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CBSE – XIIth

Physics

Central Board of Secondary Education (CBSE)

Quick Revision Notes + Sample Questions

SIERRA INNOVATIONS

INDEX

01

Electric charges and fields

1. Electric Charge :

Charge of a material body is that property due to which it interacts with other charges. There are two kinds of charges-positive and negative. S.I. unit is coulomb. Charge is quantized, conserved, and additive.

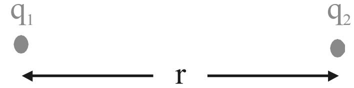
Example

If 10^9 electrons move out of a body to another body every second, how much time is required to get a total charge of 1 C on the other body? **[NCERT Pg No. 6]**

Sol. In one second 10^9 electrons move out of the body. Therefore the charge given out in one second is $1.6 \times 10^{-19} \times 10^9$ C $= 1.6 \times 10^{-10}$ C.
The time required to accumulate a charge of 1 C can then be estimated to be 1 C $\div$ (1.6×10^{-10} C/s) $= 6.25 \times 10^9$ s $= 6.25 \times 10^9 \div (365 \times 24 \times 3600)$ years = 198 years. Thus to collect a charge of one coulomb, from a body from which 10^9 electrons move out every second, we will need approximately 200 years. One coulomb is, therefore, a very large unit for many practical purposes.
It is, however, also important to know what is roughly the number of electrons contained in a piece of one cubic centimetre of a material.
A cubic piece of copper of side 1 cm contains about 2.5×10^{24} electrons.

2. Coulomb`s law :

Force between two charges $\vec{F} = \frac{1}{4\pi \epsilon_0 \epsilon_r} \frac{q_1 q_2}{r^2} \hat{r}$ $\quad \epsilon_r$ = dielectric constant



Note :

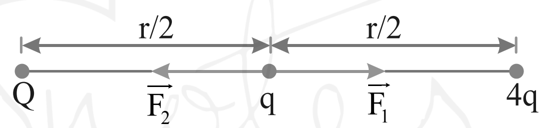
The Law is applicable only for static and point charges. Moving charges may result in magnetic interaction. And if charges are extended, induction may change the charge distribution.

Example

Two point charges Q and q are placed at distance r and $\frac{r}{2}$ respectively along a straight line from a third charge 4q. If q is in equilibrium, determine $\frac{Q}{q}$.

Sol. Net force on q = 0

$$\vec{F}_1 + \vec{F}_2 = 0$$



$$\Rightarrow \frac{1}{4\pi\epsilon_0}\frac{Qq}{(r/2)^2} - \frac{1}{4\pi\epsilon_0}\frac{4q.q}{(r/2)^2} = 0$$

$$\Rightarrow \frac{Q}{q} = 4$$

3. Principle Of Superposition :

Force on a point charge due to many charges is given by

$$\vec{F} = \vec{F}_1 + \vec{F}_2 + \vec{F}_3 + ...$$

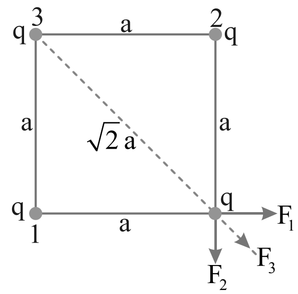
Note :

The force due to one charge is not affected by the presence of other charges.

Example

Consider four equal charges (q each) placed on the corners of a square with side a. Determine the magnitude and direction of the resultant force on the charge on lower right corner.

Sol. The forces on the charge on lower right corner due to charges 1, 2, 3 are $F_1 = kq^2/a^2$, $F_2 = kq^2/a^2$, $F_3 = kq^2/2a^2$
The resultant of F_1 and F_2 is



$$F_{12} = \sqrt{F_1^2 + F_2^2 + 2F_1F_2\cos 90°} = \sqrt{2}kq^2/a^2$$

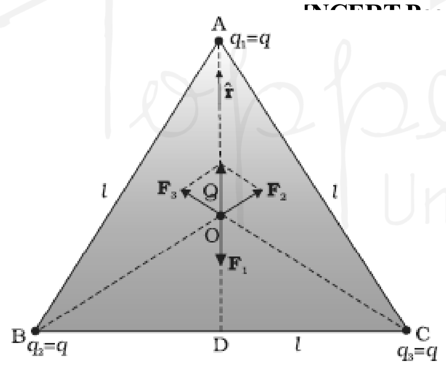
This is in the direction parallel to F_3. Therefore the total force on the said charge is $F = F_{12} + F_3$

$$F = \frac{1}{2}\frac{kq^2}{a^2}(1 + 2\sqrt{2})$$ The direction of F is 45° below the horizontal line

Example

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, as shown in below ?

[NCERT Page No 12]



Sol. In the given equilateral triangle ABC of sides of length l, if we draw a perpendicular AD to the side BC,

AD = AC cos° = $\left(\frac{\sqrt{3}}{2}\right)$ l and the distance AO of the centroid O from A is (2/3) AD = $\left(\frac{1}{\sqrt{3}}\right)$ l. By symmetry AO = BO = CO.

Thus,

Force F_1 on Q due to charge q at A = $\frac{3}{4\pi\varepsilon_0}\frac{Qq}{l^2}$ along AO

Force F_2 on Q due to charge q at B = $\frac{3}{4\pi\varepsilon_0}\frac{Qq}{l^2}$ along BO

Force F_3 on Q due to charge q at C = $\frac{3}{4\pi\varepsilon_0}\frac{Qq}{l^2}$ along CO

The resultant of forces F_2 and F_3 is $\frac{3}{4\pi\varepsilon_0}\frac{Qq}{l^2}$ along OA. by the parallelogram law. Therefore, the total force on Q = $\frac{3}{4\pi\varepsilon_0}\frac{Qq}{l^2}(\hat{r} - \hat{r}) = 0$

where $\hat{r}$ is the unit vector along OA. It is clear also by symmetry that the three forces will sum to zero. Suppose that the resultant force was non – zero but in some direction. Consider what would happen if the system was rotated through 60° about O.

4. *Electric Field or Electric Intensity or Electric Field Strength (Vector Quantity) :*

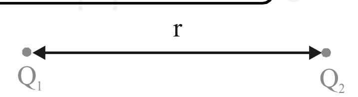
In the surrounding region of a charge there exist a physical property due to which other charge experiences a force. The direction of electric field is direction of force experienced by a positively charged particle and the magnitude of the field (electric field intensity) is the force experienced by a unit charge.

$\vec{E} = \frac{\vec{F}}{q}$ unit is N/C or V/m.

5. *Electric field intensity due to charge Q :*

$$\vec{E} = \lim_{q_0 \to 0}\frac{\vec{F}}{q_0} = \frac{1}{4\pi\epsilon_0}\frac{Q}{r^2}\hat{r}$$

6. *Null point for two charges :*



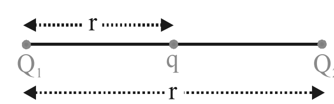
If $|Q_1| > |Q_2| \Rightarrow$ Null point near Q2

$$x = \frac{\sqrt{Q_1}r}{\sqrt{Q_1} \pm \sqrt{Q_2}}$$

(+) for like charges (–) for unlike charges

7. *Equilibrium of three point charges :*

(i) Two charges must be of like nature.

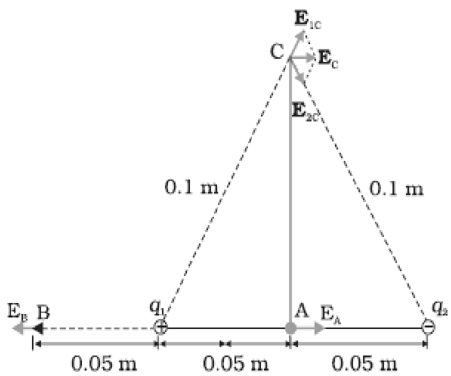


(ii) Third charge should be unlike nature.

$$x = \frac{\sqrt{Q_1}}{\sqrt{Q_1} \pm \sqrt{Q_2}}r \text{ and } q = \frac{-Q_1Q_2}{\left(\sqrt{Q_1} + \sqrt{Q_2}\right)^2}$$

Example

Two point charges q_1 and q_2, of magnitude $+10^{-8}$ C and -10^{-8} C respectively, are placed 0.1 m apart. Calculate the electric fields at points A, B and C shown below .



Sol. The electric field vector E_{1A} at A due to the postive charge q_1 points towards the right and has a magnitude

$$E_{1A} = \frac{(9\times10^9\,Nm^2C^{-2})\times(10^{-8}C)}{(0.05m)^2} = 3.6\times10^4\,N\,C^{-1}$$

The electirc field vector E_{2A} at A due to the negative charge q_2 points towards the right and has the same magnitude. Hence the magnitude of the total electric field E_A at A is

$E_A = E_{1A} + E_{2A} = 7.2 \times 10^4 N C^{-1}$

E_A is directed toward the right

The electric field vector E_{1B} at B due to the positive charge q_1 points towards the left and has a magnitude

$$E_{1B} = \frac{(9\times10^9\,Nm^2C^{-2})\times(10^{-8}C)}{(0.05m)^2} = 3.6\times10^4\,N\,C^{-1}$$

The electric field vector E_{2B} at B due to the negative charge q_2 points towards the right and has a magnitude

$$E_{2B} = \frac{(9\times10^9\,Nm^2C^{-2})\times(10^{-8}C)}{(0.15m)^2} = 4\times10^3\,N\,C^{-1}$$

The magnitude of the total electric field at B is

$E_B = E_{1B} - E_{2B} = 3.2 \times 10^4 N C^{-1}$

E_B is directed towards the left.

The magnitude of each electric field vector at point C, due to charge q_1 and q_2 is

$$E_{1C} = E_{2C} = \frac{(9\times10^9\,Nm^2C^{-2})\times(10^{-8}C)}{(0.10m)^2} = 9\times10^3\,N\,C^{-1}$$

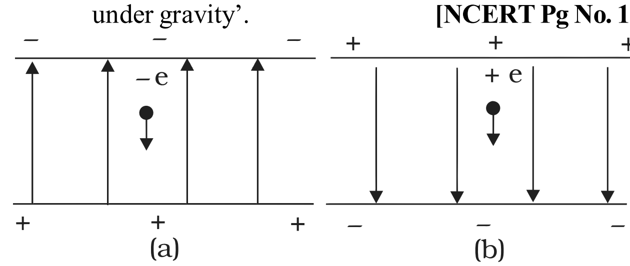
The directions in which these two vectors points are indicated in Figure. The resultant of these two vectors is

$$E_C = E_{1C}\cos\frac{\pi}{3} + E_{2C}\cos\frac{\pi}{3} = 9\times10^3\,NC^{-1}$$

E_C points towards the right.

Example

An electron falls through a distance of 1.5 cm in a uniform electric field of magnitude 2.0×10^4 N C^{-1} [Fig. (a)]. The direction of the field is reversed keeping its magnitude unchanged and a proton falls through the same distance [Fig. (b)]. Compute the time of fall in each case. Contrast the situation with that of 'free fall under gravity'. **[NCERT Pg No. 17]**



Sol. In Fig. (a) the field is upward, so the negatively charged electron experiences a downward force of magnitude *eE* where *E* is the magnitude of the electric field. The acceleration of the electron is

$a_e = eE/m_e$

where m_e is the mass of the electron.

Starting from rest, the time required by the electron to fall through a distance *h* is given by $t_e =$

$$\sqrt{\frac{2h}{a_e}} = \sqrt{\frac{2hm_e}{eE}}$$

For $e = 1.6 \times 10^{-19}$C, $m_e = 9.11 \times 10^{-31}$ kg,

$E = 2.0 \times 10^4 N C^{-1}$, $h = 1.5 \times 10^{-2}$ m,

$t_e = 2.9 \times 10^{-9}$s

In Fig. (b), the field is downward, and the positively charged proton experiences a downward force of magnitude eE. The acceleration of the proton is

$a_p = eE/m_p$

where m_p is the mass of the proton; $m_p = 1.67 \times 10^{-27}$ kg. The time of fall for the proton is

$$t_P = \sqrt{\frac{2h}{a_P}} = \sqrt{\frac{2hm_P}{eE}} = 1.3\times10^{-7}\,s$$

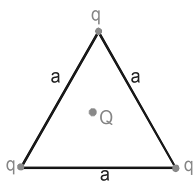
Thus, the heavier particle (proton) takes a greater time to fall through the same distance. This is in basic contrast to the situation of 'free fall under gravity' where the time of fall is independent of the mass of the body. Note that in this example we have ignored the acceleration due to gravity in calculating the time of fall. To see if this is justified, let us calculate the acceleration of the proton in the given electric field:

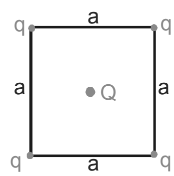
$$a_P = \frac{eE}{m_P} = \frac{(1.6\times10^{-19}\,C)\times(2.0\times10^4\,NC^{-1})}{1.67\times10^{-27}\,kg}$$

$= 1.9 \times 10^{12}$ ms^{-2}

which is enormous compared to the value of g (9.8 m s^{-2}), the acceleration due to gravity. The acceleration of the electron is even greater. Thus, the effect of acceleration due to gravity can be ignored in this example.

8. Equilibrium of symmetric geometrical point charged system :





Value of Q at centre for which system to be in state of equilibrium

(a) For equilateral triangle $Q = \frac{-q}{\sqrt{3}}$

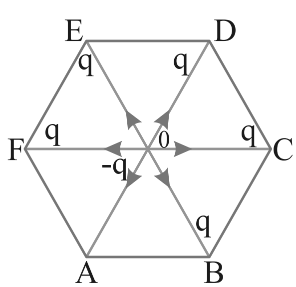
(b) For square $Q = \frac{-q\left(2\sqrt{2}+1\right)}{4}$

Example

Five point charges, each of value +q are placed on five vertices of a regular hexagon of side L. What is the magnitude of the force on a point charge of value –q coulomb placed at the centre of the hexagon?

Sol. If there had been a sixth charge +q at the remaining vertex of hexagon force due to all the six charges on -q at O will be zero (as the forces due to individual charges will balance each other),

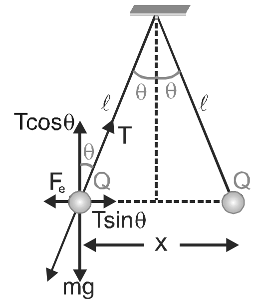
i.e., $\vec{F}_R = 0$.



Now If $\vec{f}$ is the force due to sixth charge and $\vec{F}$ due to remaining five charges, $\vec{F} + \vec{f} = 0$ i.e. $\vec{F} = -\vec{f}$ or,

$$F = f = \frac{1}{4\pi\varepsilon_0}\frac{q \times q}{L^2} = \frac{1}{4\pi\varepsilon_0}\left[\frac{q}{L}\right]^2$$

9. Equilibrium of suspended point charge system :

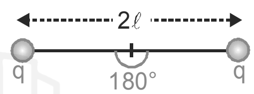


For equilibrium position

$T\cos\theta = mg$ &

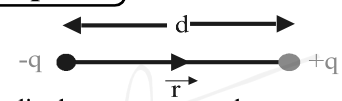
$$T\sin\theta = F_e = \frac{kQ^2}{x^2} \Rightarrow \tan\theta = \frac{F_e}{mg} = \frac{kQ^2}{x^2 mg}$$

If whole set up is taken into an artifical satelite ($g_{eff} \to 0$)



$$T = F_e = \frac{kq^2}{4\ell^2}$$

10. Electric dipole :



(a) Electric dipole moment $p = qd$

(b) Torque on dipole placed in uniform electric field $\vec{\tau} = \vec{p} \times \vec{E}$

(c) Work done in rotating dipole placed in uniform electric field

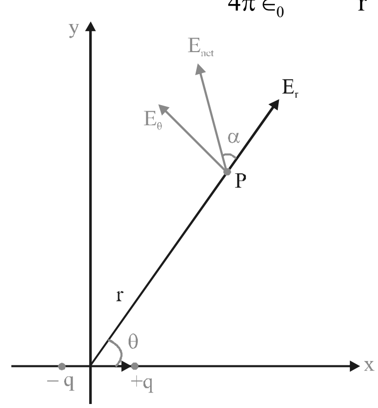
$$W = \int \tau d\theta = \int_{\theta_0}^{\theta} PE\sin\theta d\theta = pE\left(\cos\theta_0 - \cos\theta\right)$$

(d) Potential energy of dipole placed in an uniform field

$U = -\vec{p}.\vec{E}$

(e) At a point which is at a distance r from dipole midpoint and making angle θ with dipole axis.

(1) Electric field $E = \frac{1}{4\pi\epsilon_0}\frac{p\sqrt{1+3\cos^2\theta}}{r^3}$



(2) Direction $\tan\alpha = \frac{E_\theta}{E_r} = \frac{1}{2}\tan\theta$

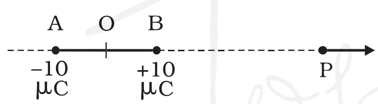
(f) Electric field at axial point (or End-on) $\vec{E} = \frac{1}{4\pi\epsilon_0}\frac{2\vec{p}}{r^3}$ of dipole

(g) Electric field at equatorial position (Broad-on) of dipole

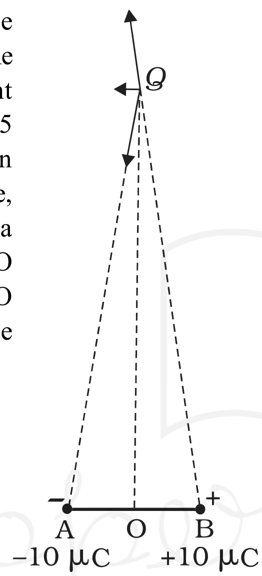
$$\vec{E} = \frac{1}{4\pi\epsilon_0}\frac{(-\vec{p})}{r^3}$$

Example

Two charges ±10 μC are placed 5.0 mm apart. Determine the electric field at (a) a point P on the axis of the dipole 15 cm away from its centre O on the side of the positive charge, as shown in Fig. (a), and (b) a point Q, 15 cm away from O on a line passing through O and normal to the axis of the dipole, as shown in Fig. (b). **[NCERT Pg No. 25]**



(a)



(b)

Sol. (a) Field at P due to charge +10 μC

$$= \frac{10^{-5}\ \text{C}}{4\pi(8.854\times10^{-12}\,\text{C}^2\text{N}^{-1}\text{m}^{-2})}\times\frac{1}{(15-0.25)^2\times10^{-4}\,\text{m}^2}$$

$= 4.13 \times 10^6$ N C^{-1} along BP

Field at P due to charge –10 μC

$$= \frac{10^{-5}\ \text{C}}{4\pi(8.854\times10^{-12}\,\text{C}^2\text{N}^{-1}\text{m}^{-2})}\times\frac{1}{(15+0.25)^2\times10^{-4}\,\text{m}^2}$$

$= 3.86 \times 10^6$ N C^{-1} along PA

The resultant electric field at P due to the two charges at A and B is $= 2.7 \times 10^5$ N C^{-1} along BP.

In this example, the ratio OP/OB is quite large (= 60). Thus, we can expect to get approximately the same result as above by directly using the formula for electric field at a far-away point on the axis of a dipole.

For a dipole consisting of charges ± q, 2a distance apart, the electric field at a distance r from the centre on the axis of the dipole has a magnitude

$$E = \frac{2p}{4\pi\varepsilon_0 r^3} \qquad (r/a >> 1)$$

where p = 2a q is the magnitude of the dipole moment.

The direction of electric field on the dipole axis is always along the direction of the dipole moment vector (i.e., from –q to q). Here,

$p = 10^{-5}\ \text{C} \times 5 \times 10^{-3}\ \text{m} = 5 \times 10^{-8}$ C m

Therefore,

$$E = \frac{2\times5\times10^{-8}\,\text{Cm}}{4\pi(8.854\times10^{-12}\,\text{C}^2\text{N}^{-1}\text{m}^{-2})}\times\frac{1}{(15)^3\times10^{-6}\,\text{m}^3}$$

$= 2.6 \times 10^5$ N C^{-1}

along the dipole moment direction AB, which is close to the result obtained earlier.

(b) Field at Q due to charge + 10 μC at B

$$= \frac{10^{-5}\ \text{C}}{4\pi(8.854\times10^{-12}\,\text{C}^2\text{N}^{-1}\text{m}^{-2})}\times\frac{1}{[15^2+(0.25)^2]\times10^{-4}\,\text{m}^2}$$

$= 3.99 \times 10^6$ N C^{-1} along BQ

Field at Q due to charge –10 μC at A

$$= \frac{10^{-5}\ \text{C}}{4\pi(8.854\times10^{-12}\,\text{C}^2\text{N}^{-1}\text{m}^{-2})}\times\frac{1}{[15^2+(0.25)^2]\times10^{-4}\,\text{m}^2}$$

$= 3.99 \times 10^6$ N C^{-1} along QA.

Clearly, the components of these two forces with equal magnitudes cancel along the direction OQ but add up along the direction parallel to BA. Therefore, the resultant electric field at Q due to the two charges at A and B is

$$= 2 \times \frac{0.25}{\sqrt{15^2+(0.25)^2}} \times 3.99 \times 10^6\ \text{N C}^{-1}\ \text{along BA}$$

$= 1.33 \times 10^5$ N C^{-1} along BA.

As in (a), we can expect to get approximately the same result by directly using the formula for dipole field at a point on the normal to the axis of the dipole:

$$E = \frac{p}{4\pi\varepsilon_0 r^3} \qquad (r/a >> 1)$$

$$= \frac{5\times10^{-8}\ \text{Cm}}{4p(8.854\times10^{-12}\,\text{C}^2\text{N}^{-1}\text{m}^{-2})}\times\frac{1}{(15)^3\times10^{-6}\,\text{m}^3}$$

$= 1.33 \times 10^5$ N C^{-1}.

The direction of electric field in this case is opposite to the direction of the dipole moment vector. Again, the result agrees with that obtained before.

Example

Find out the torque on dipole in N-m given : Electric dipole moment $\vec{P} = 10^{-7}(5\hat{i}+\hat{j}-2\hat{k})$ coulomb meter and electric field $\vec{E} = 10^7(\hat{i}+\hat{j}+\hat{k})$ Vm^{-1} is -

Sol.

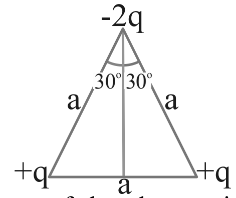
$$\vec{\tau} = \vec{P}\times\vec{E} = \begin{vmatrix} \hat{i} & \hat{j} & \hat{k} \\ 5 & 1 & -2 \\ 1 & 1 & 1 \end{vmatrix}$$

$$= \hat{i}(1+2)+\hat{j}(-2-5)+\hat{k}(5-1) = 3\hat{i}-7\hat{j}+4\hat{k}$$

$|\vec{\tau}| = 8.6$ N-m

Example

Three points charges +q, –2q, +q are arranged on the vertices of an equilateral triangle as shown in the figure. Find the dipole moment of the system.

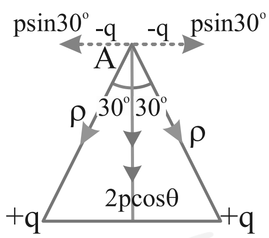


Sol. Arrangement of the charges is equivalent to two dipoles having dipole moment p each as shown above.

Net dipole moment

$P_{net} = p\cos 30° + p\cos 30°$

$P_{net} = 2p\cos 30° = p\sqrt{3} = qa\sqrt{3}$



11. Electric flux :

$\phi = \int \vec{E}.\vec{ds}$

(a) For uniform electric field ; $\phi = \vec{E}.\vec{A} = EA\cos\theta$ where θ = angle between $\vec{E}$ & area vector $(\vec{A})$. Flux is contributed only due to the component of electric field which is perpendicular to the plane.

(b) If $\vec{E}$ is not uniform throughout the area A, then $\phi = \int \vec{E}.d\vec{A}$

12. Gauss`s Law :

$\oint \vec{E}.\vec{ds} = \frac{\sum q}{\epsilon_0}$ (Applicable only to closed surface)

Net flux emerging out of a closed surface is $\frac{q_{en}}{\varepsilon_0}$.

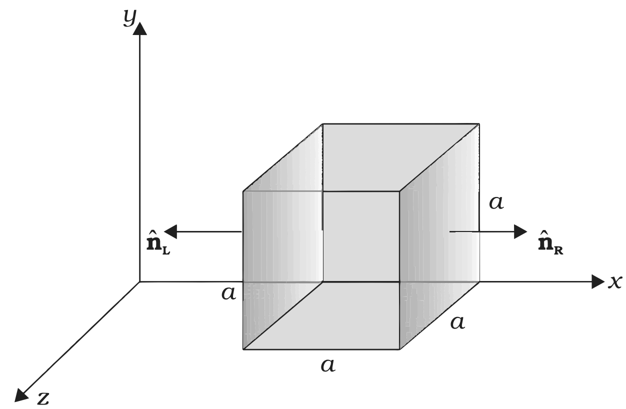
$\phi = \oint \vec{E}.d\vec{A} = \frac{q_{en}}{\varepsilon_0}$ where q_{en} = net charge enclosed by the closed surface ϕ does not depend on the

(a) Shape and size of the closed surface

(b) The charges located outside the closed surface.

Example

The electric field components in Fig. are $E_x = ax^{1/2}$, $E_y = E_z = 0$, in which $\alpha = 800$ N/C m$^{1/2}$. Calculate (a) the flux through the cube, and (b) the charge within the cube. Assume that a = 0.1 m. **[NCERT Pg No. 31]**



Sol. (a) Since the electric field has only an x component, for faces perpendicular to x direction, the angle between E and ΔS is ± π/2. Therefore, the flux $\phi = E.\Delta S$ is separately zero for each face of the cube except the two shaded ones. Now the magnitude of the electric field at the left face is

$E_L = ax^{1/2} = \alpha a^{1/2}$

(x = a at the left face).

The magnitude of electric field at the right face is

$E_R = \alpha x^{1/2} = \alpha (2a)^{1/2}$

(x = 2a at the right face).

The corresponding fluxes are

$\phi_L = E^L \cdot \Delta S = \Delta S\, E_L \cdot \hat{n}_L = E_L \Delta S \cos\theta = -E_L \Delta S$, since $\theta = 180°$

$= -E_L a^2$

$\phi_R = E_R \cdot \Delta S = E_R \Delta S \cos\theta = E_R \Delta S$, since $\theta = 0°$

$= E_R a^2$

Net flux through the cube

$= \phi_R + \phi_L = E_R a^2 - E_L a^2 = a^2 (E_R - E_L) = \alpha a^2 [(2a)^{1/2} - a^{1/2}]$

$= \alpha a^{5/2}(\sqrt{2} - 1)$

$= 800\ (0.1)^{2/2}\ (\sqrt{2} - 1)$

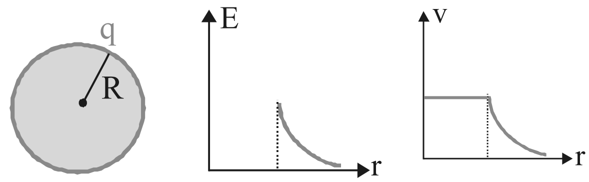
$= 1.05$ N m^2 C^{-1}

(b) We can use Gauss's law to find the total charge q inside the cube.

We have $\phi = q/\varepsilon_0$ or $q = \phi\varepsilon_0$. Therefore,

$q = 1.05 \times 8.854 \times 10^{-12}$ C $= 9.27 \times 10^{-12}$ C.

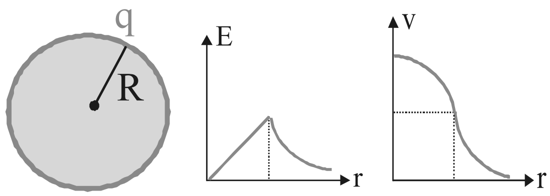
13. For a conducting sphere :



(a) For $r \geq R : E = \frac{1}{4\pi \in_0} \frac{q}{r^2}$

(b) For $r < R : E = 0$

14. For a non - conducting sphere :

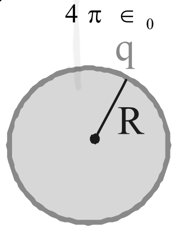


(a) For $r \geq R : E = \frac{1}{4\pi \in_0} \frac{q}{r^2}$

(b) For $r < R : E = \frac{1}{4\pi \in_0} \frac{qr}{R^3}$

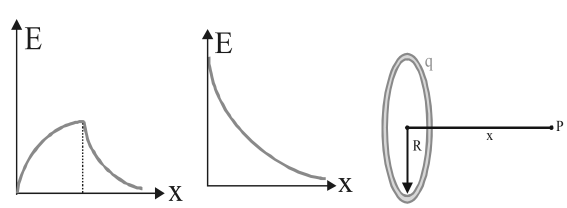
15. For a conducting/non conducting spherical shell :

(i) For $r \geq R : E = \frac{1}{4\pi \in_0} \frac{q}{r^2}$



(ii) For $r < R : E = 0$

16. For a charged circular ring :

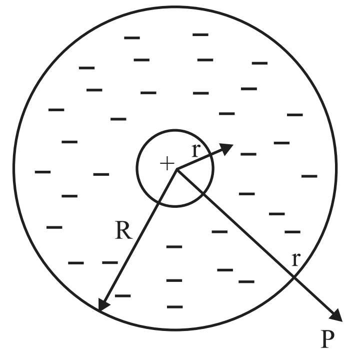


$$E_P = \frac{1}{4\pi \in_0} \frac{qx}{\left(x^2 + R^2\right)^{3/2}}$$

Electric field will be maximum at $x = \frac{\pm R}{\sqrt{2}}$

Example

An early model for an atom considered it to have a positively charged point nucleus of charge Ze, surrounded by a uniform density of negative charge up to a radius R. The atom as a whole is neutral. For this model, what is the electric field at a distance r from the nucleus? **[NCERT Pg No. 36]**



Sol. The charge distribution for this model of the atom is as shown in Fig. The total negative charge in the uniform spherical charge distribution of radius R must be –Z e, since the atom (nucleus of charge Z e + negative charge) is neutral. This immediately gives us the negative charge density r, since we must have

$$\frac{4\pi R^3}{3} \rho = 0 - Ze$$

or $\rho = -\frac{3Ze}{4\pi R^3}$

To find the electric field E(r) at a point P which is a distance r away from the nucleus, we use Gauss's law. Because of the spherical symmetry of the charge distribution, the magnitude of the electric field E(r) depends only on the radial distance, no matter what the direction of r. Its direction is along (or opposite to) the radius vector r from the origin to the point P. The obvious Gaussian surface is a spherical surface centred at the nucleus. We consider two situations, namely, r < R and r > R.

(i) r < R : The electric flux ϕ enclosed by the spherical surface is $\phi = E(r) \times 4\pi r^2$

where E (r) is the magnitude of the electric field at r. This is because the field at any point on the spherical Gaussian surface has the same direction as the normal to the surface there, and has the same magnitude at all points on the surface.

The charge q enclosed by the Gaussian surface is the positive nuclear charge and the negative charge within the sphere of radius r,

i.e., $q = Ze + \frac{4\pi r^3}{3} \rho$

Substituting for the charge density ρ obtained earlier, we have

$$q = Ze - Ze\frac{r^3}{R^3}$$

Gauss's law then gives,

$$E(r) = \frac{Ze}{4\pi\varepsilon_0}\left(\frac{1}{r^2} - \frac{r}{R^3}\right); \ r < R$$

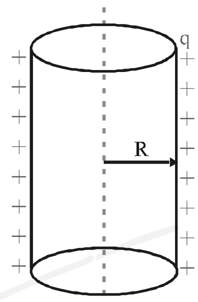
The electric field is directed radially outward.

(ii) r > R: In this case, the total charge enclosed by the Gaussian spherical surface is zero since the atom is neutral. Thus, from Gauss's law,

$E(r) \times 4\pi r^2 = 0$ or $E(r) = 0$; $r > R$

At $r = R$, both cases give the same result: $E = 0$.

17. For a charge long conducting cylinder :



(a) For $r \geq R : E = \frac{q}{2\pi \epsilon_0 r}$ **(b)** For $r < R : E = 0$

18. Electric field intensity at a point near a charged conductor :

$$E = \frac{\sigma}{\epsilon_0}$$

19. Mechanical pressure on a charged conductor :

$$P = \frac{\sigma^2}{2\epsilon_0}$$

20. For non-conducting long sheet of surface charge density :

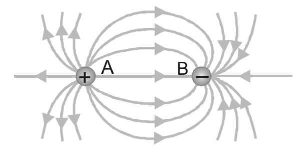
$$= \sigma \quad E = \frac{\sigma}{2\epsilon_0}$$

21. For conducting long sheet of surface charge density :

$$E = \frac{\sigma}{\epsilon_0}$$

22. Electric lines of force :

Electric lines of electrostatic field following properties



$q_A > q_B$

(a) Imaginary

(b) Can never be closed each other

(c) Can never be closed loops

(d) The number of lines originating or terminating on a charge is proportional to the magnitude of charge. In rationalised MKS system $(1/\varepsilon_0)$ electric lines are associated with it (called flux) will be q/ε_0.

(e) Lines of force ends or starts normally at the surface of a conductor.

(f) If there is no electric field there will be no lines of force.

(g) Lines of forceper unit area normal to the area at a point represents magnitude of intensity, crowded lines represent strong field while distant lines weak field.

(h) Tangent to the line of force at a point is an electric field gives the direction of intensity.

MIND MAP

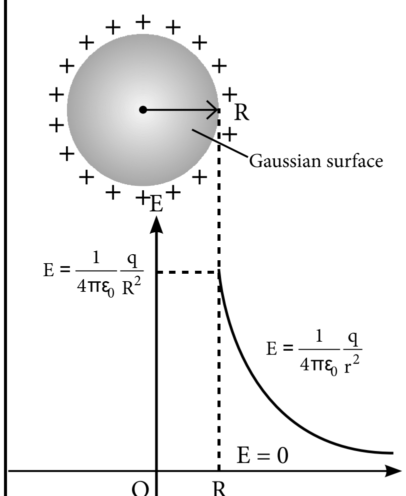
ELECTRIC CHARGES AND FIELDS

Basic Properties of Charges

Quantization of charge : Total charge on a body is always an integral multiple of a basic unit of charge denoted by e and is given by q = ± ne

Conservation of charge : Total charge of an isolated system remains unchanged with time.

Additivity of charge : Total charge of a system is the algebraic sum (i.e. sum taking into account with proper signs) of all individual charges in the system.



For uniformly charged spherical shell

Coulomb's Law

$$F_{21} = \frac{1}{4\pi\varepsilon_0}\frac{q_1q_2}{|r_{12}|^3} r_{12} \text{ for like charges}$$

$$F_{21} = \frac{q_1q_2}{4\pi\varepsilon_0 |r_{21}|^3} r_{12} \text{ for unlike charges}$$

Using Superposition Principle

- e vector sum of forces would give us the total force.
- Force between two charges is unaected by the presence of the other charges.

Electric Field : Electric eld intensity at a point distant r from a point charge q in air is

$$E = \frac{1}{4\pi\varepsilon_0 r^2}\hat{r}.$$

Basic characteristics

- Field lines start from positive charges and end at negative charges.
- Two eld lines can never cross each other.
- Electrostatic eld lines do not form any closed loops.

Electric Dipole : Every dipole is associated with a dipole moment $\vec{p}$ whose magnitude is equal to the product of the magnitude of either charge (q) and the distance $2\vec{a}$ between the charges, i.e., $\vec{p} = q \times (2\vec{a})$.

Electric eld due to dipole

- On Equatorial line (Broad on position) $E = \frac{1}{4\pi\varepsilon_0}\frac{p}{r^3}$
- On Axial line (End on position) $E = \frac{2p}{4\pi\varepsilon_0 r^3}$

Dipole in an external eld experiences

Torque

$\vec{\ } = \vec{p} \times \vec{E}$ or = pE sinθ.

Electric Flux : Electric ux over an area in an electric eld represents the total number of electric eld lines crossing this area.

Gauss's eorem : Total normal electric ux over a closed surface S in vacuum is $1/\varepsilon_0$ times the charge (Q) contained inside the surface.

$$\varphi_E = \int_S E.dS = \frac{Q}{\varepsilon_0}.$$

Applications

volume charge density, $\rho = \frac{q}{V}$

Electric eld due to a uniformly charged thin spherical shell

At a point outside the shell i.e., r > R, $E = \frac{1}{4\pi\varepsilon_0}\frac{q}{r^2} = \frac{\rho R^3}{3\varepsilon_0 r^2}$

On the surface r = R, $E = \frac{1}{4\pi\varepsilon_0}\frac{q}{R^2}$

Inside the shell i.e., r < R, E = 0

surface charge density, $\sigma = \frac{q}{A}$

Electric eld due to a uniformly charged infinite thin plane sheet, $E = \frac{\sigma}{2\varepsilon_0}$.

linear charge density, $\lambda = \frac{q}{L}$

Electric eld due to an innitely long thin uniformly charged straight wire, $E = \frac{\lambda}{2\pi\varepsilon_0 r}$.

Sample Questions CBSE

Charging by Induction

MCQ

1. Consider an uncharged conducting sphere. **(Term I 2021-22)**

A positive point charge is placed outside the sphere. The net charge on the sphere is then,

(a) negative and uniformly distributed over the surface of sphere

(b) positive and uniformly distributed over the surface of sphere

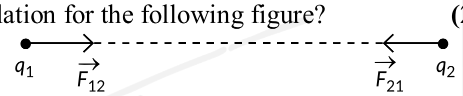
(c) negative and appears at a point surface of sphere closest to point charge

(d) zero.

1.5 Coulomb's Law

MCQ

2. According to Coulomb's law, which is the correct relation for the following figure? **(2022-23)**



(a) $q_1 q_2 > 0$ (b) $q_1 q_2 < 0$

(c) $q_1 q_2 = 0$ (d) $1 > q_1/q_2 > 0$

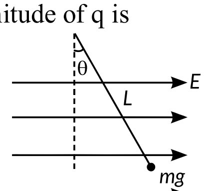
1.7 Electric Field

MCQ

3. Two point charges +8q and –2q are located at x = 0 and x = L respectively. The point on x axis at which net electric field is zero due to these charges is **(Term I 2021-22)**

(a) 8L (b) 4L (c) 2L (d) L

4. A small object with charge q and weight mg is attached to one end of a string of length 'L' attached to a stationary support. The system is placed in a uniform horizontal electric field 'E', as shown in the accompanying figure. In the presence of the field, the string makes a constant angle θ with the vertical. The sign and magnitude of q is **(Term I 2021-22)**



(a) positive with magnitude mg/E

(b) positive with magnitude (mg/E)tanθ

(c) negative with magnitude mg/E tanθ

(d) positive with magnitude E tanθ/mg

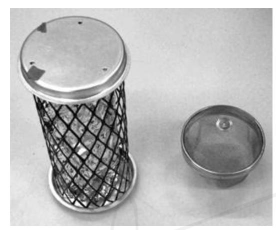
1.8 Electric Field Lines

MCQ

Question 5 is Case Study based questions and are compulsory. Attempt any 4 sub parts from each question. Each question carries 1 mark.

5. Faraday Cage : A Faraday cage or Faraday shield is an enclosure made of a conducting material. The fields within a conductor cancel out with any external fields, so the electric field within the enclosure is zero.

These Faraday cages act as big hollow conductors you can put things in to shield them from electrical fields. Any electrical shocks the cage receives, pass harmlessly around the outside of the cage. **(2020-21)**



(i) Which of the following material can be used to make a Faraday cage?

(a) Plastic (b) Glass (c) Copper (d) Wood

(ii) Example of a real-world Faraday cage is

(a) car (b) plastic box

(c) lightning rod (d) metal rod

(iii) What is the electrical force inside a Faraday cage when it is struck by lightning?

(a) The same as the lightning

(b) Half that of the lightning

(c) Zero

(d) A quarter of the lightning

(iv) An isolated point charge +q is placed inside the Faraday cage. Its surface must have charge equal to

(a) Zero (b) +q (c) –q (d) +2q

(v) A point charge of 2 C is placed at centre of Faraday cage in the shape of cube with surface of 9 cm edge.

The number of electric field lines passing through the cube normally will be

(a) 1.9×10^5 Nm^2/C entering the surface

(b) 1.9×10^5 Nm^2/C leaving the surface

(c) 2.0×10^5 Nm^2/C leaving the surface

(d) 2.0×10^5 Nm^2/C entering the surface

1.9 Electric Flux

MCQ

6. A cylinder of radius r and length l is placed in an uniform electric field parallel to the axis of the cylinder. The total flux for the surface of the cylinder is given by **(Term I 2021-22)**

(a) zero (b) pr2 (c) Epr2 (d) 2Epr2

1.11 Dipole in a Uniform External Field

MCQ

For question below two statements are given one labelled Assertion (A) and the other labelled Reason (R).
Select the correct answer to these questions from the codes (a), (b), (c) and (d) as given below :

7. Assertion (A) : In a non-uniform electric field, a dipole will have translatory as well as rotatory motion **(2020-21)**

Reason (R) : In a non-uniform electric field, a dipole experiences a force as well as torque.

(a) Both A and R are true and R is the correct explanation of A.
(b) Both A and R are true, and R is not the correct explanation of A.
(c) A is true but R is false.
(d) A is false and R is also false.

1.13 Gauss's Law

MCQ

8. Which of the statement is true for Gauss law? **(Term I 2021-22)**

(a) All the charges whether inside or outside the gaussian surface contribute to the electric flux.
(b) Electric flux depends upon the geometry of the gaussian surface.
(c) Gauss theorem can be applied to non-uniform electric field.
(d) The electric field over the gaussian surface remains continuous and uniform at every point.

1.14 Applications of Gauss's Law

MCQ

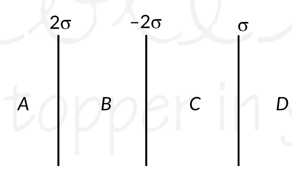
9. Two parallel large thin metal sheets have equal surface densities 26.4×10^{-12} C/m^2 of opposite signs.
The electric field between these sheets is **(Term I 2021-22)**

(a) 1.5 N/C (b) 1.5×10^{-16} N/C
(c) 3×10^{-10} N/C (d) 3 N/C

SA II

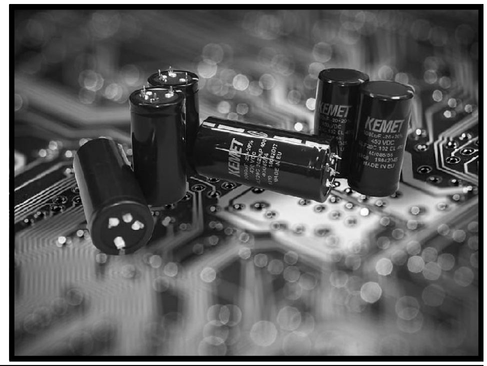
10. (a) State Gauss's law in electrostatics. Show that with help of suitable figure that outward flux due to a point charge Q, in vacuum within gaussian surface, is independent of its size and shape.

(b) In the figure there are three infinite long thin sheets having surface charge density +2σ, –2σ and +σ respectively. Give the magnitude and direction of electric field at a point to the left of sheet of charge density +2σ and to the right of sheet of charge density +σ. **(2020-21)**



02

Electrostatic Potential and Capacitance



Electric Potential :

$$V_p = -\int_{\infty}^{P} \vec{E}.d\vec{r}$$

It is the work done against the field to take a unit positive charge from infinity (reference point) to the given point

(i) For point charge : $V = K\dfrac{q}{r}$

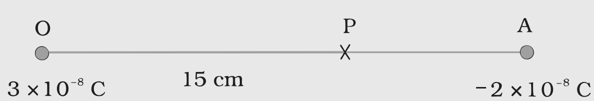
(ii) For several point charges : $V = K\sum\dfrac{q_1}{r_1}$

Example

Two charges 3×10^{-8} C and -2×10^{-8} C are located 15 cm apart. At what point on the line joining the two charges is the electric potential zero? Take the potential at infinity to be zero.

[EX NO.2.2 NCERT PAGE NO. 52]

Sol. Let us take the origin O at the location of the positive charge. The line joining the two charges is taken to be the x-axis; the negative charge is taken to be on the right side of the origin (Fig. 2.7).



[FIG NO.2.7 NCERT PAGE NO. 52]

Let P be the required point on the x-axis where the potential is zero. If x is the x-coordinate of P, obviously x must be positive. (There is no possibility of potentials due to the two charges adding up to zero for x < 0.) If x lies between O and A, we have

$$\frac{1}{4\pi\varepsilon_0}\left[\frac{3\times10^{-8}}{x\times10^{-2}} - \frac{2\times10^{-8}}{(15-x)\times10^{-2}}\right] = 0$$

where x is in cm. That is ,

$$\frac{3}{x} - \frac{1}{15-x} = 0 \quad \text{which gives } x = 9 \text{ cm.}$$

If x lies on the extended line OA, the required condition is

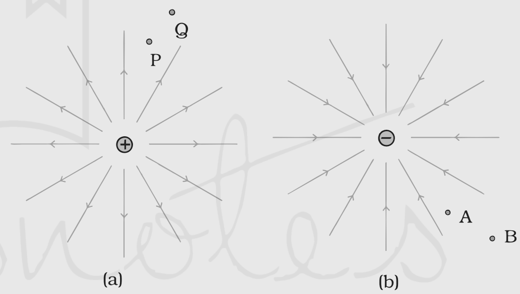
$$\frac{3}{x} - \frac{2}{x-15} = 0 \quad \text{which gives } x = 45 \text{ cm}$$

Thus, electric potential is zero at 9 cm and 45 cm away from the positive charge on the side of the negative charge. Note that the formula for potential used in the calculation required choosing potential to be zero at infinity

Example

Figures 2.8 (a) and (b) show the field lines of a positive and negative point charge respectively.

[EX NO.2.3 NCERT PAGE NO. 53]



[FIG NO.2.8 NCERT PAGE NO. 53]

(a) Give the signs of the potential difference $V_P - V_Q$; $V_B - V_A$.

(b) Give the sign of the potential energy difference of a small negative charge between the points Q and P; A and B.

(c) Give the sign of the work done by the field in moving a small positive charge from Q to P.

(d) Give the sign of the work done by the external agency in moving a small negative charge from B to A.

(e) Does the kinetic energy of a small negative charge increase or decrease in going from B to A?

Sol. As $V \propto \dfrac{1}{r}$, $V_P > V_Q$. Thus, $(V_P - V_Q)$ is positive. Also V_B is less negative than V_A . Thus, $V_B > V_A$ or $(V_B - V_A)$ is positive.

(b) A small negative charge will be attracted towards positive charge. The negative charge moves from higher potential energy to lower potential energy. Therefore the sign of potential energy difference of a small negative charge between Q and P is positive. Similarly, $(P.E.)_A > (P.E.)_B$ and hence sign of potential energy differences is positive.

(c) In moving a small positive charge from Q to P, work has to be done by an external agency against the electric field. Therefore, work done by the field is negative.
(d) In moving a small negative charge from B to A work has to be done by the external agency. It is positive.
(e) Due to force of repulsion on the negative charge, velocity decreases and hence the kinetic energy decreases in going from B to A.

Electric potential difference :

$$= \Delta V = \frac{\text{work}}{\text{charge}} = W/q$$

Relation between $\vec{E}$ & V :

$$\vec{E} = -\text{grad } V = -\nabla V ,$$

$$E = -\frac{\partial V}{\partial r} ; \ \vec{E} = -\frac{\partial V}{\partial x}\hat{i} - \frac{\partial V}{\partial y}\hat{j} - \frac{\partial V}{\partial z}\hat{k} , V = \int -\vec{E}.d\vec{r}$$

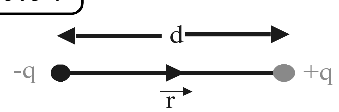
Electrical potential energy of two charges :

$$U = \frac{1}{4\pi \epsilon_0}\frac{q_1 q_2}{r}$$

Note :

- Electric field is always in the direction of decreasing potential.
  The component of electric field in any direction is equal to the negative of potential gradient in that direction
  $$\vec{E} = -\left(\frac{\partial V}{\partial x}\hat{i} + \frac{\partial V}{\partial y}\hat{j} + \frac{\partial V}{\partial z}\hat{k}\right)$$
- An Equipotential surface is a surface where all the points lying on the surface have the same electric potential. This means that a charge will have the same potential energy at every point on the equipotential surface.

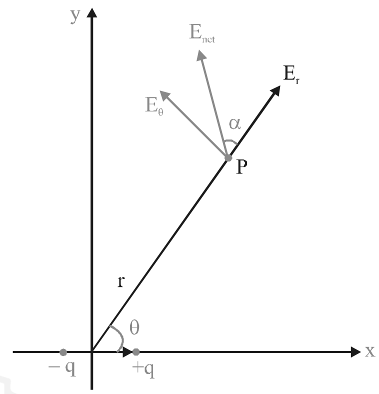
Electric Dipole :



(a) Electric dipole moment p = qd
(b) Torque on dipole placed in uniform electric field $\vec{\tau} = \vec{p} \times \vec{E}$
(c) Work done in rotating dipole placed in uniform electric field $W = \int \tau d\theta = \int_{\theta_0}^{\theta} PE\sin\theta d\theta = pE(\cos\theta_0 - \cos\theta)$
(d) Potential energy of dipole placed in an uniform field $U = -\vec{p}.\vec{E}$
(e) At a point which is at a distance r from dipole midpoint and making angle θ with dipole axis.

(1) Potential $V = \frac{1}{4\pi \epsilon_0}\frac{p\cos\theta}{r^2}$

(2) Electric field $E = \frac{1}{4\pi \epsilon_0}\frac{p\sqrt{1+3\cos^2\theta}}{r^3}$



(3) Direction $\tan\alpha = \frac{E_\theta}{E_r} = \frac{1}{2}\tan\theta$

(f) Electric field at axial point (or End-on) of dipole $\vec{E} = \frac{1}{4\pi \epsilon_0}\frac{2\vec{p}}{r^3}$

(g) Electric field at equatorial position (Broad-on) of dipole
$$\vec{E} = \frac{1}{4\pi \epsilon_0}\frac{(-\vec{p})}{r^3}$$

Conceptual Drawback

- Potential Due to a Dipole is Zero at the Equatorial Plane:
  Accurate Concept: Some students may incorrectly believe that the electric potential due to an electric dipole is zero at the equatorial plane. In reality, the potential is not zero at the equatorial plane; it's just a point where the contributions from positive and negative charges happen to cancel each other out, leading to specific mathematical expressions for the potential.

Example

A molecule of a substance has a permanent electric dipole moment of magnitude 10^{-29} C m. A mole of this substance is polarised (at low temperature) by applying a strong electrostatic field of magnitude 10^6 V m^{-1}. The direction of the field is suddenly changed by an angle of 60º. Estimate the heat released by the substance in aligning its dipoles along the new direction of the field. For simplicity, assume 100% polarisation of the sample.

[EX NO.2.6 NCERT PAGE NO. 61]

Sol. Here, dipole moment of each molecules = 10^{-29} C m
As 1 mole of the substance contains 6×10^{23} molecules, total dipole moment of all the molecules, $p = 6 \times 10^{23} \times 10^{-29}$ C m $= 6 \times 10^{-6}$ C m
Initial potential energy, $U_i = -pE \cos\theta = -6\times10^{-6}\times10^{6} \cos 0° = -6$ J
Final potential energy (when $\theta = 60°$), $U_f = -6 \times 10^{-6} \times 10^{6} \cos 60° = -3$ J
Change in potential energy = –3 J – (–6J) = 3 J
So, there is loss in potential energy. This must be the energy released by the substance in the form of heat in aligning its dipoles.

Example

A uniform electric field having a magnitude E_0 and direction along the positive X-axis exists. If the electric potential V, is zero at X = 0, then, its value at X = +x will be

(1) $V(x) = +xE_0$ (2) $V(x) = -xE_0$
(3) $V(x) = x^2E_0$ (4) $V(x) = -x^2E_0$

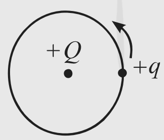
Sol. (2) By using $E = \frac{\Delta V}{\Delta r} = \frac{(V_2 - V_1)}{(r_2 - r_1)}; E_0 = \frac{\{V(x) - 0\}}{x - 0}$
$\Rightarrow V(x) = -xE_0$

Example

A charge +q is revolving around a stationary +Q in a circle of radius r. If the force between charges is F then the work done of this motion will be

(1) $F \times r$ (2) $F \times 2\pi r$ (3) $\frac{F}{2\pi r}$ (4) 0

Sol. (4) Since +q charge is moving on an equipotential surface so work done is zero.

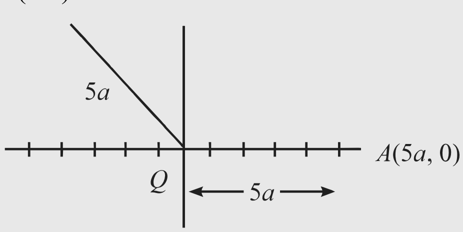


Example

An electric charge of 20 μC is situated at the origin of X – Y co-ordinate system. The potential difference between the points. (5a, 0) and (–3a, 4a) will be

(1) a (2) 2a (3) zero (4) $\frac{a}{\sqrt{2}}$

Sol. (3) $V_A = \frac{kQ}{5a}$ and $V_B = \frac{kQ}{5a}$
$\therefore V_A - V_B = 0$
B(–3a)



Equipotential Surface And Equipotential Region :

In an electric field the locus of points of equal potential is called an equipotential surface. An equipotential surface and the electric field line meet at right angles. The region where E = 0, Potential of the whole region must remains constant as no work is done in displacement of charge in it. It is called as equipotential region like conducting bodies.

Mutual Potential Energy Or Interaction Energy :

"The work to be done to integrate the charge system".

For 2 particle system $U_{mutual} = \frac{q_1q_2}{4\pi\varepsilon_0 r}$

For 3 particle system

$$U_{mutual} = \frac{q_1q_2}{4\pi\varepsilon_0 r_{12}} + \frac{q_2q_3}{4\pi\varepsilon_0 r_{23}} + \frac{q_3q_1}{4\pi\varepsilon_0 r_{31}}$$

For n particle there will be $\frac{n(n-1)}{2}$ terms.

Total energy of a system $= U_{self} + U_{mutual}$

Conceptual Drawback

- Students might incorrectly assume that the electric potential energy of a charged object is determined solely by the magnitude of the charge. In other words, they may think that doubling the charge automatically doubles the electric potential energy.
  Accurate Concept: Electric potential energy isn't just about how big the charge is. It also depends on how the charges are set up in a group. The distance between them and where they're placed relative to each other really matters. So, it's not only about the charge size but also about how the charges are arranged. To really get it, you need to look at both - the size of the charges and how they're positioned in relation to each other. It's like understanding a game not just by the players' skills but also by where they are on the field.

Example

(a) Determine the electrostatic potential energy of a system consisting of two charges 7 μC and –2 μC (and with no external field) placed at (–9 cm, 0, 0) and (9 cm, 0, 0) respectively. (b) How much work is required to separate the two charges infinitely away from each other? **[EX NO.2.5 NCERT PAGE NO. 59]**
(c) Suppose that the same system of charges is now placed in an external electric field $E = A(1/r^2)$; $A = 9 \times 10^5$ NC^{-1} m^2. What would the electrostatic energy of the configuration be?

Sol. (a) $U = \frac{1}{4\pi\varepsilon_0}\frac{q_1q_2}{r} = 9\times10^9 \times \frac{7\times(-2)\times10^{-12}}{0.18} = -0.7J$

$U = \frac{1}{4\pi\varepsilon_0}\frac{q_1q_2}{r} = 9\times10^9 \times \frac{7\times(-2)\times10^{-12}}{0.18} = -0.7J$

(b) $W = U_2 - U_1 = 0 - U = 0 - (-0.7) = 0.7$ J.

(c) The mutual interaction energy of the two charges remains unchanged. In addition, there is the energy of interaction of the two charges with the external electric field. We find

$$q_1V(r_1) + q_2V(r_2) = A\frac{7\mu C}{0.09m} + A\frac{-2\mu C}{0.09m}$$

and the net electrostatic energy is

$$q_1V(r_1) + q_2V(r_2) + \frac{q_1q_2}{4\pi\varepsilon_0 r_{12}} =$$

$$A\frac{7\mu C}{0.09m} + A\frac{-2\mu C}{0.09m} - 0.7J = 70 - 20 - 0.7 = 49.3\ J$$

Example

A hollow metal sphere of radius 5 cm is charged such that the potential on its surface is 10 volts. The potential at the centre of the sphere is

(1) Zero
(2) 10 V
(3) Same as at a point 5 cm away from the surface
(4) cm away from the surface same as at a point 25

Sol. (2) Inside the conductors potential remains same and it is equal to the potential of surface, so here potential at the centre of sphere will be 10 V

Example

A solid conducting sphere having a charge Q is surrounded by an uncharged concentric conducting hollow spherical shell. Let the potential difference between the surface of the solid sphere and that of the outer surface of the hollow shell be V. If the shell is now given a charge of –3Q, the new potential difference between the two surfaces is

(1) V (2) 2V (3) 4V (4) –2V

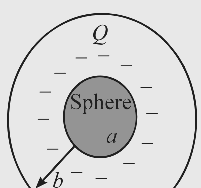
Sol. (1) If a and b are radii of spheres and spherical shell respectively, potential at their surfaces will be

$$V_{sphere} = \frac{1}{4\pi\varepsilon_0}.\frac{Q}{a} \text{ and } V_{shell} = \frac{1}{4\pi\varepsilon_0}.\frac{Q}{b}$$

and so accodrding to the given problem

$$V = V_{sphere} - V_{shell} = \frac{Q}{4\pi\varepsilon_0}\left[\frac{1}{a} - \frac{1}{b}\right] \qquad \text{...............(i)}$$

Now when the shell is given a charge –3Q the potential at its surface and also inside will change by $V_0 = \frac{1}{4\pi\varepsilon_0}\left[-\frac{3Q}{b}\right]$



Example

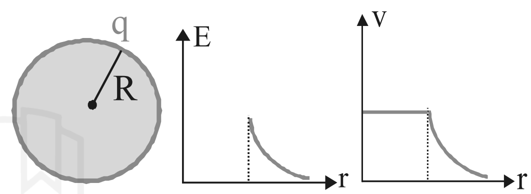
A charge (–q) and another charge (+Q) are kept at two points A and B respectively. Keeping the charge (+Q) fixed at B, the charge (q) at A is moved to another point C such that ABC forms an equilateral triangle of side 1. The net work done in moving the charge (– q) is

(1) $\frac{1}{4\pi\varepsilon_0}\frac{Qq}{1}$ (2) $\frac{1}{4\pi\varepsilon_0}\frac{Qq}{l^2}$

(3) $\frac{1}{4\pi\varepsilon_0}Qql$ (4) zero

Sol. (4) Since $V_A = V_C = = \frac{kQ}{l}$ So, $W = q(V_C - V_A) = 0$

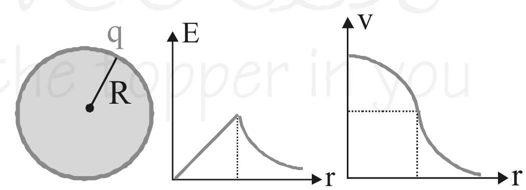
For a conducting sphere :



(a) For $r \geq R : V = \frac{1}{4\pi\in_0}\frac{q}{r}$

(b) For $r < R : V = \frac{1}{4\pi\in_0}\frac{q}{R}$

For a non - conducting sphere :

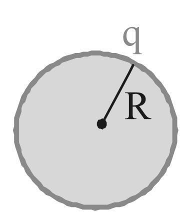


(a) For $r \geq R : V = \frac{1}{4\pi\in_0}\frac{q}{r}$

(b) For $r < R : V = \frac{1}{4\pi\in_0}\frac{q\left(3R^2 - r^2\right)}{2R^3}$

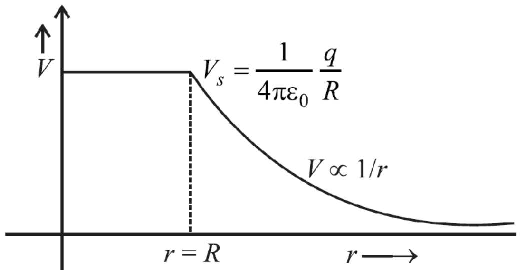
For a conducting/non conducting spherical shell :

(i) For $r \geq R : V = \frac{1}{4\pi\in_0}\frac{q}{r}$



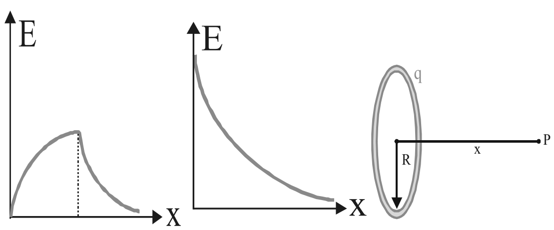
(ii) For $r < R : V = \frac{1}{4\pi\in_0}\frac{q}{R}$

Graphical Representation :



V–r graph of charged spherical shell

For a charged circular ring :



$$V_P = \frac{1}{4\pi \epsilon_0} \frac{q}{\left(x^2 + R^2\right)^{1/2}}$$

Capacitor & Capacitance :

A capacitor consist of two conductors carrying charges of equal magnitude and opposite sign. The capacitance C of any capacitor is the ratio of the charge Q on either conductor to the potential difference V between them

$$C = \frac{Q}{V}$$

Conceptual Drawback

- Capacitors store energy in the same way batteries do and can provide a continuous source of power.
  Accurate Concept: Capacitors store energy temporarily in an electric field between their plates. Unlike batteries, capacitors release their stored energy quickly, and their primary function is often to manage electrical charge rather than act as a continuous power source.

Capacitance of an Isolated Spherical Conductor :

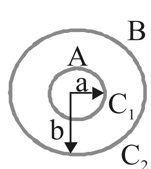
$C = 4\pi \epsilon_0 \epsilon_r R$ in a medium $C = 4\pi \epsilon_0 R$ in air

This sphere is at infinite distance from all the conductors.

Spherical Capacitor :

It consists of two concentric spherical shells. Here capacitance on region between the two shells is C_1 and that outside the shell is C_2.

We have



$$C_1 = \frac{4\pi \epsilon_0 ab}{b - a} \text{ and}$$

$$C_2 = 4\pi \epsilon_0 b$$

Parallel Plate Capacitor :

(a) Uniform Di-Electric Medium : If two parallel plates each of area A & separated by a distance d are charged with equal & opposite charge Q, then the system is called a parallel plate capacitor & capacitance is given by, $C = \frac{4\pi \epsilon_0 \epsilon_r A}{d}$ in a medium ; $C = \frac{\epsilon_0 A}{d}$ with air as medium

This result is only valid when the electric field between plates of capacitor is constant.

Dielectric :

Dielectrics are insulating (non-conducting) materials that can produce electric effect without conduction. Dielectrics are of two types

Non-polar Dielectric :

The non-polar dielectrics (like N_2, O_2, benzene, methane etc.) are made up of non-polar atoms/molecules, in which the centre of positive charge coincides with the centre of negative charge of the atom/molecule.

Polar Dielectric :

The polar dielectric (like H_2O , CO_2, NH_3 etc) are made up of polar atoms/molecules, in which the centre of positive charge does not coincide with the centre of negative charge of the atom.

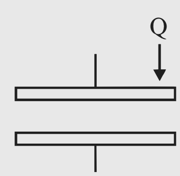
Dielectric Constant (K) :

The ratio of the strength of the applied electric field to the strength of the reduced value of electric field on placing the dielectric between the plates of a capacitor is the dielectric constant. It is denoted by K (or ε_r).

$$K = \frac{E_0}{E}$$

Example

Charge Q is given to the upper plate of an isolated parallel plate capacitor of capacitance C. The potential difference between the plates



Sol. In general, for charge Q_1 and Q_2 on upper and lower plate respectively the charge distributions on outer and inner part of the plates are shown in figure.

Here $Q_1 = Q_2 = 0$

Charge on inner side of plate are $\frac{Q}{2}$ and $-\frac{Q}{2}$ respectively. Hence $V = \frac{Q/2}{C}$

Example

The energy density in a parallel plate capacitor is given as 2.1×10^{-9} J/m^3. The value of the electric field in the region between the plates is:

(1) 2.1 NC^{-1} (2) 21.6 NC^{-1} (3) 72 NC^{-1} (4) 8.4 NC^{-1}

Sol. (2) Use $U = \frac{1}{2}\epsilon_0 E^2$

Example

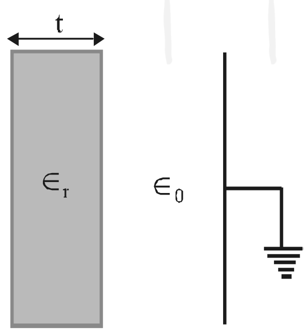
The capacitance of a capacitor is 4×10^{-6} F and it is connected to a cell of 100V. The energy required to discharge it completely.

(1) 0.025 J (2) 0.06 J (3) 0.02 J (4) 0.04 J

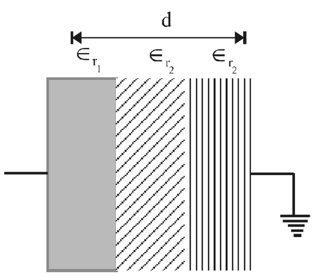
Sol. (3) Energy required to discharge must be equal to Energy stored in the capacitor

(b) Medium Partly Air : $C = \dfrac{\epsilon_0 A}{d - \left(t - \dfrac{t}{\epsilon_r}\right)}$

When a di-electric slab of thickness t & relative permittivity ϵ_r is introduced between the plates of an air capacitor, then the distance between the plates is effectively reduced by $\left(t - \dfrac{t}{\epsilon_r}\right)$ irrespective of the position of the di-electric slab.



(c) Composite Medium :



$$C = \frac{\epsilon_0 A}{\dfrac{t_1}{\epsilon_{r_1}} + \dfrac{t_2}{\epsilon_{r_2}} + \dfrac{t_3}{\epsilon_{r_3}}}$$

Conceptual Drawback

- Dielectric materials store electrical energy like a capacitor.
  Accurate Concept: Dielectrics don't store electrical energy themselves; rather, they enhance the ability of a capacitor to store charge by reducing the electric field between the capacitor plates.

Example

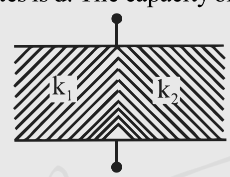
If 50μF be the capacity of a capacitor in air, and 110μF in oil then the dielectric constant of oil will be

Sol. $C \propto K \Rightarrow \dfrac{C_1}{C_2} = \dfrac{K_1}{K_2} \quad \Rightarrow \dfrac{50\times10^{-6}}{110\times10^{-6}} = \dfrac{1}{K_2}$

[for air $K_1 = 1$] $\Rightarrow K_2 = 2.20$

Example

Two materials of dielectric constant k_1 and k_2 are filled between two parallel plates of a capacitor as shown in figure. Where area of each plate is A and the distance between the plates is d. The capacity of the capacitor is:



(1) $\dfrac{A\epsilon_0(k_1+k_2)}{d}$ (2) $\dfrac{2A\epsilon_0}{2d}\left(\dfrac{k_1k_2}{k_1+k_2}\right)$

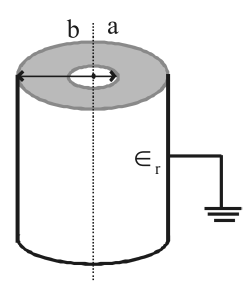
(3) $\dfrac{A\epsilon_0}{d}\left(\dfrac{k_1k_2}{k_1+k_2}\right)$ (4) $\dfrac{A\epsilon_0}{2d}\left(\dfrac{k_1+k_2}{k_1k_2}\right)$

Sol. Equivalent capacitor C" = $C_1 + C_2$

$$= \frac{K_1\varepsilon_0 A/2}{d} + \frac{K_2\varepsilon_0 A/2}{d} = \frac{(K_1+K_2)\varepsilon_0 A}{d}$$

Cylindrical Capacitor :

If consists of two co-axial cylinders of radii a & b the outer conductor is earthed. The di-electric constant of the medium filled in the space between the cylinders is ϵ_r .



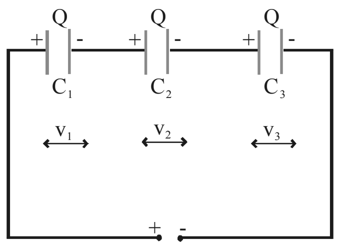
The capacitance per unit length is $C = \dfrac{2\pi\epsilon_0\epsilon_r}{?n\left(\dfrac{b}{a}\right)}$

Combination of Capacitors :

(a) Capacitors in Series :

In this arrangement all the capacitors when uncharged get the same charge Q but the potential difference across each will differ (if the capacitance are unequal).

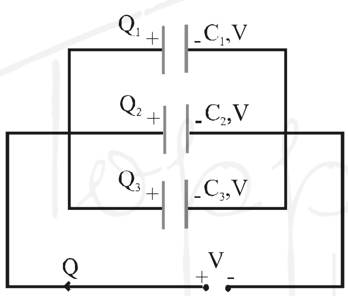
$$\frac{1}{C_{eq.}} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + ... + \frac{1}{C_n}$$



(b) Capacitors in Parallel :

When one plate of each capacitor is connected to the positive terminal of the battery & the other plate of each capacitor is connected to the negative terminals of the battery, then the capacitors are said to be in parallel connection. The capacitors have the same potential difference, V but the charge on each one is different (if the capacitors are unequal).

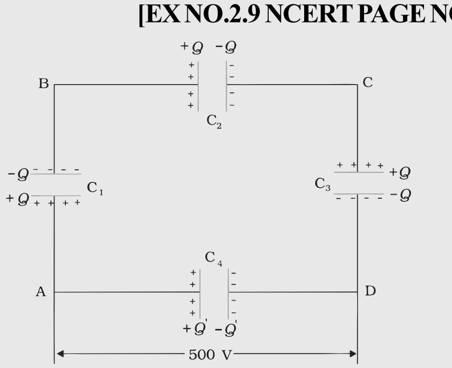
$$C_{eq.} = C_1 + C_2 + C_3 + ... + C_n$$



Example

A network of four 10 mF capacitors is connected to a 500 V supply, as shown in Fig. 2.29. Determine (a) the equivalent capacitance of the network and (b) the charge on each capacitor. (Note, the charge on a capacitor is the charge on the plate with higher potential, equal and opposite to the charge on the plate with lower potential.)

[EX NO.2.9 NCERT PAGE NO. 73]



[FIG NO.2.29 NCERT PAGE NO. 73]

Sol. (a) In the given network, C_1, C_2 and C_3 are connected in series. The effective capacitance C' of these three capacitors is given by

$$\frac{1}{C'} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}$$

For $C_1 = C_2 = C_3 = 10$ mF, C' = (10/3) μF. The network has C' and C_4 connected in parallel. Thus, the equivalent capacitance C of the network is

$$C = C' + C_4 = \left(\frac{10}{3} + 10\right) \mu F = 13.3 \mu F$$

(b) Clearly, from the figure, the charge on each of the capacitors, C_1, C_2 and C_3 is the same, say Q. Let the charge on C_4 be Q'. Now, since the potential difference across AB is Q/C_1, across BC is Q/C_2, across CD is Q/C_3 , we have

$$\frac{Q}{C_1} + \frac{Q}{C_2} + \frac{Q}{C_3} = 500V$$

Also, $Q'/C_4 = 500$ V.

This gives for the given value of the capacitances

$Q = 500\ V \times \frac{10}{3} \mu F = 1.7 \times 10^{-3}$ C and Q' = 500V × 10 μF = 5.0×10^{-3} C

Energy Stored in a Charged Capacitors :

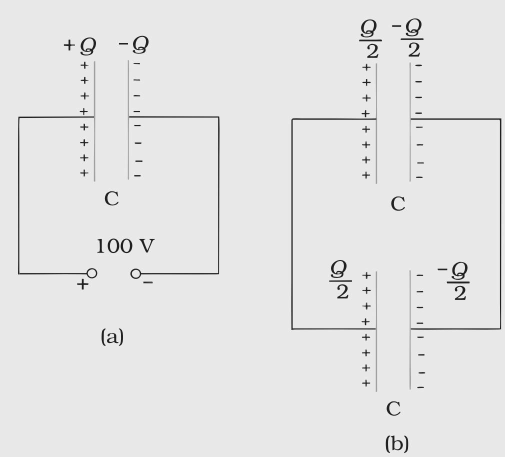
Capacitors C, charge Q & potential difference V; then energy stored is

$$U = \frac{1}{2}CV^2 = \frac{1}{2}QV = \frac{1}{2}\frac{Q^2}{C}$$

This energy is stored in the electrostatic field set up in the di-electric medium between the conducting plates of the capacitor.

Example

(a) A 900 pF capacitor is charged by 100 V battery [Fig. 2.31(a)]. How much electrostatic energy is stored by the capacitor? (b) The capacitor is disconnected from the battery and connected to another 900 pF capacitor [Fig. 2.31(b)]. What is the electrostatic energy stored by the system? **[EX NO.2.10 NCERT PAGE NO. 75]**



[FIG NO.2.31 NCERT PAGE NO. 75]