ELECTROSTATICS

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That branch of physics in which we study electric charges at rest under the action of electric forces is called electrostatics.

ELECTRIC CHARGE

Electric charge has no significant definition. It may be defined by its property as

DEFINITION: A particle or a body which has ability to attract other neutral particles, is said to be electrically charged.

ELECTRIC FORCE

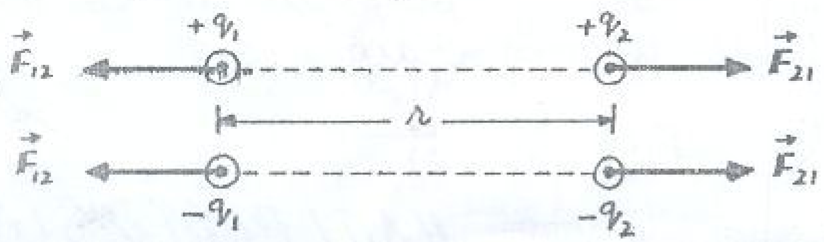
"That force which holds the positive and negative charges that make up atoms and molecules is called electric force."

As human body consists of molecules and atoms, so we said that our existance is due to the electric force.

COULOMB'S OR ELECTROSTATIC FORCE

"The force of attraction or repulsion between any two point charges is called coulomb's or electrostatic force."

For like charges i-e; positive, positive or negative, negative, the coulomb's forces are repulsive.



For unlike charges i-e; positive and negative, the coulomb's forces are attractive.

Coulomb's Law

The first measurement of the electric force between electric charges was made in 1874 A.D. by CHARLES COULOMB (a French military engineer). On the basis of measurements, he deduces a law known as Coulomb's law.

Statement: The force of attraction or repulsion between two point charges is directly proportional to the product of the magnitudes of charges and inversely proportional to the square of the distance between them.

Mathematically

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

Derivation

Consider two point charges q_1 and q_2 separated by a distance r, then according to Coulomb's law, the mutual force between the two charges is

The magnitude of the Coulomb's force is directly proportional to the product of the magnitudes of charges i-e;

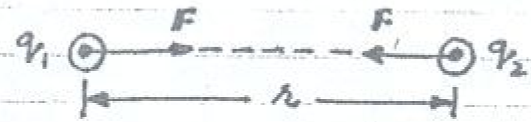
$$F \propto q_1 q_2 \longrightarrow ①$$

And inversely proportional to the square of the distance between charges i-e;

$$F \propto \frac{1}{r^2} \longrightarrow ②$$

Combining equation ① and ②, we get

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



or $$F = (\text{Constant}) \frac{q_1 q_2}{r^2}$$

or $$\boxed{F = k \frac{q_1 q_2}{r^2}} \longrightarrow ③$$

Where k is constant of proportionality and known as Coulomb's constant. Its value depends upon the nature of the medium between the two charges and the systems of units in which F, r, q_1 and q_2 are measured. If the medium between two charges is free space or vacuum, then

$$k = \frac{1}{4\pi\varepsilon_0} \longrightarrow ④$$

Where ε_0 is an electrical constant, known as permitivity of free space. In SI-units, its value is

$$\varepsilon_0 = 8.85 \times 10^{-12}\ C^2 \cdot N^{-1} \cdot m^{-2}$$

Put this value in equation ④

$$\therefore \quad k = \frac{1}{4 \times 3.14 \times 8.85 \times 10^{-12}}$$

$$\boxed{k = 9 \times 10^{9}\ N \cdot m^2 \cdot C^{-2}}$$

Put value of k from equation ④ in equation ③, we get

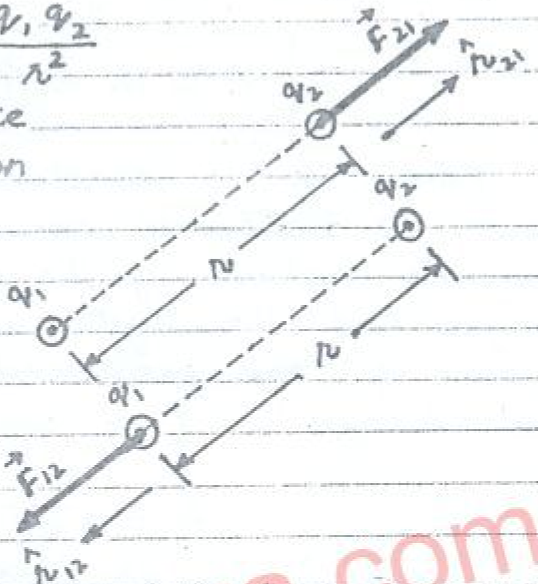
$$\boxed{F = \frac{1}{4\pi\varepsilon_0} \cdot \frac{q_1 q_2}{r^2}} \longrightarrow ⑤$$

This is the expression of Coulomb's force in free space.

Vector Form Of Coulombs Law

As we know that the Coulomb's force between two point charges q_1 and q_2 separated by a distance r in free space is given as

$$F = \frac{1}{4\pi\varepsilon_0} \cdot \frac{q_1 q_2}{r^2}$$



Now if we denote the force exerted by q_1 on q_2 as $\vec{F}_{21}$, then this force is given as

$$\vec{F}_{21} = \frac{1}{4\pi\varepsilon_0} \cdot \frac{q_1 q_2}{r^2} \cdot \hat{r}_{21} \longrightarrow (1)$$

Equation (1) is the vector form of Coulomb's law and $\hat{r}_{21}$ is the unit vector in the direction of force $\vec{F}_{21}$ directed from point charge q_1 to q_2.

If the charges q_1 and q_2 are like charges, then force between them is repulsive and R.H.S. of equation (1) is positive. And if charges are unlike charges, then force between them is attractive and R.H.S. of equation (1) is negative.

Similarly, if we denote the force exerted by q_2 on q_1 as $\vec{F}_{12}$, then

$$\vec{F}_{12} = \frac{1}{4\pi\varepsilon_0} \cdot \frac{q_1 q_2}{r^2} \cdot \hat{r}_{12} \longrightarrow (2)$$

Where $\hat{r}_{12}$ is the unit vector in the direction of force $\vec{F}_{12}$ directed from q_2 to q_1.

As from figure, it is clear that

$$\hat{r}_{12} = -\hat{r}_{21}$$

Put in equation (2)

$$\therefore \vec{F}_{12} = \frac{1}{4\pi\varepsilon_0} \cdot \frac{q_1 q_2}{r^2} (-\hat{r}_{21})$$

or $$\vec{F}_{12} = -\frac{1}{4\pi\varepsilon_o}\cdot\frac{q_1 q_2}{r^2}\cdot\hat{r}_{21} \longrightarrow (3)$$

Comparing equation (1) and (3)

$$\boxed{\vec{F}_{12} = -\vec{F}_{21}}$$

or $$\boxed{\vec{F}_{21} = -\vec{F}_{12}}$$

This relation shows that Coulomb's force is mutual force. It means that if q_1 exerts a force on q_2 i-e; $\vec{F}_{21}$, then q_2 also exerts an equal and opposite force on q_1 i-e; $\vec{F}_{12}$.

Coulomb's Law In Dielectrics or Effect Of Medium On Coulomb's Force

As the Coulomb's force between two point charges q_1 and q_2 separated by a distance r in free space is given as

$$F = \frac{1}{4\pi\varepsilon_o}\cdot\frac{q_1 q_2}{r^2} \longrightarrow (1)$$

If we place an insulator medium which is usually known as dielectric having dielectric constant or relative permitivity ε_r, then Coulomb's force is given as

$$F' = \frac{1}{4\pi\varepsilon_o\varepsilon_r}\cdot\frac{q_1 q_2}{r^2} \longrightarrow (2)$$

Comparing equation (1) and (2)

$$F' = \frac{1}{\varepsilon_r}\cdot F = F/\varepsilon_r$$

or $$\boxed{F = \varepsilon_r F'}$$

As $\varepsilon_r = 1$ for vacuum or free space
and $\varepsilon_r > 1$ for any dielectric medium.
So

$$\boxed{F' < F}$$

Hence Coulomb's force reduces by a factor ε_r when dielectric medium is placed between charges as compared to free space or vacuum.

Dielectric Constant or Relative Permitivity

As

$$F = \varepsilon_r F'$$

or

$$\boxed{\varepsilon_r = \frac{F}{F'}}$$

Definition: The ratio between Coulomb's force when free space or vacuum between the charges to the force when some dielectric medium between the charges is called dielectric constant.

Electric Field

The space or region around a charge within which other charges are influenced by it is called electric field.

Fields Of Force

Newton's gravitational law and Coulomb's electrostatic law are not able to calculate the magnitude and the direction of the gravitational and electric force respectively. However, the questions arises are

(i) What are the origins of these forces?

(ii) How are these forces transmitted from one mass to another or from one charge to another?

The answer of first question is still unknown and the existance of these forces is accepted as it. Due to this reason, these forces are called natural basic forces.

In order to describe the transmission of electric force from one charge to another, Michael Faraday introduced a theory of an electric field given as

Field Theory or Field Effect

According to this theory, electric field is a physical quantity that exists in the space around an electric charge. The electric field act as a force field that exerts a force on other charges placed in that field.

For example, the interaction between the two charges q and q_0 separated by some distance can be explained in two steps.

STEP (a) → The charge q produces a field in its surrounding space

STEP (b) → The field interacts with charge q_0 to produce a force $\vec{F}$ on q_0.

These two steps are shown in figure below.

The strength of the electric field is directly proportional to the density of the dots as shown in figure. It means that electric field is stronger where dots are closer to each other and weaker where dots are further apart.

ELECTRIC FIELD INTENSITY OR ELECTRIC FIELD STRENGTH

DEFINITION

The force per unit charge in an electric field is called electric field intensity.

It is denoted by $\vec{E}$.

FORMULA

Consider a force $\vec{F}$ experienced by a positive test charge q_0 placed at a certain point within the field. The test charge q_0 must be very small so that it may not distort the field. Hence electric field intensity $\vec{E}$ is given as

$$\boxed{\vec{E} = \frac{\vec{F}}{q_0}}$$

or $$\boxed{\vec{F} = q_0\vec{E}}$$

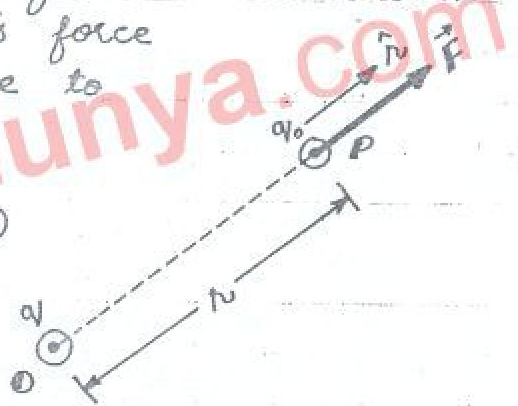
Electric field intensity $\vec{E}$ is a vector quantity and its direction is same as that of the force $\vec{F}$.

UNITS OF $\vec{E}$

In SI-units, the unit of electric field intensity $\vec{E}$ is N/C or $N\cdot C^{-1}$.

ELECTRIC INTENSITY DUE TO A POINT CHARGE

Consider an electric field due to a charge q in vacuum at point O. Let a test point charge q_0 is placed at point P in the field of charge q at a distance r from it as shown.



Now the Coulomb's force experienced by charge q_0 due to charge q is

$$\vec{F} = \frac{1}{4\pi\varepsilon_0}\cdot\frac{qq_0}{r^2}\cdot\hat{r} \longrightarrow (1)$$

Where $\hat{r}$ is the unit vector directed from charge q to the test charge q_0 as shown.

The electric intensity $\vec{E}$ at point P is

$$\vec{E} = \frac{\vec{F}}{q_0}$$

Put value of $\vec{F}$ from equation (1)

$$\therefore \quad \vec{E} = \frac{1}{4\pi\varepsilon_0}\cdot\frac{qq_0}{r^2}\cdot\hat{r}\times\frac{1}{q_0}$$

or $$\boxed{\vec{E} = \frac{1}{4\pi\varepsilon_0}\cdot\frac{q}{r^2}\cdot\hat{r}} \longrightarrow (2)$$

Its magnitude is

$$\boxed{E = \frac{1}{4\pi\varepsilon_0}\cdot\frac{q}{r^2}}$$

The above equation shows that

$$\boxed{E \propto 1/r^2}$$

It means that the electric field intensity due to point charge is inversely proportional to the square of the distance from the test charge.

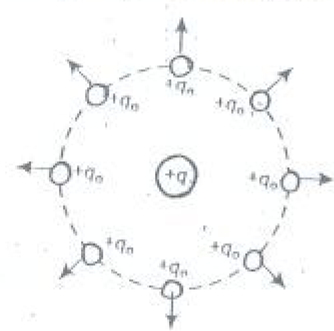
Electric Field Lines or Electric Force Lines

The path along which a unit positive charge moves in an electric field is called electric field or force lines.

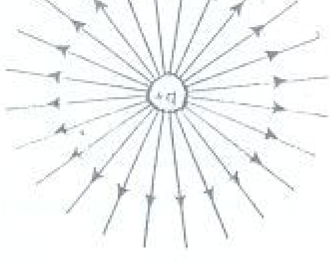
Electric field lines are used to express the electric field graphically. These lines gives the information about the electric force exerted on a charge that is why electric field lines are called **Lines Of Force.**

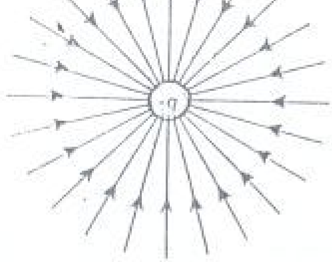
Explanation

In order to understand the concept of electric field lines, we place positive test charges each of magnitude q_0 at different places but at equal distances from a positive charge $+q$ as shown in figure. Each test charge will experience a repulsive force which is indicated by arrows.



The electric field created by the charge $+q$ is directed radially outward as shown in figure.





The electric field lines created by a negative charge $-q$ are directed radially inward because the force on positive test charges is now attractive as shown in figure.

The electric field lines emit from the charges in three dimensions and an infinite number of lines could be drawn around charges.

MAGNITUDE OF ELECTRIC FIELD

The electric field lines map also provides information about the magnitude or strength of the electric field. It should be noted that

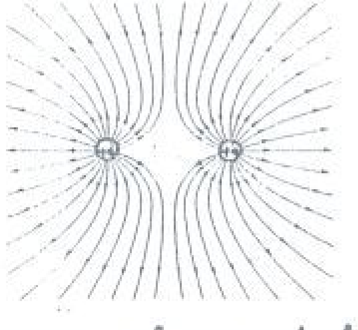
"The number of lines per unit area passing perpendicularly through an area is proportional to the magnitude of the electric field."

If number of lines per unit area is large, then the field will be strong. In such a field, the electric lines of force are closer to each other that is why electric field is stronger near the charges.

Similarly, if number of lines per unit area is small, then the field will be small. In such a field, the lines of forces are further apart to each other that is why electric field is weaker away from the charges. As the field lines are continuously spread out, so the field strength is decreasing continuously.

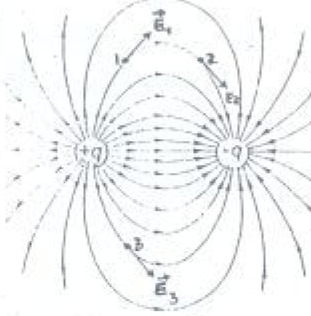
ELECRIC FIELD BETWEEN LIKE OR IDENTICAL CHARGES

In case of identical charges of equal magnitudes, the electric field lines are curved. The lines in the region between two like charges repel each other as shown in figure. The middle region between the similar charges shows the presence of a neutral zone or zero field spot as shown.



Electric Field Between Unlike or Opposite Charges

Figure shows the pattern of electric field lines of two opposite charges of same magnitudes. The field lines start from the positive charge (+q) and end on negative charge (−q). The electric field at points 1, 2, 3 is the resultant of fields created by the two charges at these points as shown in figure. The directions of the resultant intensities are given by the tangents drawn to the field lines at these points.



Uniform And Non-Uniform Field

The electric field is uniform in the region where electectric field lines are parallel and equally spaced. In this case same number of electric field lines passes per unit area at all points. Figure shows the field lines between the plates of a parallel plate capacitor. The field is uniform in the middle region where the field lines are equally spaced.

The electric field is non-uniform in the field where the field lines are not parallel and are not equally spaced. At the edges of the plates, the lines are curved and field is non-uniform as shown in figure.

Properties Of Electric Field Lines

1. Electric field lines originate from positive charges and end on negative charges.
2. The tangent to a field line at any point gives the direction of the electric field at that point.

3. The lines are closer where the field is strong and the lines are farther apart where the field is weak.
4. No two lines cross each other. This is because electric field intensity $\vec{E}$ has only one direction at any given point. If the lines cross each other, $\vec{E}$ could have more than one direction.

APPLICATIONS OF ELECTROSTATICS

There are two important applications of electrostatics given as

(i) Xerography (Photocopier)
(ii) Inkjet Printers

XEROGRAPHY (PHOTOCOPIER)

The copying process is called xerography. Xerography is a combination of Greek word 'XEROS' and 'GRAPHOS' that means 'dry writing'.

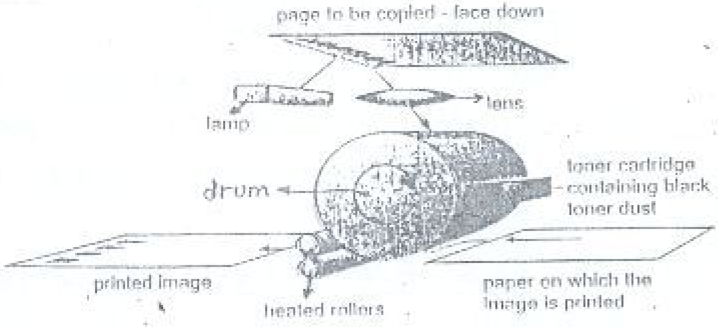
WORKING PRINCIPLE

The working principle of xerography is 'The lamp transfers an image of the page to the drum, which leaves a static charge. The drum collects toner dust and transfers it to the paper. The toner is melted onto the page'.

CONSTRUCTION

The main parts of photocopier are given as

1. Lamp
2. Drum
3. Selenium Surface
4. Toner
5. Sheet of Paper
6. Heated Pressure Rollers



Lamp

The lamp transfers an image of the page to the drum.

Drum

The heart of the machine is a drum which is an aluminium cylinder. Aluminium is an excellent conductor.

Selenium Surface

Aluminium cylinder is coated with a layer of selenium. It is an insulator in the dark and becomes a conductor in the light. So, it is a photoconductor. When the drum is exposed to light, the electrons from aluminium pass through the conducting selenium and neutralize the positive charge.

Toner

It is a special dry black powder. When negatively charged toner spread over the drum, it sticks to the positive charge areas.

Sheet Of Paper

The toner from the drum is shifted on to a sheet of paper on which the photocopy is produced.

Heated Pressure Rollers

Heated rollers melt the toner into the paper to fix impression of the document.

Working Of Photocopier

When the drum is exposed to an image of the document, the dark and light areas of the document produce corresponding areas on the drum. The dark areas retain their positive charge, but light areas become conducting, lose their positive charge and become neutral.

In this way, a positive charge image of the document remains on the selenium surface. Now the negatively charged toner spread over the drum. It sticks to the positively charged areas. Here the toner is transferred on to a sheet of paper on which the document is to be copied. Heated pressure rollers then melt the toner into the paper to produce the permanent impression of the document.

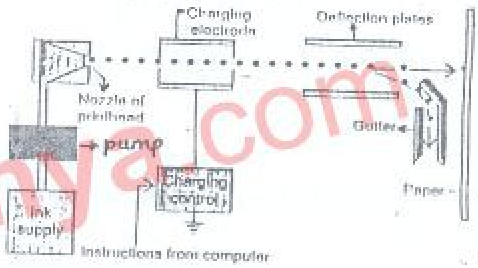
INKJET PRINTERS

Inkjet printer is a type of printer which uses electric charge in its operation.

CONSTRUCTION

The main parts of inkjet printers are

1. Printhead
2. Nozzle
3. Charging Electrode
4. Deflection Plates
5. Gutter
6. Paper



PRINTHEAD

Printhead shuttles back and forth across the paper. It ejects a thin stream of ink.

NOZZLE

The ink is forced out of a small nozzle and breaks up into extremely small droplets.

CHARGING ELECTRODE

The charging electrode charges the ink droplets.

DEFLECTION PLATES

The deflection plates divert charged droplets into a gutter.

GUTTER

It collects unused ink.

PAPER

Paper is used to collect the uncharged droplets in the form of print.

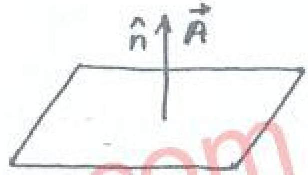
Working

An inkjet printhead ejects a steady flow of ink droplets. The charging electrode charges the droplets that are not needed on the paper. Charged droplets are deflected into a gutter by the deflection plates. The uncharged droplets fly straight onto the paper to print the document.

Vector Area

An area whose magnitude is equal to the area of given surface and always directed outward normal to the given surface is called vector area.

From figure, vector area is



$$\vec{A} = |\vec{A}| \cdot \hat{n}$$

or $$\vec{A} = A \cdot \hat{n}$$

Electric Flux

The number of electric field lines passing through a certain element of area is known as electric flux through that area.

OR

The scalar or dot product of electric field intensity and vector area is called electric flux. It is denoted by ϕ.

$$\phi = \vec{E} \cdot \vec{A}$$

Where

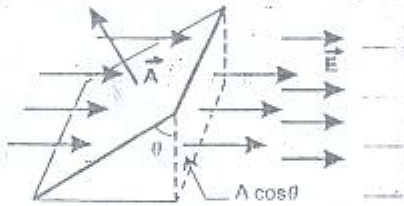
$\vec{E}$ = Electric field intensity
$\vec{A}$ = Vector area

➡ Electric flux is a scalar quantity.
➡ Its SI-units is $N \cdot m^2 \cdot C^{-1}$.

Explanation

Consider an electric field of electric field intensity $\vec{E}$ in which a surface of vector area $\vec{A}$ is placed at a certain angle θ as shown in figure. The field lines passing through the perpendicular surface of vector area $\vec{A}$ which is $A\cos\theta$ as shown in figure.

So, electric flux through the vector area is given as



$$\phi = EA\cos\theta$$

or $$\phi = \vec{E}\cdot\vec{A}$$

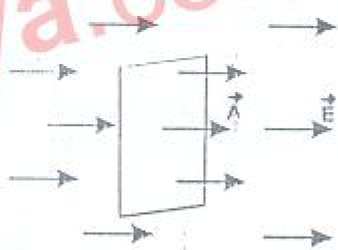
Where θ is the angle between the electric field lines and the normal to the surface area.

Maximum Flux

If the surface area is held perpendicular to the field lines i-e; vector area is parallel to the field lines, then EA lines will pass through it.

Now electric flux in this case is

$$\phi = \vec{E}\cdot\vec{A} = EA\cos\theta$$



Here $\theta = 0°$

$\therefore$ $\phi = EA\cos 0°$

or $\phi = EA(1)$

or $\phi = EA$

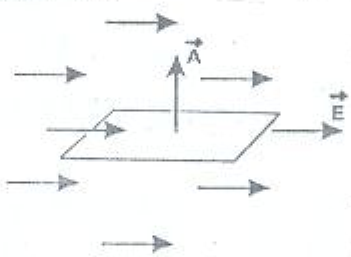
In this case electric flux will be maximum.

Minimum Flux

If surface area is held parallel to the field lines i-e; vector area is perpendicular to the field lines, then no line will pass through it.

Now electric flux in this case is

$$\phi = \vec{E}\cdot\vec{A} = EA\cos\theta$$



Here $\theta = 90°$

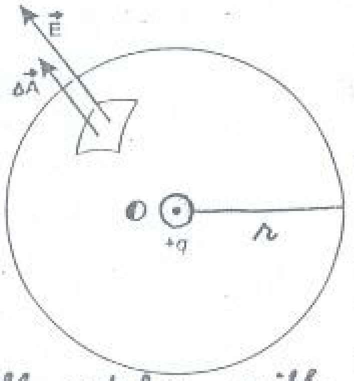
$\therefore$ $\phi = EA\cos 90°$

$\phi = EA(0)$

$\phi = 0$

In this case electric flux will be minimum.

Electric Flux Through A Surface Enclosing A Charge



Consider a closed surface in shape of a sphere of radius r and centre at point O as shown in the figure. In order to calculate the electric flux due to a point charge +q placed at the centre of the sphere, we apply the formula $\phi = \vec{E}\cdot\vec{A}$. For this, the sphere area is divided into n small patches with areas of magnitudes $\Delta A_1, \Delta A_2, \Delta A_3, ------, \Delta A_n$ respectively.

If n is very large, then each patch would be a flat element of area having corresponding vector areas are $\Delta\vec{A}_1, \Delta\vec{A}_2, \Delta\vec{A}_3, -------, \Delta\vec{A}_n$ respectively. The electric intensities at the centres of vector areas $\Delta\vec{A}_1, \Delta\vec{A}_2, \Delta\vec{A}_3, -------, \Delta\vec{A}_n$ are $\vec{E}_1, \vec{E}_2, \vec{E}_3, -------, \vec{E}_n$ respectively.

Now the electric flux through one patch of vector area $\Delta\vec{A}_1$ is

$$\phi_1 = \vec{E}_1 \cdot \Delta\vec{A}_1 = E_1 \Delta A_1 \cos\theta$$

As the direction of each vector area is along perpendicular drawn outward of each patch. So, the direction of electric intensity and vector area is same at each patch. Hence

$$\theta = 0^\circ$$

$$\therefore \quad \phi_1 = E_1 \Delta A_1 \cos 0^\circ = E_1 \Delta A_1 (1) \quad (\because \cos 0^\circ = 1)$$

or $\phi_1 = E_1 \Delta A_1$

Similarly, for other patches

$$\phi_2 = E_2 \Delta A_2 , \quad \phi_3 = E_3 \Delta A_3 , \quad -------, \quad \phi_n = E_n \Delta A_n$$

Now, the total flux through closed sphere is

$$\phi_e = \phi_1 + \phi_2 + \phi_3 + ---------- + \phi_n$$

or $\phi_e = E_1 \Delta A_1 + E_2 \Delta A_2 + E_3 \Delta A_3 + ------ + E_n \Delta A_n \longrightarrow (1)$

As the patches are so small that the magnitude of electric intensity over each patch is practically remains constant, so

$$E_1 = E_2 = E_3 = \text{---------} = E_n = E$$

Hence, equation ① becomes as

$$\phi_e = E\Delta A_1 + E\Delta A_2 + E\Delta A_3 + \text{-------} + E\Delta A_n$$

or $$\phi_e = E \times (\Delta A_1 + \Delta A_2 + \Delta A_3 + \text{--------} + \Delta A_n)$$

or $$\phi_e = E \times \sum_{i=1}^{n} \Delta A_i \longrightarrow ②$$

Where, Electric field intensity $= E = \frac{1}{4\pi\varepsilon_o} \cdot \frac{q}{r^2}$

Spherical Surface Area $= \sum_{i=1}^{n} \Delta A_i = 4\pi r^2$

Put these values in equation ②

$$\therefore \quad \phi_e = \frac{1}{4\pi\varepsilon_o} \cdot \frac{q}{r^2} \times 4\pi r^2$$

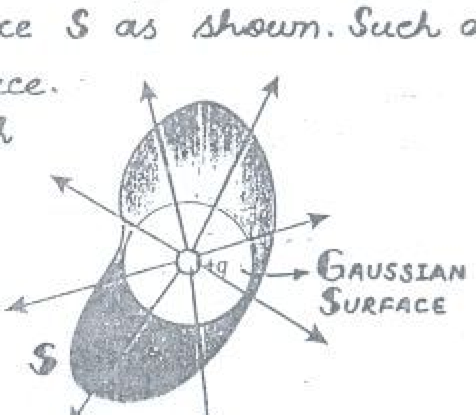
or $$\boxed{\phi_e = \frac{1}{\varepsilon_o} \times q = \frac{q}{\varepsilon_o}}$$

Hence, electric flux through a closed sphere is $1/\varepsilon_o$ times the charge enclosed at its centre.

Electric Flux Is Independent Of The Shape Of Closed Surface

Consider a closed surface S enclosing a charge +q as shown. Now imagine a closed sphere around charge +q inside closed surface S as shown. Such a surface is called Gaussian surface.

It is clear that the flux through the sphere and closed surface S is same i-e; $\phi = q/\varepsilon_o$. So, we can say that total flux through a closed surface is independent of the shape of the closed surface. Flux only depends upon the medium and the charge enclosed.



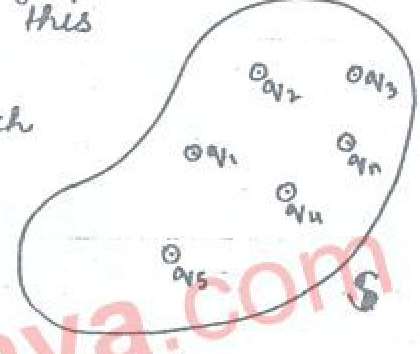
GAUSS'S LAW

STATEMENT: The total flux through any closed surface is $1/\varepsilon_o$ times the total charge enclosed in it. i-e;

TOTAL FLUX = $1/\varepsilon_o$ × (TOTAL CHARGE ENCLOSED)

PROOF:

Consider point charges q_1, q_2, q_3, ----------, q_n are distributed non-uniformly in an arbitrary shaped closed surface S as shown in figure.



In order to find flux through this surface, imagine closed spheres around each point charge such that each point charge lies at their centres. Here flux through each sphere is same as that for surface S.

Now, flux due to charge q_1 is

$$\phi_1 = 1/\varepsilon_o \times q_1 = q_1/\varepsilon_o$$

Similarly, flux due to other charges are

$$\phi_2 = \frac{q_2}{\varepsilon_o}, \ \phi_3 = \frac{q_3}{\varepsilon_o}, \ ----------, \ \phi_n = \frac{q_n}{\varepsilon_o}$$

So, total flux through surface S is

$$\phi_e = \phi_1 + \phi_2 + \phi_3 + ------ + \phi_n$$

or $$\phi_e = \frac{q_1}{\varepsilon_o} + \frac{q_2}{\varepsilon_o} + \frac{q_3}{\varepsilon_o} + -------- + \frac{q_n}{\varepsilon_o}$$

or $$\phi_e = \frac{1}{\varepsilon_o} \times (q_1 + q_2 + q_3 + ----- + q_n)$$

Where

$$Q = q_1 + q_2 + q_3 + ----- + q_n = \text{Total Charge Enclosed}$$

So

$$\phi_e = \frac{1}{\varepsilon_o} \times Q$$

$$\boxed{\text{TOTAL FLUX} = \frac{1}{\varepsilon_o} \times (\text{TOTAL CHARGE ENCLOSED})}$$

Which is the required result.

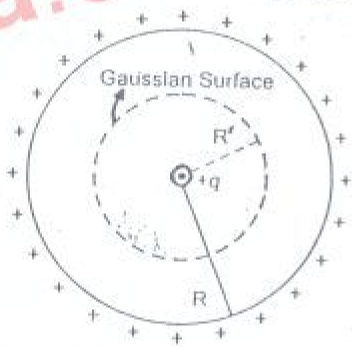
Applications Of Gauss's Law

Gauss's law is applied to calculate the electric intensity due to different charge distributions. For this, imaginary closed surface is assumed which passes through the point where electric field intensity can be calculated. Such an imaginary closed surface is known as 'Gaussian Surface'. The choice of Gaussian surface is such that the flux through it can easily calculated.

Now the charge enclosed by the Gaussian surface is calculated and then applying Gauss's law $\phi_e = Q/\varepsilon_o$ to calculate the electric intensity $\vec{E}$.

a. Intensity Of Field Inside A Hollow Charged Sphere

Consider a hollow conducting sphere of radius R on which a positive charge $+Q$ is distributed as shown.



In order to find the electric intensity $\vec{E}$ at a point inside the hollow sphere, imagine a closed sphere of radius $R' < R$ inside the hollow charged sphere. Such a closed surface is known as Gaussian surface.

Now, electric flux through this closed surface is

$$\phi_e = \vec{E} \cdot \vec{A} \longrightarrow (1)$$

According to Gauss's law, we have

$$\phi_e = \frac{q}{\varepsilon_o}$$

As there is no charge inside the Gaussian surface, so $q = 0$

So

$$\phi_e = \frac{0}{\epsilon_o} = 0 \longrightarrow (2)$$

Comparing equation (1) and (2)

$$\therefore \quad \vec{E} \cdot \vec{A} = 0$$

As $\quad \vec{A} \neq 0$

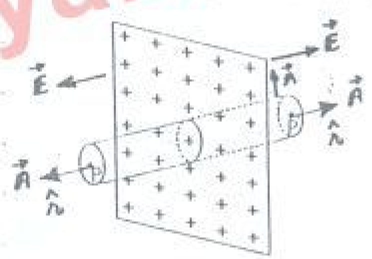
Therefore

$$\boxed{\vec{E} = 0}$$

Hence, electric intensity inside a hollow charged sphere is zero that is it is a field free region. So any apparatus placed inside the charge distribution is shielded from electric fields.

b. Electric Intensity Due To An Infinite Sheet Of Charge

Consider a sheet on which positive charges are distributed uniformly as shown. To find the electric intensity $\vec{E}$ at a point P close to the sheet, imagine a closed Gaussian surface in form of a cylinder passing through the sheet such that point P lies at its one end face as shown in figure.



The charge enclosed by the closed cylinderical surface of area A can be calculated by surface charge density σ as

$$\sigma = \frac{Q}{A}$$

or $\quad Q = \sigma A \longrightarrow (1)$

Now we find the electric flux through the closed cylinderical surface. As cylinderical surface has three faces, one curved face and two end faces.

Electric flux through curved surface is

$$\phi_1 = \vec{E} \cdot \vec{A} = EA \cos\theta$$

Here $\vec{E}$ and $\vec{A}$ are perpendicular, so $\theta = 90°$

$$\therefore \quad \phi_1 = EA \cos 90° = EA(0) = 0$$

Now, flux through one end face is

$$\phi_2 = \vec{E} \cdot \vec{A} = EA \cos\theta$$

Here $\vec{E}$ and $\vec{A}$ are in same direction, so $\theta = 0°$

$$\therefore \quad \phi_2 = EA \cos 0° = EA(1) = EA$$

Similarly, flux through other end face is

$$\phi_3 = EA \cos 0° = EA(1) = EA$$

So, total electric flux through cylinderical surface is

$$\phi_e = \phi_1 + \phi_2 + \phi_3$$

or $\phi_e = 0 + EA + EA$

or $\phi_e = 2EA \longrightarrow (2)$

Now according to Gauss's law, we have

$$\phi_e = \frac{1}{\varepsilon_o} \times Q$$

or $\phi_e = \frac{1}{\varepsilon_o} \times \sigma A \qquad (\because Q = \sigma A)$

or $\phi_e = \frac{\sigma A}{\varepsilon_o} \longrightarrow (3)$

Comparing equation (2) and (3)

$$2EA = \frac{\sigma A}{\varepsilon_o}$$

or $\boxed{E = \frac{\sigma}{2\varepsilon_o}}$

In vector form, we have

$$\boxed{\vec{E} = \frac{\sigma}{2\varepsilon_o} \cdot \hat{r}}$$

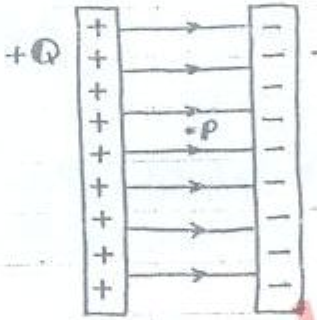
Where $\hat{r}$ is the unit vector in the direction of $\vec{E}$ directed outward normal from sheet as shown.

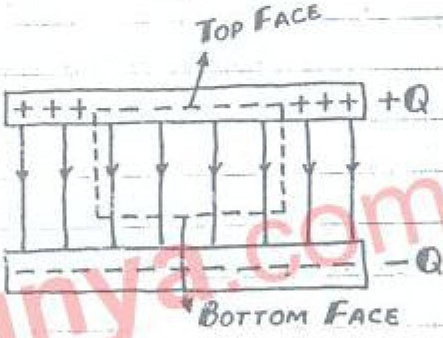
In case of negatively charged sheet

$$\boxed{\vec{E} = -\frac{\sigma}{2\varepsilon_o} \cdot \hat{r}}$$

6. Electric Intensity Between Two Oppositely Charged Parallel Plates

Consider two oppositely charged parallel metal plates having vacuum between them. The plates are separated by a small distance so that electric field intensity between the plates will be uniform. The direction of electric intensity is from positively charged plate towards negatively charged plate as shown in figure. Under such conditions the charges are concentrated on the inner surfaces of plates.





To calculate the electric field intensity $\vec{E}$ at point P in between the parallel plates, imagine a Gaussian surface in the form of a hollow box with its top face inside the upper metal plate and its bottom face in the space between the plates as shown in figure.

Now the electric flux through the top face of the hollow box is

$$\phi_1 = \vec{E}\cdot\vec{A} = EA\cos\theta$$

As there is no field inside the metal charged plate, so $E = 0$

$$\therefore \quad \phi_1 = (0)A\cos\theta = 0$$

Now flux through sides of the box is

$$\phi_2 = \vec{E}\cdot\vec{A} = EA\cos\theta$$

As electric intensity is perpendicular to the vector area of sides of the box, so $\theta = 90°$

$$\therefore \quad \phi_2 = EA\cos 90^\circ = EA(0) = 0$$

And flux through the bottom face of box is

$$\phi_3 = \vec{E}\cdot\vec{A} = EA\cos\theta$$

Here electric intensity and vector area of the bottom face of the box are in same direction, so $\theta = 0^\circ$

$$\therefore \quad \phi_3 = EA\cos 0^\circ = EA(1) = EA$$

So, total electric flux through the box is

$$\phi_e = \phi_1 + \phi_2 + \phi_3$$

$$\phi_e = 0 + 0 + EA$$

$$\text{or} \quad \phi_e = EA \longrightarrow (1)$$

Now according to Gauss's law, we have

$$\phi_e = \frac{1}{\varepsilon_0}\times Q = \frac{Q}{\varepsilon_0} \longrightarrow (2)$$

If A is the area of each plate, then charge on each plate can be calculated by surface charge density σ as

$$\sigma = Q/A$$

$$\text{or} \quad Q = \sigma A$$

Put this value in eq. (2)

$$\therefore \quad \phi_e = \frac{Q}{\varepsilon_0} = \frac{\sigma A}{\varepsilon_0} \longrightarrow (3)$$

Comparing equation (1) and (3)

$$EA = \frac{\sigma A}{\varepsilon_0}$$

$$\text{or} \quad \boxed{E = \frac{\sigma}{\varepsilon_0}}$$

This electric field intensity is same at all points between the parallel plates.

In vector form, electric intensity is

$$\boxed{\vec{E} = \frac{\sigma}{\varepsilon_0}\cdot\hat{r}}$$

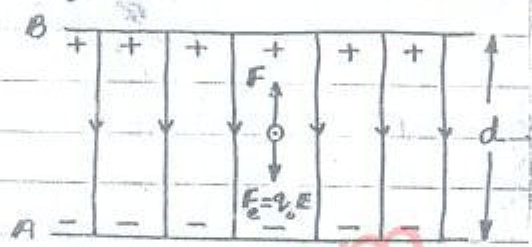
Where $\hat{r}$ is the unit vector in the direction of $\vec{E}$ and directed from positive to negative charge plate.

ELECTRIC POTENTIAL ENERGY

The work done by an external force in moving a unit positive charge against the electric field from one point to another in the electric field is called electric potential energy.

EXPLANATION

Consider that W_{AB} is the work done by the external force in carrying the unit positive charge q_o from point A to B against the electric field while keeping the charge in equilibrium as shown in figure, then the change in P.E is given as



$$\Delta U = W_{AB}$$

or

$$U_B - U_A = W_{AB}$$

Where U_A and U_B are the electric potential energies at points A and B respectively.

ELECTRIC POTENTIAL DIFFERENCE

The work done per unit positive charge in moving it from one one point to another against the electric field while keeping the charge in equilibrium is called electric potential difference.

OR

The change in electric potential energy per unit positive charge between two points is called electric potential difference.

EXPLANATION

OR RELATION BETWEEN ELECTRIC P.E. AND ELECTRIC P.D.

Consider an electric field $\vec{E}$ due to two oppositely charged parallel plates A and B separated by a small distance d as shown in figure. Let a unit positive charge q_o placed between the parallel plates. The positive charge

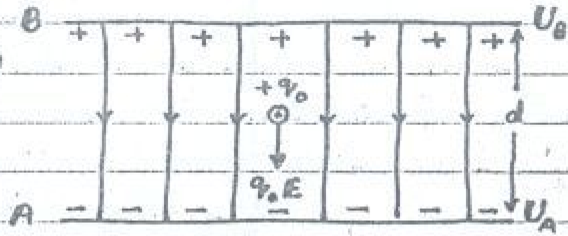
q_o is moved from B to A and will gain K.E. If it is to be moving from A to B, an external force is needed to do so against the electric field. So, the work done in moving the unit positive charge from A to B will change its P.E. Hence

Change in P.E. = Work

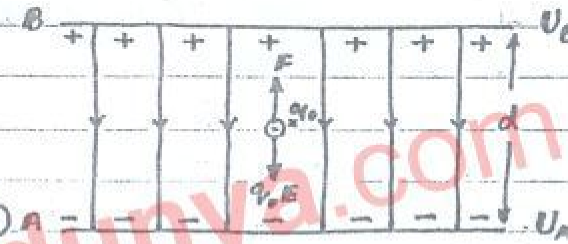
or $\Delta U = W_{AB}$ ⟶ ①

or $U_B - U_A = W_{AB}$

Where U_A and U_B are the electric P.E's at points A and B resp.



Now dividing by q_o on both sides



$$\frac{U_B - U_A}{q_o} = \frac{W_{AB}}{q_o}$$

or $$\frac{U_B}{q_o} - \frac{U_A}{q_o} = \frac{W_{AB}}{q_o} \longrightarrow ②$$

Where

$\frac{U_A}{q_o} = V_A$ = Electric potential at point A

$\frac{U_B}{q_o} = V_B$ = Electric potential at point B

Put these values in equation ②

$$V_B - V_B = \frac{W_{AB}}{q_o} \qquad (\because V_B - V_A = \Delta V = P.D.)$$

or $$\boxed{\Delta V = \frac{W_{AB}}{q_o}} \longrightarrow ③$$

or $W_{AB} = q_o \Delta V$

From equation ①

$W_{AB} = \Delta U$

So

$$\boxed{\Delta U = q_o \Delta V}$$

Which is the relation between electric potential energy and electric potential difference.

UNITS OF ELECTRIC POTENTIAL DIFFERENCE

The SI-units of electric P.D. is volt (V).

$$\boxed{1\ \text{volt} = \frac{1\ \text{joule}}{1\ \text{second}}} \Rightarrow \boxed{1V = \frac{1J}{1s}}$$

VOLT

The electric potential difference is said to be one volt if work is done in moving a unit positive charge of one coulomb from one point to another is one joule, keeping the charge in equilibrium.

ELECTRIC POTENTIAL OR ABSOLUTE ELECTRIC POTENTIAL

The work done in bringing a unit positive charge from infinity to that point keeping it in equilibrium is called electric potential.

Electric potential is still potential difference between the potential at infinity and the potential at that point.

EXPLANATION

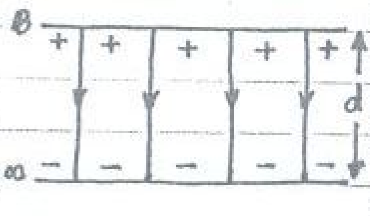
As electric potential difference between two points A and B in moving a unit positive charge from A to B is

$$\Delta V = V_B - V_A = \frac{W_{AB}}{q_0}$$

If point A is at infinity, then

$$V_A = V_\infty = 0$$

$$\therefore \quad V_B - 0 = \frac{W_{\infty B}}{q_0}$$



or $$V_B = \frac{W_B}{q_0}$$

In general

$$\boxed{V = \frac{W}{q_0}}$$

ELECTRIC POTENTIAL GRADIENT

The rate of change of electric potential with respect to distance is called potential gradient.

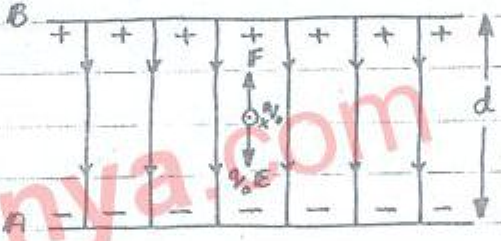
$$\boxed{\text{Potential Gradient} = \frac{\Delta V}{\Delta r}}$$

ELECTRIC FIELD AS POTENTIAL GRADIENT

OR PROVE THAT

$$E = -\frac{\Delta V}{\Delta r}$$

Consider two oppositely charged parallel plates A and B separated by a distance d, so that electric intensity between the plates will be uniform as shown in figure. The work done in moving a unit positive charge q_o from A to B is given as



$$W_{AB} = \vec{F} \cdot \vec{d}$$

or $\quad W_{AB} = Fd\cos\theta$

Here $\vec{F}$ and $\vec{d}$ are in opposite direction, so

$$\theta = 180^\circ$$

$\therefore \quad W_{AB} = Fd\cos 180^\circ = Fd(-1)$

or $\quad W_{AB} = -Fd$

Where

$$E = \frac{F}{q_o} \implies F = q_o E$$

$\therefore \quad W_{AB} = -Fd = -q_o E d$

Now the potential difference between points A and B is given as

$$\Delta V = V_B - V_A = \frac{W_{AB}}{q_o}$$

or $\quad \Delta V = \dfrac{-q_o E d}{q_o}$

or $\quad \Delta V = -Ed$

or $\quad E = -\dfrac{\Delta V}{d}$

If plates A and B are separated by a very small distance Δr, then take

$$d = \Delta r$$

$$\therefore \boxed{E = -\frac{\Delta V}{\Delta r}}$$

Hence electric intensity is minus potential gradient.

PROVE THAT

$$1\,\frac{\text{volt}}{\text{metre}} = 1\,\frac{\text{newton}}{\text{coulomb}}$$

PROOF: As

$$1\text{ volt} = 1\,\frac{\text{joule}}{\text{coulomb}}$$

or $$1\,\frac{\text{volt}}{\text{metre}} = 1\,\frac{\text{joule}}{\text{coulomb} \times \text{metre}}$$

or $$1\,\frac{\text{volt}}{\text{metre}} = 1\,\frac{\text{newton} \times \text{metre}}{\text{coulomb} \times \text{metre}}$$

or $$\boxed{1\,\frac{\text{volt}}{\text{metre}} = 1\,\frac{\text{newton}}{\text{coulomb}}}$$

Which is required result.

ELECTRIC POTENTIAL AT A POINT DUE TO A POINT CHARGE

As electric potential or absolute electric potential is defined as

The work done in moving a unit positive charge from infinity to that point keeping the charge in equilibrium is called electric potential or absolute electric potential.

DERIVATION

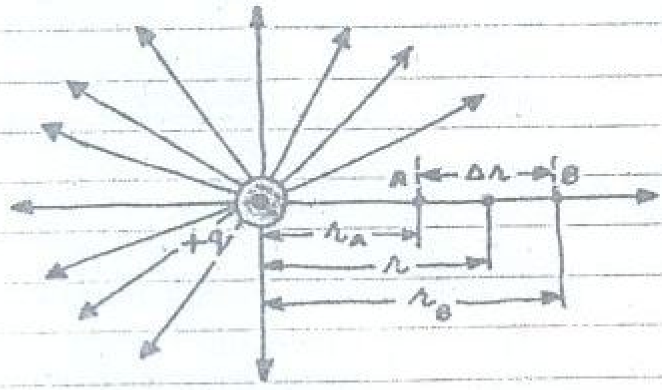
In order to find the electric potential due to a point charge $+q$, we use following relation

$$E = -\frac{\Delta V}{\Delta r}$$

or $$\Delta V = -E\Delta r$$

We can use this relation only when electric field between two points is uniform.

As electric intensity E is inversely proportional to the square of the distance from the point charge i-e; $E \propto 1/r^2$. For this consider two points A and B very close to each other in the field of point charge +q, so that E almost remains constant between points A and B as shown in figure.



Let

r_A = Distance of point A from +q

r_B = Distance of point B from +q

Now the distance between points A and B from figure is given as

$$r_B = r_A + \Delta r$$

or $$\Delta r = r_B - r_A \longrightarrow (1)$$

The magnitude of electric intensity at mid-point between points A and B is

$$E = \frac{1}{4\pi\epsilon_o} \cdot \frac{q}{r^2} \longrightarrow (2)$$

Where r is the midpoint distance between points A and B is given as

$$r = \frac{r_A + r_B}{2} \longrightarrow (3)$$

CALCULATION OF r^2.

As

$$r^2 = r \cdot r$$

Since points A and B are very close to each other, so using the approximation as

$$r_A = r_B = r$$

So

$$r^2 = r\,r = r_A r_B$$

Put this value of r^2 in equation ②

$$\therefore \quad E = \frac{1}{4\pi\varepsilon_0} \cdot \frac{q}{r_A r_B} \longrightarrow ④$$

Now if a unit positive charge is moved from B to A against the electric field, then the work done is equal to the potential difference between A and B given as

$$\Delta V' = -E \Delta r'$$

Where

$$\Delta V' = V_A - V_B$$
$$\Delta r' = r_A - r_B$$

So

$$V_A - V_B = -E(r_A - r_B)$$

or $$V_A - V_B = E(r_B - r_A)$$

Put value of E from equation ④

$$V_A - V_B = \frac{1}{4\pi\varepsilon_0} \cdot \frac{q}{r_A r_B}(r_B - r_A)$$

or $$V_A - V_B = \frac{q}{4\pi\varepsilon_0} \cdot \left(\frac{r_B - r_A}{r_A r_B}\right)$$

or $$V_A - V_B = \frac{q}{4\pi\varepsilon_0} \cdot \left(\frac{r_B}{r_A r_B} - \frac{r_A}{r_A r_B}\right)$$

or $$V_A - V_B = \frac{q}{4\pi\varepsilon_0} \cdot \left(\frac{1}{r_A} - \frac{1}{r_B}\right) \longrightarrow ⑤$$

Which is the potential difference between points A and B.

ABSOLUTE ELECTRIC POTENTIAL

In order to calculate the absolute electric potential at point A, point B assumed to be at infinity point, so that

$$r_B = \infty \quad , \quad V_B = V_\infty = 0$$

and $$\frac{1}{r_B} = \frac{1}{\infty} = 0$$

Put these values in equation ⑤

$$V_A - 0 = \frac{q}{4\pi\varepsilon_0}\cdot\left(\frac{1}{r_A} - 0\right)$$

or $$V_A = \frac{q}{4\pi\varepsilon_0}\cdot\frac{1}{r_A}$$

or $$V_A = \frac{1}{4\pi\varepsilon_0}\cdot\frac{q}{r_A}$$

The general expression for electric potential V at a distance r from q is

$$\boxed{V_{(r)} = \frac{1}{4\pi\varepsilon_0}\cdot\frac{q}{r}}$$

ELECTRON VOLT (eV)

The amount of energy acquired or lost by an electron as it transverses a potential difference of one volt is called one electron-volt (1eV).

So, eV is the unit of energy.

$$1eV = 1.6\times10^{-19}J$$

EXPLANATION
OR PROVE THAT $1eV = 1.6\times10^{-19}J$

Consider a particle of charge q moves from point A to B having electric potentials V_A and V_B respectively, keeping the charge in electrostatic equilibrium, then the change in P.E. of the charged particle is

$$\Delta U = q(V_B - V_A)$$

or $$\Delta U = q\,\Delta V \longrightarrow ①$$

If no external force acts on the charge then this change in P.E. appears as change in K.E., so

$$\Delta K.E. = \Delta U = q\,\Delta V$$

Let

$q = e$ = charge on electron $= 1.6\times10^{-19}C$

and ΔV = P.D. = 1 volt $= \frac{1J}{1C}$

$\therefore \quad \Delta K.E. = e\Delta V$

or $\quad \Delta K.E. = 1.6 \times 10^{-19} C \times 1 \text{ volt}$

or $\quad \Delta K.E. = 1.6 \times 10^{-19} C \times 1 J/C$

or $\quad \Delta K.E. = 1.6 \times 10^{-19} J$

This amount of energy i-e; $1.6 \times 10^{-19} J$ is called one electron volt and denoted by 1eV.

So

$$\boxed{1eV = 1.6 \times 10^{-19} J}$$

Comparision Between Electric And Gravitational Forces

Similarities

(i) Both electric and gravitational forces are conservative that is work done in such fields is independent of the path.

(ii) The electric force between two point charges $F_e = q_1 q_2 / 4\pi\varepsilon_o r^2$, is similar in form to the gravitational force between two point masses $F_g = G m_1 m_2 / r^2$.

(iii) Both forces are inversely proportional to the square of the distance between the two charges or between the two masses.

Dissimilarities

(i) Gravitational force is very weak force as compared to electric force because the value of gravitational constant G is very small as compared to the electrical constant $k = 1/4\pi\varepsilon_o$.

(ii) Electric force may be attractive or repulsive while gravitational force is only attractive.

(iii) Electric force between two charges is directly proportional to the product of charges while gravitational force between two masses is directly proportional to the product of masses.

(iv) Electric force is medium dependent while gravitational force lacks this property.

Charge On An Electron By Milikan's Method

R.A. Milikan developed a technique to find the charge on an electron in 1909.

Construction

The Milikan's oil drop experiment consists on

1. Container

The oil drop experiment consists on a container C having two windows W_1 and W_2 as shown in figure. There are two parallel plates PP' placed inside the container to avoid disturbances due to air currents.

2. Parallel Plates

Two plates P and P' are placed parallel to each other inside the container C separated by a small distance d as shown in figure. The upper plate P has a small hole H.

3. Power Supply

A voltage V is applied across the plates PP' due to which electric field E produced between the plates and controlled by a power supply. The magnitude of electric field E is

$$E = \frac{V}{d}$$

4. Atomizer

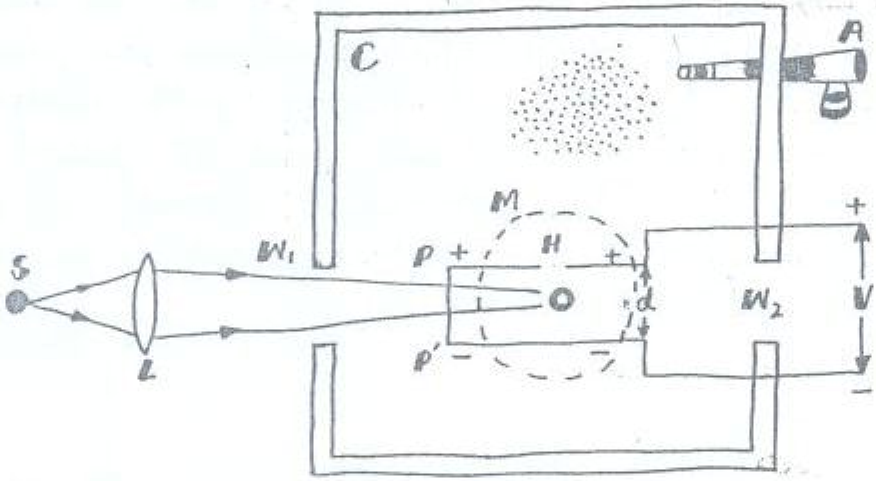
An atomizer A is used for spraying oil drops into the container through a nozzle. These oil drops are very small and are actually in the form of mist. The oil drops gets charged because of friction between oil drops and walls of the atomizer.

5. Source Of Light

A source of light S is used to visible the path of oil drops pass through the hole H of the upper plate P. The light from source is focussed by a lens L.

6. Microscope

A microscope M is used to observe the path of the oil drops.



Working

Consider an oil droplet of mass m and charge q pass through the hole H of plate P, then two forces acting on it given as

(i) The gravitational force $F_g = W = mg$, acting downward.

(ii) The electrical force $F_e = qE$, acting upward.

The oil droplet between the plates can be suspended in air if gravitational force is equal to the electrical force i-e;

$$F_e = F_g$$

or $$qE = mg$$

If V is the voltage applied between the plate then the magnitude of electric field E is

$$E = \frac{V}{d}$$

$$\therefore \quad q\frac{V}{d} = mg$$

or $$\boxed{q = \frac{mgd}{V}} \longrightarrow (1)$$

Here g, d and V are known while mass of the oil droplet m is unknown.

Mass Of Oil Droplet

In order to find the mass m of the oil drop, we use Stoke's law. The electric field between the plates P and P' is switched off. The oil droplet falls under the action of gravity through the air and it gains terminal velocity v_t in air. Terminal velocity can be calculated by measuring the time t during which droplet falls through a distance d as

$$v_t = \frac{d}{t}$$

When oil droplet falls under the action of gravity with constant terminal velocity v_t, then the drag force F due to air acting on the droplet equal to its weight, so

$$F = W$$

According to Stoke's law, $F = 6\pi\eta r v_t$

and $W = mg$

So

$$6\pi\eta r v_t = mg \longrightarrow (2)$$

Where r is the radius of the oil droplet and η is the coefficient of viscosity for air. If ρ is the density of the oil droplet, then

$$\rho = \frac{m}{V}$$

or $\quad m = V\rho$

Where volume of oil droplet $= V = \frac{4}{3}\pi r^3$

$$\therefore \quad m = \frac{4}{3}\pi r^3 \rho \longrightarrow (3)$$

Put this value of m in eq. (2)

$$6\pi\eta r v_t = \frac{4}{3}\pi r^3 \rho g$$

or $\quad r^2 = \dfrac{3 \times 6\eta v_t}{4\rho g}$

or $$\boxed{r^2 = \frac{9\eta v_t}{2\rho g}} \longrightarrow ④$$

Using this value of r in equation ③, we can calculate the mass m of the oil droplet and hence charge q on droplet can be calculated from equation ①.

Milikan measured the charge on many oil droplets and found that charge on each droplet is an integral multiple of 1.6×10^{-19}C. So, minimum value of charge on any droplet is equal to 1.6×10^{-19}C. Milikan concluded that this minimum value of charge is the charge on an electron.

Hence

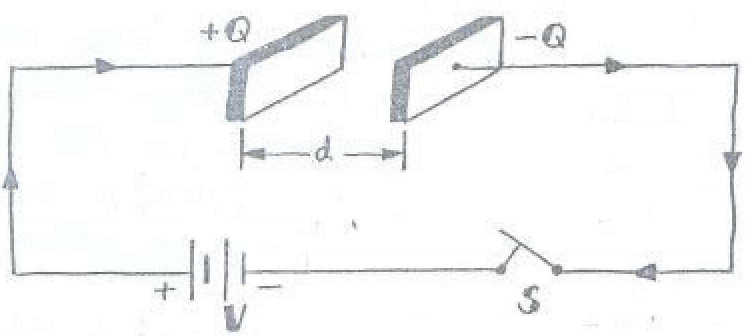
$$\boxed{\text{CHARGE ON ELECTRON} = 1.6 \times 10^{-19}\text{C}}$$

CAPACITOR

A device used to store electrical charge is called capacitor.

CONSTRUCTION OF A PARALLEL PLATE CAPACITOR

It consists on two conducting metal plates placed near one another separated by vacuum, air or any other insulator, known as dielectric. Usually, the metal plates are in the form of parallel plates and such a capacitor is called parallel plate capacitor as shown in figure.



WORKING

If the plates of the capacitor are connected to a battery of voltage V, it creates a potential difference of V volts between the two plates of the capacitor. The plate which is connected with positive terminal of the battery stores positive charge $+Q$ while other plate store same amount of negative charge $-Q$ which is connected with negative terminal of the battery.

Let Q is the magnitude of charge on each plate, then it is found that charge Q on each plate is directly proportional to the P.D. produced between the plates of the capacitor i-e;

$$Q \propto V$$

or $$Q = (\text{Constant})V$$

or $$\boxed{Q = CV}$$

Where C is constant of proportionality is called capacitance of the parallel plate capacitor. It depends upon the shape, size and medium between the plates of the capacitor.

CAPACITANCE

The measure of the ability of a capacitor to store charge is called capacitance.

It is denoted by C.

OR

As

$$Q = CV$$

or $$C = Q/V$$

Capacitance of capacitor is also defined as "The ratio between the charge stored on one of the plate of the capacitor to the potential difference produced between the plates is called capacitance of the parallel plate capacitor (C)".

UNITS OF CAPACITANCE

The SI-units of capacitance is "farad (F)".

$$\text{farad}\ (1F) = \frac{\text{coulomb}\ (1C)}{\text{volt}\ (1V)}$$

FARAD

The capacitance of a parallel plate capacitor is one farad if a charge of one coulomb given to one of the plates of a parallel plate capacitor, produces a potential difference of one volt between them.

$$1\mu F = 10^{-6} F$$

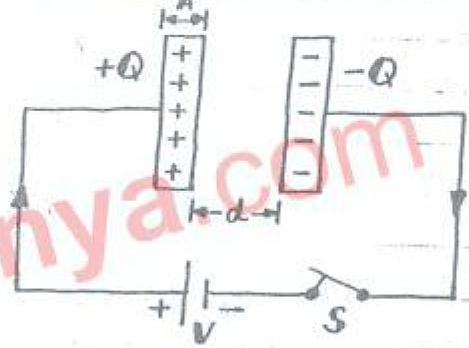
$$1pF = 10^{-12} F$$

CAPACITANCE OF A PARALLEL PLATE CAPACITOR

Capacitance of a parallel plate capacitor can be calculated in two cases.

CASE (i) WHEN VACUUM OR AIR BETWEEN THE PLATES

Consider a parallel plate capacitor consisting of two metal plates each of area 'A' separated by a small distance 'd' having vacuum or air between the plates as shown. The distance between the plates is so small that the electric field E between the plates is uniform.



Now the capacitance of parallel plate capacitor is

$$Q = C_{vac} V$$

or

$$C_{vac} = \frac{Q}{V} \longrightarrow ①$$

Where Q is the charge stored on each plate of the capacitor and V is the potential difference between the plates. Now the magnitude of electric field E produced between the plates of the capacitor is

$$E = \frac{V}{d} \longrightarrow ②$$

As the electric intensity between two oppositely charged parallel plates is

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

Now the surface charge density σ is

$$\sigma = \frac{Q}{A}$$

So

$$E = \frac{\sigma}{\varepsilon_o} = \frac{Q/A}{\varepsilon_o}$$

or

$$E = \frac{Q}{A\varepsilon_o} \longrightarrow (3)$$

Comparing equation (2) and (3)

$$\frac{Q}{A\varepsilon_o} = \frac{V}{d}$$

or

$$\frac{Q}{V} = \frac{A\varepsilon_o}{d}$$

Put this value in equation (1)

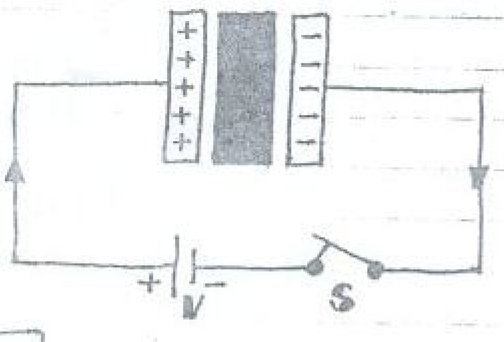
$$\boxed{C_{vac} = \frac{Q}{V} = \frac{A\varepsilon_o}{d}} \longrightarrow (4)$$

This equation shows that

$$\boxed{C_{vac} \propto A \quad \text{and} \quad C_{vac} \propto 1/d}$$

CASE (ii) WHEN DIELECTRIC MEDIUM BETWEEN PLATE

If an insulator, called a dielectric of relative permitivity or dielectric constant ε_r is placed between the plates, then the capacitance of the capacitor is given as



$$\boxed{C_{med} = \frac{A\varepsilon_o\varepsilon_r}{d}} \longrightarrow (5)$$

Comparing equation (4) and (5)

$$\boxed{C_{med} = C_{vac} \times \varepsilon_r} \longrightarrow (6)$$

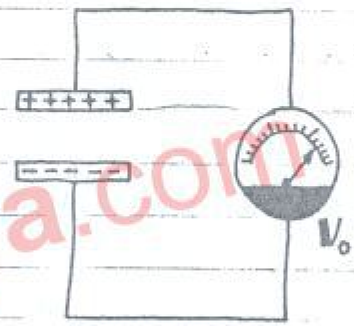
As $\varepsilon_r > 1$ for dielectrics, so capacitance of a parallel plate capacitor increases by a factor

ε_r when a dielectric medium is placed between the plates of the capacitor. Equation ⑤ shows that the capacitance depends upon

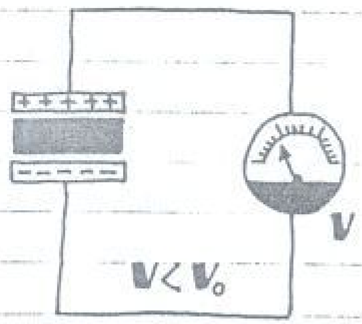
(i) Area of the plates (A)
(ii) Separation between the plates (d)
(iii) Medium between the plates.

As capacitance of capacitor increases when dielectric medium is placed between the plates, this fact experimentally observed as:

EXPERIMENT



Consider a charged capacitor connected to a voltmeter as shown in figure. The voltmeter reading V_o is a measure of the P.D. between the plates of the capacitor. When a dielectric substance is placed between the plates, then the voltmeter reading V drops shows a decrease in the P.D. between the plates i-e; $V < V_o$.



As we know that

$$Q = CV$$

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

Since Q remains constant and V decreases, so the value of capacitance C increases when dielectric substance is placed between the plates.

DIELECTRIC CONSTANT OR RELATIVE PERMITIVITY

As from equation ⑥

$$C_{med} = C_{vac}\,\varepsilon_r$$

$$\Rightarrow \quad \boxed{\varepsilon_r = \frac{C_{med}}{C_{vac}}}$$

DEFINITION: Dielectric constant is defined as "The ratio of the capacitance of a parallel plate capacitor with an insulating substance as medium between the plates to the capacitance with vacuum (or air) as medium between them."

DIPOLE

Two equal and opposite point charges separated by a small distance, form a dipole.

POLAR MOLECULES

Those molecules of a substance in which centres of positive and negative charges do not concide, called polar molecules.

For example, NaCl crystal.

NON-POLAR MOLECULES

Those molecules of a substance in which the centres of positive and negative charges concided in the absence of electric field, called non-polar molecules.

For example, dielectrics or insulators.

ELECTRIC POLARIZATION OF DIELECTRICS

When a dielectric substance is placed in between the plates of the capacitor, the positive charges will be shifted on one of the face of dielectric and negative charges will be shifted on its other face. In this condition, the dielectric substance is said to be polarized and this phenomenon is called electric polarization.

EXPLANATION

Electric polarization of dielectrics increases the capacitance of the capacitor if a dielectric medium is placed between the plates of the capacitor.

This effect can be explained as follows.

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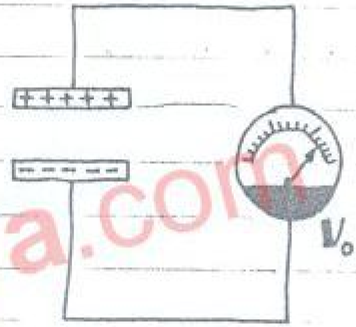

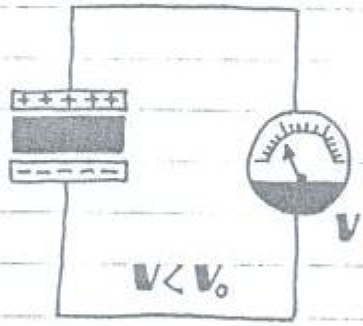

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Expression For Energy

Initially, when capacitor is uncharged, then the P.D. between plates is zero i-e;

For $q = 0$, $V = 0$

Finally, when capacitor stored charge q, then the P.D. between its plates becomes V i-e;

For q , $P.D. = V$

So, the average P.D. is

$$\text{Average P.D.} = \frac{0+V}{2} = \frac{1}{2}V$$

Also P.D. is given as

$$P.D. = \frac{P.E}{q} = \frac{\text{Energy}}{q}$$

or $\text{Energy} = q\,(P.D.)$ $\quad (\because P.D. = \frac{1}{2}V)$

or $\text{Energy} = q\left(\frac{1}{2}V\right)$

or $\text{Energy} = \frac{1}{2}qV \longrightarrow (1)$

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As charge stored on capacitor is

$$q = CV$$

Where C is the capacitance of the capacitor, so equation (1) becomes as

$$\text{Energy} = \frac{1}{2}(CV)V$$

or $\boxed{\text{Energy} = \frac{1}{2}CV^2} \longrightarrow (2)$

Equation (2) gives the expression for energy stored in a capacitor.

Expression For Energy In The Form Of Electric Field

Energy stored in a capacitor is in the form of electric field strength between the plates.

This fact can be calculated as follows:

As P.D. between the plates of capacitor is

$$V = Ed \longrightarrow (3)$$

Where E is the electric field strength between the plates and d is the distance between them.

Also the capacitance of capacitor is

$$C = \frac{A\varepsilon_o\varepsilon_r}{d} \longrightarrow (4)$$

Where A is the area of each plate of capacitor. Put values of V and C in equation (2), we get

$$\text{Energy} = \frac{1}{2}CV^2$$

or $$\text{Energy} = \frac{1}{2}\left(\frac{A\varepsilon_o\varepsilon_r}{d}\right)(Ed)^2$$

or $$\text{Energy} = \frac{1}{2}\left(\frac{A\varepsilon_o\varepsilon_r}{d}\right)(E^2d^2)$$

or $$\boxed{\text{Energy} = \frac{1}{2}\varepsilon_o\varepsilon_r E^2 (Ad)} \longrightarrow (5)$$

Where

Ad = Volume between the plates = υ

$$\therefore \quad \boxed{\text{Energy} = \frac{1}{2}\varepsilon_o\varepsilon_r E^2 (\upsilon)} \longrightarrow (6)$$

Energy Density

The energy stored in a capacitor per unit volume is called energy density.

$$\text{Energy Density} = \frac{\text{Energy}}{\text{Volume}}$$

$$\text{Energy Density} = \frac{\frac{1}{2}\varepsilon_o\varepsilon_r E^2(\upsilon)}{\upsilon}$$

$$\boxed{\text{Energy Density} = \frac{1}{2}\varepsilon_o\varepsilon_r E^2} \longrightarrow (7)$$

This equation is valid for any electric field strength.

Charging And Discharging A Capacitor

Charging Of Capacitor

Many electrical circuits consists of both capacitors and resistors. Figure (a) shows a resistor-capacitor circuit, called R-C-

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Where

$$Ad = \text{Volume between the plates} = \upsilon$$

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The energy stored in a capacitor per unit volume is called energy density.

$$\text{Energy Density} = \frac{\text{Energy}}{\text{Volume}}$$

$$\text{Energy Density} = \frac{\frac{1}{2}\varepsilon_o\varepsilon_r E^2 (\upsilon)}{\upsilon}$$

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Many electrical circuits consists of both capacitors and resistors. Figure (a) shows a resistor - capacitor circuit, called R-C-

QUESTIONS

12.1. The potential is constant throughout a given region of space. Is the electrical field zero or non-zero in this region? Explain.

Ans. If value of electric potential is constant $\neq 0$ in a region of space, then there is non zero electric field. Because electric potential is there only when electric field is present.

12.2. Suppose that you follow an electric field line due to a positive point charge. Do electric field and the potential increase or decrease?

Ans. If we follow line of electric force due to positive charge, then we move away from it. So, due to increase of distance from positive charge, the value of electric intensity, as well as electric potential decrease.

12.3. How can you identify that which plate of a capacitor is positively charged?

Ans. In order to charge a capacitor we apply potential difference across its plates. Therefore a source of emf is connected with the plates of capacitor. The plate of capacitor which is connected with positive terminal of battery is patiently charged.

12.4 How the orbits of planets will be modified, if the planets were electrically charged?

Ans. If all the planets were electrically charged then there would be force of repulsion between them. In order to have orbits of the planets the sun must be oppositely charged. If it is so, then radii must be very large so that force of attraction of the sun on the planets must be properly balanced.

12.5 Describe the force or forces on a positive point charge when placed between parallel plates?

With similar and equal charges

With opposite and equal charges

Ans. (a) When a positive charge is placed in the space between the parallel plates having similar and equal charge, then net force on it is zero. Because force of repulsion due to one plate is opposite to the force of repulsion acting on the charge due to the similar charge on other plates.

12.6 Electric lines of force never cross. Why?

Ans. The lines of electric force determine the direction of electric force on a positive test charge. As, at a given point there is one particular direction of force experienced by positive test charge. No two lines of electric field can cross at a point because it is impossible to have two different directions of electric force at single point inside electric field.

12.7 If a point charge q of mass m is released in a non-uniform electric field, will it make a rectilinear motion?

Ans. If a point charge q of mass m is released inside a non-uniform electric field, then it will move due to non-uniform electric field. Its acceleration is also non-uniform and it will move along line of force which may be in curved shape. The two possibilities are

(i) If lines of electric force are straight then point charge will have rectilinear motion.

(ii) If lines of electric force are curved then point charge will not have rectilinear motion.

12,8 Is E necessarily zero inside a charged rubber balloon if balloon is spherical? Assume that charge is distributed uniformly over the surface.

Ans. If a spherical rubber balloon has uniform charge distribution all over its surface. The electric intensity is equal to zero. It is according to "gauss's Law", because if we imagine any Gaussion surface inside the balloon then electric flux through it zero this proves that 'E' is also zero everywhere inside the balloon.

12.9 Is it true that Gauss's law states that the total number of lines of forces crossing any closed surface in the outward direction is proportional to the net positive charge enclosed within surface?

Ans. In the statement of Gauss's Law there is no condition that lines of electric force must be coming outward the closed surface. And also there is no condition imposed on the sign of electric charge which is enclosed by a closed surface. Hence, net flux passing through the closed surface may in outward or inward direction. Its value is directly proportional to the net charge (may be positive or negative) enclosed by the closed surface.

12.10. Do electrons tend to region of high potential or of low potential?

Ans. Electrons have negative charge. So these try to move from a region of low potential to the region at high potential. Their motion is opposite to the motion of positive free charge. Conventionally positive charge moves from higher to lower potential regions.