} kQq_0 \left(\frac{1}{r_A^2} + \frac{1}{r_B^2}\right) = \frac{1}{2} kQq_0 \left(\frac{r_A^2 + r_B^2}{r_A^2 r_B^2}\right) \quad \text{... (23)}$$

And $(r_A - r_B)^2 = r_A^2 - 2r_Ar_B + r_B^2$

If points A and B are taken very close to each other, then $(r_A - r_B)^2$ can be ignored relative to $2r_Ar_B$.

$$\because \quad (r_A - r_B)^2 \cong 0 \Rightarrow \qquad \therefore \quad r_A^2 - 2r_Ar_B + r_B^2 = 0$$

$$\therefore \quad r_A^2 + r_B^2 = 2r_Ar_B \quad \text{... (24)}$$

From Equation (23) and (24),

$$F_{AB} = \frac{1}{2} kQq_0 \left(\frac{2r_Ar_B}{r_A^2 r_B^2}\right)$$

$$= \frac{1}{2} kQq_0 \left(\frac{2}{r_A r_B}\right)$$

$$= \left(\frac{kQq_0}{r_A r_B}\right) \quad \text{... (25)}$$

The work done on q_0 while moving from A to B

$$W_{AB} = F_{AB}(r_B - r_A) = \frac{kQq_0}{r_A r_B}(r_B - r_A)$$

$$\therefore \quad W_{AB} = kQq_0\left(\frac{1}{r_A} - \frac{1}{r_B}\right)$$

The work done on q_0 while moving from B to C, $W_{BC} = kQq_0\left(\frac{1}{r_B} - \frac{1}{r_C}\right)$

And the work done on q_0 while moving from C to D, $W_{CD} = kQq_0\left(\frac{1}{r_C} - \frac{1}{r_D}\right)$

Thus, the total work required to move the charge from infinity to given point A,

$$W = W_{AB} + W_{BC} + W_{CD} + ... = \Sigma W$$

$$\therefore \quad W = kQq_0\left[\left(\frac{1}{r_A} - \frac{1}{r_B}\right) + \left(\frac{1}{r_B} - \frac{1}{r_C}\right) + \left(\frac{1}{r_C} - \frac{1}{r_D}\right) + ... + \left(\frac{1}{r_A} - \frac{1}{r_\infty}\right)\right]$$

$$\therefore \quad W = kQq_0\left(\frac{1}{r_A} - \frac{1}{r_\infty}\right) \quad \text{where } \frac{1}{r_\infty} = 0$$

$$\therefore \quad W = \frac{kQq_0}{r_A} \qquad ... (26)$$

According to the definition of electric potential, the work done per unit positive charge is called the electric potential at that point.

$$\text{Thus, } V_A = \frac{W}{q_0} = \frac{kQ}{r_A} \qquad ... (27)$$

$$\therefore \quad V_A = \left(\frac{1}{4\pi\varepsilon_0}\right)\frac{Q}{r_A} \qquad ... (28)$$

Using Equation (28), the electric potential due to positive charge +Q, at point A that is r distance away from it, can be determined.

$$V = \frac{kQ}{r} \qquad ... (29)$$

The potential of a positive charge is positive and negative for a negative charge. It is easier to find the potential of a given electric field than to find its intensity E. the superposition principle is well applicable in the case of electric potential also. In order to find the electric potential due to many point–charges, the potential due to every point charge is to be found and then their algebraic sum is taken. Just as we find the potential V from the electric field E, it is easier to find the electric field E from the potential V. Let us see that.

2.4.4 Electric Potential from Electric Field :

Consider two points A and B in the same electric field as shown in **Figure 2.12**, where $V_A > V_B$. Now the work done to bring the unit positive charge q_0 from B to A is $W = q_0 (V_A - V_B)$. To move the charge q_0 from B to A, the work is to be done against electric force in an electric field.

Work = force × Displacement in the direction of Force.

$$\therefore \quad W = F \cdot r = E \cdot q_0 r = (V_A - V_B)\, q_0$$

$$\therefore \quad E = \frac{V_A - V_B}{r} \qquad \text{.... (30)}$$

If B is taken as a reference point and $V_B = 0$ is taken for simplicity; then V_A = Potential of point A with respect to point B.

$$\therefore \quad E = \frac{V_A}{r}$$

Broadly speaking, $E = \dfrac{V}{r}$ .... (31)

The electric field (intensity) E of at a given point, is obtained by the ratio of potential difference (V) of that point to the distance of electric charge(s) from the given point. The SI unit of E from **Equation (31)** is also volts per meter (V/m). Thus the intensity of the electric field at a given point can be measured in N/C or V/m.

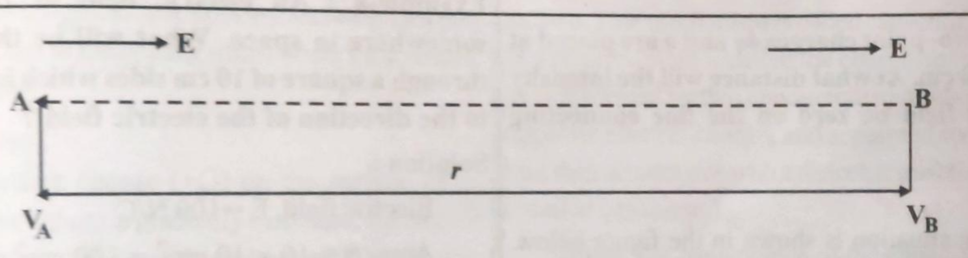


Fig. 2.12 : Two Points Having Potential Difference in the Uniform Electric Field

The following points are clear from the above–paragraphed discussion.

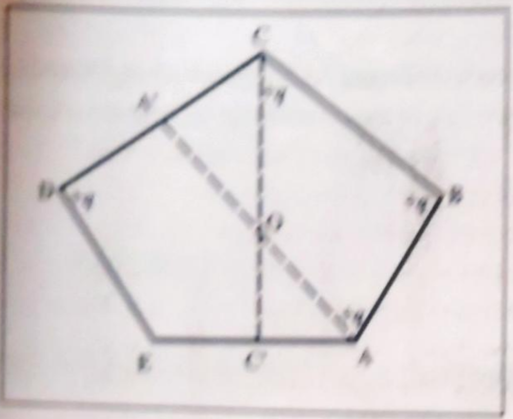
1. If the work done on electric charge is positive ($W > 0$) then it is said that the work is done on electric charge by an external force, and that point is said to be at higher electric potential than other points.
2. If the work done on electric charge is negative ($W < 0$), then it is said that the electric charge moves by working with the energy stored in the electric charge. i.e. The work is done by electric charge, and that point is said to be at the lowest electric potential than other points.
3. If the work done on electric charge is zero ($W = 0$), then it is said that the potential of that point is taken to be the same as that of other points.

2.4.5 Illustrations :

Example-6 : The same electric charge $+q$ is placed on the four corners A, B, C, D of a regular pentagon as shown in the figure. Find the value of the electric field at the center of the pentagon if the distance from each angle of the pentagon to center O is r.

Solution :

Suppose that the electric field at point O due to each point is E_A, E_B, E_C, E_D and E_E respectively. As shown in the figure, the electric field due to a positive charge is in the direction out of the electric charge. So, the electric field at point O, due to the charge placed at point A, will be in the direction of AA'. The same will happen to the electric field of the other four charges. Therefore, the total electric field at point O due to all the five charges, since the distance of point O from each angle is equal (r), will be zero.



Thus, $E_A + E_B + E_C + E_D + E_E = 0$

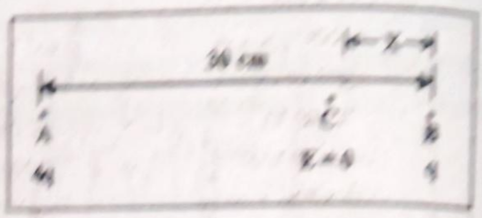
$\therefore E_A + E_B + E_C + E_D = -E_E$

Thus, the total electric field at point O will be equal to the electric fields generated by the other four charges but in opposite directions. Now, the electric field at point O due to the +q charge at point E is in the direction of E to O, where $E_E = kq/r^2$.

Example-7 : Two-point charges 4q and q are placed at a distance of 30 cm. At what distance will the intensity of the electric field be zero on the line connecting them ?

Solution :

The given situation is shown in the figure below. Suppose 4q and q charges are placed at points A and B, respectively. On the line connecting them, suppose the electric field at point C at a distance x from point B is ze



$\therefore E_A + E_B = 0$

$\therefore E_A = -E_B$

Electric fields generated by points A and B at poin will be in the equal and opposite direction.

$\therefore |E_A| = |E_B|$

$$\therefore k\frac{4q}{(30-x)^2} = \frac{kq}{x^2}$$

$$\therefore \frac{2}{(30-x)} = \frac{1}{x} \qquad \therefore x = 10 \text{ cm}$$

Example-8 : An electric field of 100 N/C exis somewhere in space. What will be the flux passin through a square of 10 cm sides which is perpendicula to the direction of the electric field ?

Solution :

Electric field, E = 100 N/C

Area, A = 10 × 10 cm² = 100 cm² = 10^{-4} m²

Electric flux, $\varphi = EA = 100 \times 100 \times 10^{-4} = 1$ Nm²C

Example-9 : If the distance of point A from two charges of 2 μC and 40 μ is 20 m and 40 m respectively, calculat the potential difference at point A. Also, obtain the work to be done upon the charges on bringing 0.2 C and −0.4 C charges from infinite distance to point A.

Solution :

In the given situation, the potential at point A, $V_A = \frac{kq_1}{r_1} + \frac{kq_2}{r_2}$

$$\therefore V_A = k\left[\frac{q_1}{r_1} + \frac{q_2}{r_2}\right]$$

$k = 9 \times 10^9 \frac{Nm^2}{C^2}$

$q_1 = 2\mu C = 2 \times 10^{-6} C$

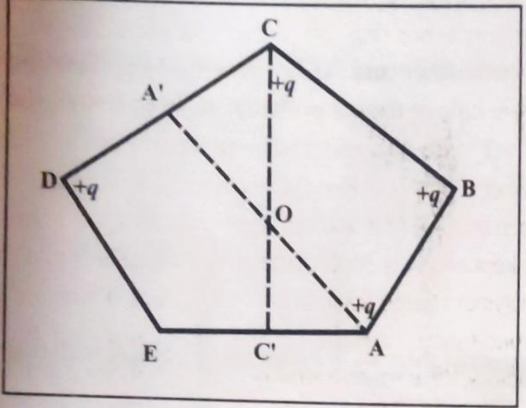
$q_2 = 4\mu C = 4 \times 10^{-6} C$

$$V_A = (9 \times 10^9)\left[\frac{2 \times 10^{-6}}{20} + \frac{4 \times 10^{-6}}{40}\right] = 1800 \text{ volt}$$

If the work is done on charges for bringing them from infinite distance to point A are W_1 and W_2 respectively then

$W_1 = V_A q_1 = 1800 \times 0.2 = 360$ J

$W_2 = V_B q_2 = 1800 \times (-0.4) = -720$ J



Thus, $E_A + E_B + E_C + E_D + E_E = 0$

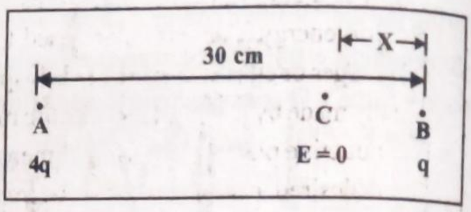
$\therefore \quad E_A + E_B + E_C + E_D = -E_E$

Thus, the total electric field at point O will be equal to the electric fields generated by the other four charges but in opposite directions. Now, the electric field at point O due to the +q charge at point E is in the direction of E to O, where $E_E = kq/r^2$.

Example-7 : Two–point charges 4q and q are placed at a distance of 30 cm. At what distance will the intensity of the electric field be zero on the line connecting them ?

Solution :

The given situation is shown in the figure below. Suppose $4q$ and q charges are placed at points A and B, respectively. On the line connecting them, suppose the electric field at point C at a distance x from point B is zero.



$\therefore \quad E_A + E_B = 0$

$\therefore \quad E_A = -E_B$

Electric fields generated by points A and B at point C will be in the equal and opposite direction.

$\therefore \quad |E_A| = |E_B|$

$$\therefore \quad k\frac{4q}{(30-x)^2} = \frac{kq}{x^2}$$

$$\therefore \quad \frac{2}{(30-x)} = \frac{1}{x} \qquad \therefore x = 10 \text{ cm}$$

Example-8 : An electric field of 100 N/C exists somewhere in space. What will be the flux passing through a square of 10 cm sides which is perpendicular to the direction of the electric field ?

Solution :

Electric field, E = 100 N/C

Area, $A = 10 \times 10 \text{ cm}^2 = 100 \text{ cm}^2 = 10^{-4} m^2$

Electric flux, $\varphi = EA = 100 \times 100 \times 10^{-4} = 1 \text{ Nm}^2\text{C}^{-1}$

Example-9 : If the distance of point A from two charges of 2 μC and 40 μ is 20 m and 40 m respectively, calculate the potential difference at point A. Also, obtain the work to be done upon the charges on bringing 0.2 C and – 0.4 C charges from infinite distance to point A.

Solution :

In the given situation, the potential at point A, $V_A = \frac{kq_1}{r_1} + \frac{kq_2}{r_2}$

$k = 9 \times 10^9 \frac{\text{Nm}^2}{\text{C}^2}$

$q_1 = 2\mu\text{C} = 2 \times 10^{-6}\text{C}$

$q_2 = 4\mu\text{C} = 4 \times 10^{-6}\text{C}$

$$\therefore \quad V_A = k\left[\frac{q_1}{r_1} + \frac{q_2}{r_2}\right]$$

$$V_A = (9 \times 10^9)\left[\frac{2 \times 10^{-6}}{20} + \frac{4 \times 10^{-6}}{40}\right] = 1800 \text{ volt}$$

If the work is done on charges for bringing them from infinite distance to point A are W_1 and W_2 respectively then,

$W_1 = V_A q_1 = 1800 \times 0.2 = 360$ J

$W_2 = V_B q_2 = 1800 \times (-0.4) = -720$ J

2.5 Capacitor and Capacitance :

2.5.1 Introduction to Capacitors :

A capacitor is a simple device that stores electric charge and electric energy. Capacitors are used to store more electrical charges or electrical energy in less space. A capacitor is usually made by placing a die–electric medium between two conductive plates of the same dimension. A capacitor of the desired capacitance can be made by changing the distance between the plates and its dimensions. Capacitors are an important component in almost all electrical, electronic and micro–electronic circuits. Different types of capacitors are used in all devices for generating, carrying and storing energy. One or more capacitors are important component in the circuits like Ultrasonic, Microwave, Radio, Laser, etc. for the production, amplification, and transmission of sound or electromagnetic waves. Capacitors are used to tune radio receivers and televisions over the appropriate frequency band. Capacitors are used in almost all decoration and entertainment devices related to sound and light. Capacitors are an important part of all types of circuits of measuring instruments for scientific research and testing.

2.5.2 Capacitance :

As the positive charge (+Q) on the surface of an isolated conductive sphere is gradually increased, the electric potential (V) on the surface of the sphere and the electric field (E) around the sphere also go on increasing accordingly. In this process, at one stage, the sphere becomes electrically saturated, means the sphere can no longer store more electricity than its capacity. So, the electric field due to the sphere becomes sufficiently strong that it can ionize the surrounding air particles that the insulating property of the air gets destroyed. Because, at this point, an electric charge in addition to its capacity leaks from the sphere and causes ionization (separation of atomic positive and negative electric charges) of the surrounding air. Throughout this process, the ratio (Q/V) of the electric charge (Q) on the sphere and its magnitude (V) remains constant. This ratio is called its capacitance (C). Here, conductors of any shape can be taken instead of spheres.

$$\text{Capacitance (C)} = \frac{\text{Electric charge (Q)}}{\text{Electroc Potential (V)}}$$

$$\therefore C = Q/V \qquad \text{... (32)}$$

Potential Difference (pd) arises between two conductors when they are placed at a short distance apart from each other and same magnitude (Q coulomb) of opposite charge (one is positively charged and another is negatively charged) is stored upon them. Here, the ratio of electric charge (Q coulomb) and potential difference (V volt) between the two identical but oppositely charged conductive plates kept at a very small distance apart is called capacitance of the system made up of these conductors. The magnitude of capacitance depends on the dimensions of the two conductors, their relative arrangement, the dielectric medium between them and the distance between the two.

2.5.3 Capacitor :

When a positively charged conductor (positive plate) and a negatively charged conductor (negative plate) are separated by a distance less than their dimensions (length and breadth) and a dielectric medium is placed between the two, and both conductors are connected to the two terminals of the battery, a potential difference (V) is formed between the two. This mechanism is called capacitor. The charge (Q) of a positive plate is called the charge on the capacitor. (A device formed by two conductive plates bearing equal but opposite electric charge; and separated by a distance less than their dimensions with a dielectric material between them is called capacitor.)

Here, the capacitance of the capacitor, $C = Q/V$

The SI unit of capacitance is the coulomb/volt called farad (F). Since farad (F) is a very large unit for measuring the capacitance of real capacitors, in practice microfarad (microfarad; $1\mu F = 10^{-6}$ F), nanofarad (nanofarad; $1nF = 10^{-9}$ F) and picofarad (picofarad; $1pF = 10^{-12}$ F) are used.

A capacitor is a device designed to store a large amount of electric charge and hence electric energy in a small space. In general, a system in which the two oppositely charged plates separated by a dielectric medium is called a capacitor. Mostly, plates of a capacitor are charged by attaching them to different terminals of the battery. The electric charge on two plates of a capacitor is usually taken as $+Q$ and $-Q$ with their electric potentials are V_1 and V_2 respectively. Here, the potential difference between the two plates is $V = V_1 - V_2$ and the electric chrge of the capacitor is said to be Q.

The capacitance of a charged conductor can be significantly increased by bringing an uncharged earth–connected conductor closer to that charged conductor. When two conductive plates are separated by a dielectric medium in this way is called a capacitor.

The capacitors with fixed capacitance are denoted by –||– symbol while the capacitors with variable capacitance are denoted by ⫲ symbols.

As an interesting case, a single conducting sphere of radius R and having charge Q with potential difference of $V = kQ/R$ can also be consider as a capacitor, because it also has some capacity to store electric charge. For such a capacitor, imagine another sphere at infinite distance having –Q charge will have zero potential difference ($V = 0$). The potential difference between the proposed sphere and the imaginary sphere at infinite distance will also be $V = kQ/R$. So, the capacitance of the sphere will be, $C = \frac{Q}{V} = \frac{Q}{(kQ/R)} = \frac{R}{k} = 4\pi\varepsilon_0 R$, where ε_0 is absolute (vacuum) permeability.

Capacitance C is independent of Q or V, but it depends only on the shape, size and separtion of two plates besides the dielectric material of the capacitor.

2.5.4 Types of Capacitors [Only for Information] :

There are different types of capacitors depending on the material used in their fabrication. Such as : Electrolytic Capacitor, Mica Capacitor, Paper Capacitor, Film Capacitor, Non–Polarized Capacitor and Ceramic Capacitor. An Electrolytic capacitor uses a thin metallic film as anode and a paste of electrolyte chemical as a cathode, where the thin layer of oxide is dielectric. A mica capacitor is made by sandwiching a thin mica sheet between the conductor plates. A Paper capacitor is made by placing a waxpaper between tin plates. A film capacitor is made by placing a plastic film between a thin films of conductive metal. A non–polarized capacitor is made by placing plastic foil in it or two electrolytic capacitors are arranged in series connection. Ceramic capacitors contain ceramic dielectric material.

The types of capacitors depending on the shape of the conductive plate used in it are : In a Parallel–Plate Capacitor, the flat conductor plates are kept parallel to each other. A capacitor in which the conductive plates are spherical is called a spherical capacitor. In the cylindrical capacitor, cylindrical conductor plates are used.

2.5.5 Parallel Plate Capacitor and Its Capacitance :

Parallel plate capacitors are the most widely used. In a parallel plate capacitor, two parallel conducting plates of the same area (A) are separated at very short distance (d) from each other where a dielectric medium (insulating material) is placed between the two plates. Here the distance between two plates is kept very short in comparison to the dimensions (length, width or radius) of that plate ($d^2 << A$

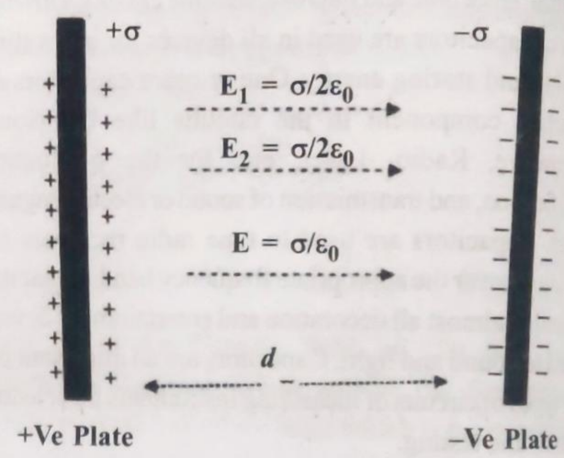


Fig. 2.13 : A Parallel Plate Capacitor

Let us derive the formula for the capacitance of a parallel plate capacitor with vacuum or as a dielectric medium, as shown in **Figure 2.13**. The charge of one plate is +Q and that of the other is –Q. The distance between two plates (d) is too short for their linear length so that $d^2 << A$

Area of capacitor = A M^2

Distance between two plates of the capacitor = d metre

Capacitor plate charge = Q coulomb

Charge density = $\sigma = Q/A$ coulomb/metre^2 .... (33)

The uniform electric field in the region between two plates due to positive plate in the direction from positive plate to the negative plate is $E_1 = \sigma/2\varepsilon_0$.

The uniform electric field in the region between two plates due to negtive plate in the direction from positive plate to the negative plate is $E_2 = \sigma/2\ \varepsilon_0$.

Since both the electric fields are in the same direction, the resultant uniform electric field

$$E = E_1 + E_2 \quad \text{... (34)}$$

$$\therefore \quad E = \frac{\sigma}{2\varepsilon_0} + \frac{\sigma}{2\varepsilon_0} = \frac{\sigma}{\varepsilon_0} \quad \text{... (35)}$$

$$\therefore \quad E = \frac{(Q/A)}{\varepsilon_0} + \frac{Q}{A\varepsilon_0} \quad \text{... (36)}$$

In the regions on the other side of the capacitor plates, electric fields E_1 and E_2 being equal and in opposite direction, the resultant electric field becomes zero.

$$\therefore \quad E = E_1 - E_2 = \frac{\sigma}{2\varepsilon_0} - \frac{\sigma}{2\varepsilon_0} = 0 \quad \text{... (37)}$$

The potential difference between the two plates is, $V = E.d$

$$\therefore \quad V = \frac{Qd}{A\varepsilon_0} \quad \text{... (38)}$$

Now, the capacaitance of the capacitor is $C = \frac{Q}{V}$

$$\therefore \quad C = \frac{Q}{\left(\frac{Qd}{A\varepsilon_0}\right)}$$

$$\therefore \quad C = \frac{A\varepsilon_0}{d} \quad \text{... (39)}$$

The capacitance of a parallel plate capacitor depends on the plate area dielectric meduim and the distance between two plates.

2.5.6 Combinations of Capacitors :

There are two types of connections of different capacitors having capacitances. Two or more capacitors can be connected in series combination or parallel combination. Equivalent, effective or resultant capacitance (C) of a system formed by series combination or parallel combination of two or more capacitors can be found.

Series Combination of Capacitors :

As shown in Figure 2.14, capacitors having capacitances $C_1, C_2, C_3, C_4, \dots C_n$ are connected in series by conducting wires and potential difference V is given to the system. We intend to obtain the resultant capacitance C_s in the series combination of capacitors.

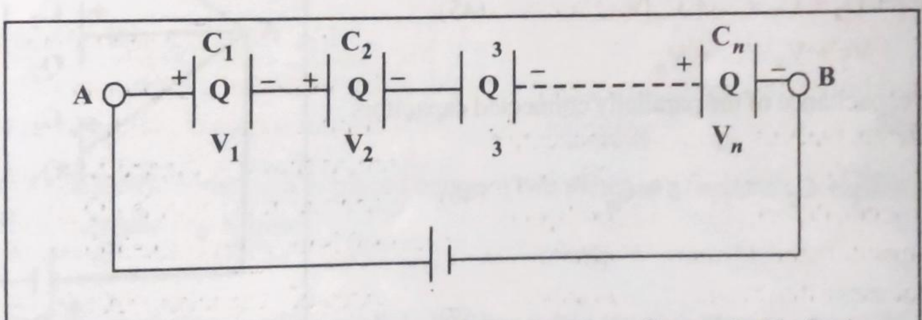


Fig. 2.14 : Resultant Capacitance of the capacitors Connected in Series

Let the left side plate of capacitor C_1 is given a $+Q$ charge. Electrostatic induction gives a $-Q$ charge on the inside and $+Q$ charge on the outside of the right side plate of capacitor C_1. This $+Q$ electric charge is transmitted to the plate on the left. And this process continues. (In the same way a negatively charged electron–current flows in the opposite direction.) Thus, each capacitor will receive an equal charge of $+Q$ magnitude. Since the capacitance of each capacitor is different, the potential difference with respect to each capacitor is different. If potential difference across $C_1, C_2, C_3, \dots, C_n$ are $V_1, V_2, V_3, \dots V_n$ respectively. Then $V_1 = Q/C_1$, $V_2 = Q/C_2$, $V_3 = Q/C_3$.....

In series combination of capacitors, the net (effective) potential difference (V) is the sum total of individual potential difference across each capacitor.

$$\therefore \quad V = V_1 + V_2 + V_3 + \dots + V_n \quad \text{... (40)}$$

The resultant capacitance in the series combination of capacitors is $C_s = \frac{Q}{V}$

$$\therefore \quad \frac{Q}{C_s} = \frac{Q}{C_1} + \frac{Q}{C_2} + \frac{Q}{C_3} + ... + \frac{Q}{C_n} = Q\left[\frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + ... + \frac{1}{C_n}\right] \qquad ... (41)$$

$$\therefore \quad \frac{1}{C_s} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + ... + \frac{1}{C_n} \qquad ... (42)$$

$$\therefore \quad \frac{1}{C_s} = \sum_{i=1}^{n} \frac{1}{C_i} \qquad ... (43)$$

The value of the effective (net or equivalent) capacitance C_s of the series connection of capacitors is obtaine summing the multiplicative inverse of the capacitance values of each of the capacitors. The value of effective capacita in series connection is even smaller than the smallest value of capacitance in the combination.

Parallel Combination of Capacitors :

As shown in **Figure 2.15**, capacitors having capacitances $C_1, C_2, C_3, C_4, ..., C_n$ are connected parallel to eachot by conducting wires and potential difference V is given to the two common joining points of all capacitors. We inten obtain the resultant capacitance C_p in the parallel combination of capacitors. In parallel combination of capacitors, potential difference (V) between the plates of every capacitor is the same and it is equal to the potential difference betw their common points, however the electric charge on each capacitor is different.

Here, $Q_1 = C_1V, Q_2 = C_2V, Q_3 = C_3V, ... Q_n = C_nV$ ... (44)

The total electric charge $Q_p = Q_1 + Q_2 + Q_3 + ... + Q_n$

$$\therefore \quad Q_p = C_1V + C_2V + C_3V + ... + C_nV$$

$$= [C_1 + C_2 + C_3 + ... + C_n]V \qquad ... (45)$$

$$\therefore \quad V = V_1 + V_2 + V_3 + ... + V_n$$

The effective capacitance of the parallelly connected capacitors

$$C_p = \frac{Q}{V} = C_1 + C_2 + C_3 + ... + C_n \qquad ... (46)$$

$$\therefore \quad C_p = \sum_{i=1}^{n} C_i \qquad ... (47)$$

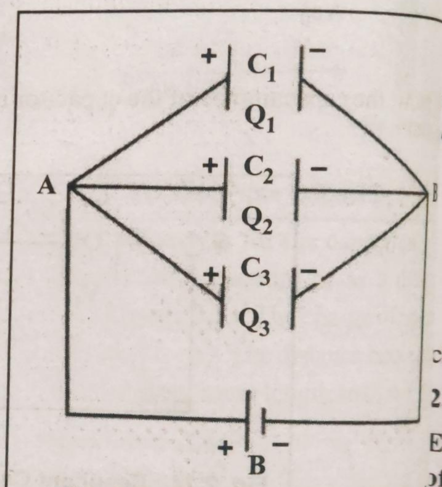


Fig. 2.15 : Resultant Capacitance of the capacitors Connected in Series

The value of the effective (net or equivalent) capacitance C_p of the parallel connection of capacitors is obtained summing the capacitance each of these capacitors. The value of effective capacitance is even higher than the largest va of capacitance in the combination.

In a series or parallel connection capacitor, the electric current is generated only where the battery is connected the capacitor plate. In the rest of the plates, only the shifting of the charge occurs.

2.5.7 Effect of Dielectric Material on the Capacitance of Parallel Plate Capacitor :

Any insulating medium is called dielectric medium. Faraday found that placing an insulating substance between the plates of a capacitor increases its capacitance.

According to Coulomb's law, when two charges q_1 and q_2 are r distance apart from each other in vacuum or the force of attraction between them is, $F_0 = \frac{1}{4\pi\varepsilon_0}\frac{q_1q_2}{r^2}$ where ε_0 is the absolute permittivity.

If the same charges q_1 and q_2 are kept r distance apart from each other in the medium of ε electrical permittivity, the force attraction between them is, $F_m = \frac{1}{4\pi\varepsilon}\frac{q_1 q_2}{r^2}$.

Taking ratio of both, $\frac{F_0}{F_m} = \frac{\varepsilon}{\varepsilon_0} = \varepsilon_r = K$ ... (48)

Where, ε_r is called the relative (electric) permittivity or dielectric constant (K) of the medium.

$$\varepsilon_r \text{ or } K = \frac{\text{Capacitance when a dielectric medium is inserted between two plates of the capacitor}}{\text{Capacitance when there is air between two plates of the same capacitor}}$$

$$\therefore \quad \varepsilon_r \text{ and } K = \frac{C_m}{C_0} \qquad \text{... (49)}$$

$$\therefore \quad C_m = KC_0 = \varepsilon_r \frac{\varepsilon_0 A}{d} = \frac{\varepsilon A}{d} \qquad \text{... (50)}$$

If there is an air or vacuum as a dielectric medium between the two plates of the capacitor, then its capacitance will be, $C_0 = \varepsilon_0 A/d$ ... (51)

The ratio of the permittivity of the medium (ε) to that of the vacuum (ε_0) is called the relative permittivity of the medium (ε_r) or dielectric constant (K), where K is always greater than 1. Instead of air if a medium of permittivity ε and dielectric constant K is placed beween two plates of a capacitor, its capacitance will be,

$$C_m = \frac{\varepsilon A}{d} = \frac{\varepsilon_r \varepsilon_0 A}{d} = \frac{K\varepsilon_0 A}{d}$$

$$\therefore \quad C_m = KC_0 \qquad \text{... (52)}$$

When a medium of dielectric constant K is placed between two plates of a capacitor, is capacitance and hence its charge storage capacity is increased by K times.

2.5.8 Illustrations :

Example-10 : Calculate the capacitance of a parallel plate capacitor if 1 mm distance is kept between the plates of 1 mm sides.

Solution :

Side = Length = Width = 1 mm = 10^{-3} m

Area of each plate, A = $1 \text{mm}^2 = 10^{-6} \text{m}^2$

Distance between two plates, d = 1 mm = 10^{-3} m

Absolute permittivity, $\varepsilon_0 = 8.85 \times 10^{-12}$ F/m

Capacitance of a parallel plate capacitor,

$$C = \frac{\varepsilon_0 A}{d}$$

$$= \frac{8.85 \times 10^{-12} \times 10^{-6}}{10^{-3}}$$

$$= 8.85 \times 10^{-9} \text{ F} = 8.85 \text{ nF}$$

Example-11 : What should be the length and width of two parallel plates separated by a distance of 1 mm in a capacitor to obtain 1 F capacitance ?

Solution :

Distance between two plates, $d = 1\ mm = 10^{-3}\ m$

Absolute Permittivity, $\varepsilon_0 = 8.85 \times 10^{-12}$ F/m

Length = Width = Side of the plate = ?

Area of each plate in the parallel plate capacitor,

$$A = \frac{C_d}{\varepsilon_0} = \frac{1 \times 10^{-3}}{8.85 \times 10^{-12}} = 1.13 \times 10^{8}\ m^2$$

Length = Width = Side of the capacitor

$$l = \sqrt{A} = \sqrt{1.13 \times 10^{8}} \approx 1.06 \times 10^{4}\ m$$

Each plate should have atleast 10 km sides.

Example-12 : Calculate the capacitance of two plates of 100 cm × 100 cm of a parallel plate capacitor separated by a 2 mm thick glass plate of dielectric constant, K = 4.

Solution :

Area of each capacitor plate

$A = 100 \times 100 = 10^4\ cm^2 = 1\ m^2$

Distance btween two plates,

$d = 2\ mm = 2 \times 10^{-3}\ m$

Dielectric constant, $K = \varepsilon_r = 4$

Absolute permittivity,

$\varepsilon_0 = 8.85 \times 10^{-12}$ F/m

Capacitance due to medium of dielectric consant K is given by,

$$C = \frac{K \varepsilon_0 A}{d}$$

$$\therefore\ C = \frac{4 \times 8.85 \times 10^{-12} \times 1}{2 \times 10^{-3}} = 1.77 \times 10^{-8}\ \text{farad}$$

Example-13 : In a parallel plate capacitor the area of the plate is 200 and the distance between the plates is 1 mm. (i) If capacitor is given 1n C charge, calculate the potential difference between the two plates. (ii) If distance between two plates is increased up to 2 mm without changing its charge, what will be potential difference ? (iii) What will be the electric field between the plates ?

Solution :

Distance between two plates,

$d = 1\ mm = 10^{-3}\ m$

Plate area, $A = 200\ cm^2 = 2 \times 10^{-2}\ m^2$

Electric charge on a plate,

$Q = 1\ nC = 1 \times 10^{-9}\ C$

Absolute permittivity, $\varepsilon_0 = 8.85 \times 10^{-12}$ F/m

Capacitance of parallel plate capacitor, $C = \varepsilon_0 A/d$

$$\therefore\ C = \frac{(8.85 \times 10^{-12})(2 \times 10^{-2})}{10^{-3}}$$

$$= 0.177 \times 10^{-9}\ F = 0.177\ nF$$

(1) Potential difference between two plates of the capacitor,

$$V = \frac{Q}{C} = \frac{1 \times 10^{-9}}{0.177 \times 10^{-9}} = 5.65\ V$$

(2) If the distance between two plates is increased up to 2 mm, the potential difference between the plates will be double.

$$\therefore\ V = 5.65 \times 2 = 11.3\ V$$

(3) Electric field, $E = \dfrac{\sigma}{\varepsilon_0} = \dfrac{Q}{A\varepsilon_0}$

$$\therefore \quad E = \frac{1 \times 10^{-9}}{2 \times 10^{-2} \times 8.85 \times 10^{-12}} = 5650 \text{ N/C}$$

Example-14 : The capacitance of a parallel plate capacaitor with air as dielectric medium is 8 pF. Calculate the capacitance of the capacitor, if the distance between plates is halved and a material of dielectric constant (K = 6) will be provided to you.

Solution :

Initially, when the distance between two plates of a capacitaor is *d*, then its capacitance will be $C_0 = \varepsilon_0 A/d = 8$ pF

Dielectric material with constant, $K = \varepsilon = 6$

The relative permittivity of the medium $(\varepsilon_r) = \dfrac{\text{Permittivity of medium } (\varepsilon)}{\text{Absolute permittivity } (\varepsilon_0)} \Rightarrow \varepsilon = \varepsilon_0 \cdot \varepsilon_r$

Now, capacitance of the capacitor when the distance between its two plates is d/2 and a dielectric material of K = 6 is placed between them,

$$C = \frac{KA}{d} = \frac{\varepsilon_0 \cdot \varepsilon_r A}{d/2} = \frac{2\varepsilon_0 \cdot \varepsilon_r A}{d} = 2\varepsilon_r \frac{\varepsilon_0 A}{d} = 2\varepsilon_r C_0$$

$$\therefore \quad C = 2 \times 6 \times 8 = 96 \text{ pF}$$

Example-15 : The capacitance of a parallel plate capacitor is 5 F. Its capacitance is 60 μF if a dielectric object is placed between its two plates. Multiply the constant of dielectric matter.

Solution :

Capacitance due tot a medium having a dielectric constant K is , $C = \dfrac{K\varepsilon_0 A}{d}$ $\quad \therefore \dfrac{\varepsilon_0 A}{d} = \dfrac{C}{K}$

When there is no dielectric medium (K = 1) its capacitance, C = 5 μF

$$\therefore \frac{\varepsilon_0 A}{d} = \frac{5}{1} = 5$$

When there is medium of unknown dielectric constant (K = ?) is placed between two plates of capacitor, its capacitance, C = 60 μF

$$\therefore \frac{\varepsilon_0 A}{d} = \frac{60}{K}$$

Comparing both, $\dfrac{\varepsilon_0 A}{d} = 5 = \dfrac{60}{K}$

∴ The dielectric constant of the material, K = 12

Example-16 : Obtain equivalent capacitance for series and parallel combination of 3 capacitors having capacitances 5 μF, 10 μF and 15 μF respectively, where a potential difference of 4 V is given by the battery.

Solution :

Equivalent capcacitance for the series combination $\dfrac{1}{C_s} = \sum_{i=1}^{n} \dfrac{1}{C_i}$

Equivalent capcacitance for the parallel combination, $C_p = \sum_{i=1}^{n} \dfrac{1}{C_i}$

$$C_p = C_1 + C_2 + C_3$$

$$C_p = 5 + 10 + 15 = 30 \text{ μF}$$

$$\frac{1}{C_s} = \frac{1}{5} + \frac{1}{10} + \frac{1}{15} = \frac{6+3+2}{30} = \frac{11}{30}$$

$C_s = 30/11 = 2.72\ \mu F$

Example-17 : When a slab with a dielectric constant of K = 3 is placed between two plates of a capacitor, i[ts] capacitance is 15 μF. If there is air between the plates of this capacitor, what will be its capacity ?

Solution : $K = C_m/C_0$

$$\therefore \quad C_0 = \frac{C_m}{K} = \frac{10}{2} = 5\ \mu F$$

SUMMARY

→ Every substance (atom) is basically made up of electrons, protons and neutrons, called Fundamental Particles.

→ The mass of an electron is $M_e = 9.1 \times 10^{-31}$ Kg, the mass of a proton and a neutron are considered to be nearly the same, i.e. $M_p \cong M_n = 1.6 \times 10^{-27}$ kg.

→ There are two types of electric charges– Positive and Negative. The force acting between two like charges is repulsive and it is attractive between unlike charges.

→ When two suitable objects are rubbed together, electric charge is transferred to them. For example, while rubbing a glass rod with a silk cloth, the glass rod becomes positively charged by losing electrons and silk becomes negatively charged by getting electrons.

→ The charge that is fixed on an object is called static charge and the study of their effects is called static electricity.

→ Two objects can be charged by rubbing them together (friction). When an electrically charged object is brought closure to another object, it can be charged by induction.

→ When electric charges are made to move by applying some force, the movement of charges is called electric current and the study of effects produced by an electric current is called current electricity.

→ A repulsive force called electric force of $F = 2.24 \times 10^{-24}$ N exists between two electrons.

→ Electric force is 10^{43} times greater than the gravitational force. The property of particles due to which an electric force exists between them is called the electric charge of the particle. A specific property of matter due to which a much more powerful force exists between two objects than the gravitational force (10^{43} times higher) is called electric charge.

→ The magnitude of all electric charges found in nature are always in integral multiple of a fundamental charge. This fundamental charge is $e = 1.6 \times 10^{-19}$ coloumb (C) that is equal to the charge on an electron or a proton. This is called the quantisation of electric charge $Q = ne$.

→ The charge of an electron is $e_e = -1.6 \times 10^{-19}$C and the charge of a proton is $e_p = 1.6 \times 10^{-19}$ C.

→ The net electric charge in an isolated system remains the same before and after any reaction or process takes place in it. The net electric charge (or the algebraic sum of charges) in an electrically isolated system remains constant, irrespective of any process takes place. This is the quantization of electric charge.

→ "The electric force (Coulombian force) between two stationary point charges is directly proportional to the product of their charges and inversely proportional to the square of the distance between them." This is Coulomb's law. This force is along the line of joining the two charges.

$$F \propto \left(\frac{q_1 q_2}{r^2}\right) \Rightarrow F = k\,\frac{q_1 q_2}{r^2} \Rightarrow F = \left(\frac{1}{4\pi\varepsilon_0}\right)\frac{q_1 q_2}{r^2}.$$

If $q_1 q_2 > 0$, repulsive force exists between the two charges and for $q_1 q_2 < 0$, there is an attractive force between the charges.

→ The electric (Coulombian) force between two stationary point charges q_1 and q_2 separated by a distance r is given by $F = k\left(\frac{q_1 q_2}{r^2}\right)$, where Coulombian constant

$$k = \left(\frac{1}{4\pi\varepsilon_0}\right) = 8.9875 \times 10^9 \approx 9 \times 10^9 \text{ Nm}^2 \text{ C}^{-2}$$

(SI) and $k = 1$ dyne cm C^{-2} (CGS). Also, Permittivity of Free Space, $\varepsilon_0 = \left(\frac{1}{4\pi k}\right) = 8.854 \times 10^{-12}$ C^2/Nm^2.

→ The Relative Permittivity (ε_r) or Dielectric constant (K) of the given medium > 1.

Where,

$$\varepsilon_r = \frac{\text{Permittivity of medium } (\varepsilon)}{\text{Permittivity of Free Space or Vacuum } (\varepsilon_0)} = K$$

→ Since the relative permeability of the medium (ε_r), is always greater than one, the Columbian force (F_m) in a given medium is less than the force exerted in a vacuum (F). Thus $\varepsilon_r > 1 \Rightarrow F_m < F$.

→ Superposition Principle : The net electric force between more than two electric charges in space can be obtained by taking the algebraic sum of all the individual forces exerted between each pair of electric charges. This is called the superposition principle. (Coulomb's law can be used to obtain the electric (Coulombian) force acting between two stationary electric point charges.)

→ The force experienced by (acting on) a unit positive charge (q_0) at a given point at a certain distance from a charge Q (or a system of charges) in the electric field is called intensity of electric field (or electric intensity) $\vec{E}$ at that point.

→ A charge experiences electric force by another charge or a system of charges (Q) in the vicinity area is called (intensity of) electric field due to that charge (or the system of charges). If we know the electric field generated by a charge or a set of charges in a given area, then the electric force $F = qE$ applied to another charge at one point in that area can be found. According to Super Position Principle, $E = k\sum_{i=1}^{n}\frac{q_i}{r_i^2}$.

→ The (intensity of) electric field at a distance r is $E = \frac{kq}{r^2}$. Electric field is a vector quantity having unit N/C in SI; and it is in the direction of the force exerted on the electric charge.

→ An electric field of point $+q$ charge is in the radial direction away from that electric charge and, similarly, the electric field of $-q$ charge is inward in the radial direction. The electric field always exits (starts from) $+q$ and hangs on (ends at) $+q$.

→ Electric field (force) lines start from the positive charge and end on a negative charge. The tangent drawn at any point on the electric field line indicates the direction of the electric field at that point. Two electric field lines never intersect each other. The distance between the electric field lines indicates the intensity of the electric field in that area. The closely (Densely) arranged electric field lines indicates a strong (high) electric field (intensity) and vice versa. Spaciously arranged (scattered) electric field lines indicates weak (poor) electric field (intensity) and vice versa. Field lines of the homogeneous (uniform) electric field are parallel to each other and at equal distances from each other. Electric field lines are imaginary, but electric field is reality. Electric Field lines are always perpendicular to the conducting surface.

→ The electric flux (φ) is the number of electric field lines passing perpendicular to a given surface area. φ = E.A. = EA cos θ. Electric flux is a scalar quantity and its SI unit is Vm or Nm^2/C.

→ Some work is to be done on the electric charge to make it move in the electric field. The work done on the unit electric charge to move it in the electric field is called electric potential at that point. The electric potential at distance r from the charge q in its electric field is $V = kq / r$.

→ The potential difference (PD) due to charge (q) between two points at r distance is as follows.

$$V_B - V_A = -k\frac{Q}{r_{AB}} = -\frac{W_{AB}}{q_0}.$$

→ A capacitor is a device designed to store a large amount of electric charge and hence electric energy in a small space.

→ When a positively charged conductor (positive plate) and a negatively charged conductor (negative plate) are separated by a distance less than their dimensions (length and breadth) and a dielectric medium is placed between the two, and both conductors are connected to the two terminals of the battery, a potential difference (V) is formed between the two. This mechanism is called capacitor.

→ The charge (Q) of a positive plate is called the charge on the capacitor.

→ The value of capacitance depends on the dimensions (shape, size and area) of the two conducting plates and the distance between them. It also depends on the dielectric medium. The distance between two plates in a capacitor is kept very short in comparison to the dimensions (length/ width/radius) of the plates $d^2 << A$.

→ Capacitance (C) = Electric charge (Q)/ Potential difference (V)

→ The SI unit of capacitance is the coulomb/volt called farad (F). Since farad (F) is a very large unit for measuring the capacitance of real capacitors, in practice microfarad (microfarad; 1 μF = 10^{-6} F), nanofarad(nanofarad; 1nF = 10^{-9}F) and picofarad (picofarad; 1 pF = 10^{-12}F) are used.

→ The capacitors with fixed capacitance are denoted by −||− symbol while the capacitors with variable capacitance are denoted by symbols.

→ In a parallel plate capacitor, two parallel conducting plates of the same area (A) are separated at very short distance (d) from each other where a dielectric medium (insulating material) is placed between the two plates.

→ A single conducting sphere of radius R and hav charge Q with potential difference of V = kQ/R c also be considered as a capacitor, where ano imaginary conducting sphere having −Q charge w have zero potential difference (V = 0) at infin distance. The capacitance of the sphere will b

$$C = \frac{Q}{V} = \frac{Q}{(kQ/R)} = \frac{R}{k} = 4\pi\varepsilon_0 R,$$

where ε_0 is absolute (vacuum) permeability.

→ In the area inside the parallel plate capacitor, th electric field originating from + ve to − ve and from ve to + ve charged plates is in one direction. i.e $E_+ = E_- = \sigma/2\varepsilon_0$. The resultant electric field will be

$E = E_1 + E_2 = \dfrac{Q}{A\varepsilon_0}$ In the regions on the other side of the capacitor plates, electric fields E_1 and E_2 being equal and in opposite direction, the resultant electric field becomes zero.

→ The capacitance of a parallel plate capacitor

$$C = \frac{A\varepsilon_0}{d}.$$

→ Connection of C_1, C_2, C_3, ... C_n capacitors i

$$\frac{1}{C_s} = \frac{1}{C_1} + \frac{1}{C_2} + ... + \frac{1}{C_n} + \frac{1}{C_s} = \sum_{i=1}^{n}\frac{1}{C_i}.$$

→ The value of the effective capacitance of the series connection of capacitors is obtained by summing the multiplicative inverse of the capacitance values of each individual capacitors. The value of effective capacitance in series connection is even smaller than the smallest value of capacitance in the combination.

→ The net/effective capacitance C_p of the parallel connection of C_1, C_2, C_3, ... C_n capacitors is

$$C_p = \frac{Q}{V} = C_1 + C_2 + ... + C_n \text{ and } C_p = \sum_{i=1}^{n} C_i.$$

→ The value of the effective (net or equivalent) capacitance C_p of the parallel connection of capacitors is obtained by summing the capacitance each of these capacitors. The value of effective capacitance is even higher than the largest value of capacitance in the combination.

- Any insulating medium is called dielectric medium. Faraday found that placing an insulating substance between two plates of a capacitor increases its capacitance.
- The ratio of the permittivity of the medium (ε) to that of the vacuum (ε_0) is called the relative permittivity of the medium (ε_r) or dielectric constant (K), where K is always greater than 1.
- $$\varepsilon_r \text{ or } K = \frac{\text{Capacitance when a dielectric medium is inserted between two plates of the capacitor}}{\text{Capacitance when there is air between two plates of the same capacitor}}$$
- If there is a dielectric medium, instead of air, between the two plates of the capacitor, then its capacitance will be

$$C_m = \frac{\varepsilon A}{d} = \frac{\varepsilon_r \varepsilon_0 A}{d} = \frac{K \varepsilon_0 A}{d} \quad \therefore C_m = KC_0$$