UNIT-9 Electrostatics & Magnetostatics

Electrostatic → If the charge is at rest then the branch of physics dealing with it is called electrostatic.

Coulomb's law → like charges repel each other and unlike charges attract each other. The magnitude of the force of attraction or repulsion between two charges is given by Coulomb's law.

Statement → It states that the magnitude of the force of attraction or repulsion between two charges (charged bodies) is directly proportional to the product of their charges and inversely proportional to the square of the separation between them.

Explanation → Consider two bodies A & B having charges q_1 & q_2 respectively, separated by a distance 'x' from each other. If 'F' be the force of attraction or repulsion between them. Then, according to the statement

(i) $F \propto q_1 q_2$

(ii) $F \propto \frac{1}{x^2}$

Combindly, $F \propto \frac{q_1 q_2}{x^2}$

$$\Rightarrow F = k' \frac{q_1 q_2}{x^2}$$

where k' is a constant.

The above equation represents the coulomb's law in scalar form.

One coulomb is the amount of charge which when separated from another similar charge by a distance of 1m in air, experiences a repulsive force of $9 \times 10^9 N$.

Value of k

(a) In C.G.S $\Rightarrow$ $k = \frac{1}{K}$ where, K is the dielectric constant of the medium.

For air/vacuum K = 1, So, the coulomb's law in C.G.S is given by $F = \frac{1}{K}\frac{q_1 q_2}{r^2}$ — (I) (For any medium)

$$F = \frac{q_1 q_2}{r^2} \text{ (For air/free space)} \quad \text{— (II)}$$

(b) In S.I $\Rightarrow$ $k' = \frac{1}{4\pi\epsilon}$

where ϵ is the permitivity of the medium.

For air/free space $k' = \frac{1}{4\pi\epsilon_0}$

Therefore, the Coulomb's law in S.I is given by

$$F = \frac{1}{4\pi\epsilon}\frac{q_1 q_2}{r^2} \text{ — (III) (For any medium)}$$

& $$F = \frac{1}{4\pi\epsilon_0}\frac{q_1 q_2}{r^2} \text{ — (IV) (For air/free space)}$$

The value of $\epsilon_0 = 8.854 \times 10^{-12}$

$$k' = \frac{1}{4\pi\epsilon_0} = \frac{1}{4 \times 3.14 \times 8.854 \times 10^{-12}}$$

$$\simeq 9 \times 10^9$$

So, the coulomb's law in S.I for free space can be written as $F = 9 \times 10^9 \frac{q_1 q_2}{r^2}$

The ratio between the permitivity of a medium to the permitivity of the free space is called relative permitivity and its denoted by ϵ_r.

i.e; $\epsilon_r = \frac{\epsilon}{\epsilon_0} \Rightarrow \boxed{\epsilon = \epsilon_r \epsilon_0}$ — (V)

∴ the coulomb's law in S.I. may be written as

$$F = \frac{1}{4\pi\epsilon_0\epsilon_r}\frac{q_1 q_2}{r^2} \quad \text{— (vi)} \quad (\text{For any medium})$$

Unit of ϵ

We know, $F = \frac{1}{4\pi\epsilon}\frac{q_1 q_2}{r^2}$

$$\Rightarrow \epsilon = \frac{q_1 q_2}{4\pi F r^2} \quad \text{— (VII)}$$

∴ the unit of ϵ is $C^2N^{-1}m^{-2}$ and the dimensional formula of ϵ is $\frac{[AT][AT]}{[MLT^{-2}][L^2]} = [M^{-1}L^{-3}T^4A^2]$.

Dielectric Constant (K) → Dielectric constant of a medium is defined as the ratio between the force between two charges separated by some distance in air to the force between the same two charges separated by the same distance in that medium. i.e; $K = \frac{F_{air}}{F_{medium}}$

$$= \frac{\frac{1}{4\pi\epsilon_0}\frac{q_1 q_2}{r^2}}{\frac{1}{4\pi\epsilon}\frac{q_1 q_2}{r^2}} = \frac{\epsilon}{\epsilon_0} = \epsilon_r$$

$$\Rightarrow \boxed{K = \epsilon_r}$$

Therefore, dielectric ~~me~~ constant of a medium is numerically equal to relative permittivity of the medium.

It has no dimension.

The value of air medium for $\boxed{K = 1}$

$\boxed{K > 1}$ (For other medium).

Unit of charge

(a) In C.G.S →

(i) Electrostatic unit → stat coulomb
(e.s.u)

$$F = \frac{q_1 q_2}{x^2} \text{ (For air medium)}$$

If $F = 1\,dyne,\ q_1 = q_2 = q,\ x = 1cm$

Then, $q^2 = (1\,stat\text{-}c)^2$

$$\boxed{q = 1\,stat\text{-}c}$$

Therefore, 1 stat coulomb charge is the amount of charge which when separated from another similar charge by a distance of 1 cm in air medium, experiences a repulsive force of one dyne.

(ii) Electromagnetic unit → The electromagnetic unit of charge is e.m.u of charge / ab coulomb.

(b) In S.I → The S.I unit of charge is coloumb.

In $S.I = F = 9 \times 10^9 \frac{q_1 q_2}{x^2}$ (For air/vacum)

If $F = 9 \times 10^9 N,\ q_1 = q_2 = q,\ x = 1m$

Then, $q^2 = (1C)^2$

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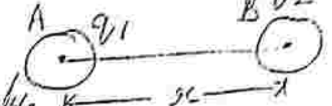

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Unit of ϵ

We know, $F = \frac{1}{4\pi\epsilon}\frac{q_1q_2}{x^2}$

$$\Rightarrow \epsilon = \frac{q_1q_2}{4\pi F x^2} \quad \text{(VII)}$$

So, the unit of ϵ is $C^2N^{-1}m^{2}$ and the dimensional formula of ϵ is $\frac{[AT][AT]}{[MLT^{-2}][L^2]} = [M^{-1}L^{-3}T^{4}A^{2}]$.

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Unit of charge

(a) In C.G.S →

(i) Electrostatic unit → stat coulomb
(e.s.u)

$$F = \frac{q_1 q_2}{x^2} \text{ (For air medium)}$$

If $F = 1 \text{dyne}$, $q_1 = q_2 = q$, $x = 1\text{cm}$

Then, $q^2 = (1 \text{stat-c})^2$

$$\boxed{q = 1 \text{ stat c}}$$

Therefore, 1 stat coulomb charge is the amount of charge which when seperated from another similar charge by a distance of 1cm in air medium, experiences a repulsive force of one dyne.

(ii) Electromagnetic unit → The electromagnetic unit of charge is e.m.u of charge / ab coulomb.

(b) In S.I → The S.I unit of charge is coloumb.

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If $F = 9 \times 10^9 N$, $q_1 = q_2 = q$, $x = 1m$

Then, $q^2 = (1C)^2$

$\Rightarrow q = \pm 1C$

Therefore, 1 coulomb charge is the amount of charge which when seperated from another similar charge by a distance of 1m in air, experiences a repulsive force of $9 \times 10^9 N$.

Relation between coulomb & stat coulomb

Let $1C = x$ stat coulomb

Consider two charges each of 1C, seperated by a distance 1m the force between them in S.I is given by

$$F = 9\times10^9 \frac{1\times1}{1^2}$$

$$= 9\times10^9 N \quad - (1)$$

In C.G.S $F = \frac{q_1 q_2}{x^2}$

$$= \frac{x \times x}{(10^2)^2} \text{ dyne}$$

$$= \frac{x^2}{10^4} \times \frac{1}{10^5} N = \frac{x^2}{10^9} N \quad - (2)$$

$$\Rightarrow \frac{x^2}{10^9} = 9\times10^9.$$

$$\Rightarrow x^2 = 9\times10^{18}$$

$$\Rightarrow x = \sqrt{9\times10^{18}}$$

$$\Rightarrow x = 3\times10^9$$

$$\Rightarrow \boxed{1C = 3\times10^9 \text{ stat coulomb}}$$

Relation between coulomb & ab coulomb

$$1 \text{ coulomb} = \frac{1}{10} \text{ ab coulomb}$$

Dimensional formula of charge = [AT].

(6)

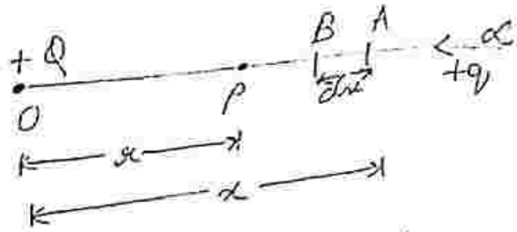
Electric Potential →

(Electric field Potential) → Electric field potential at a point within an electric field is defined as the amount of work done in bringing a unit +ve charge from infinity to that point.

i.e; $\boxed{V = \frac{W}{+q}}$

It is a scalar quantity.

Expression for Electric field Potential



Consider a charge '+Q' placed at 'O'. 'P' be a point within its field at '+Q' distance of 'x' from 'O'. Let us consider at '+q' charge at ∞.

The amount of work done in bringing '+q' charge from ∞ to the point 'P' is W.

Let A & B are the two instantaneous positions very close to each other separated by a small distance 'dx', at a distance of 'x' from the point O.

Let dw be the small amount of work done due to the small amount of displacement dx from A to B against electric field.

Then, $dw = \vec{F}\cdot\vec{dx}$

$= F \cdot dx \cdot \cos 180^\circ$

$= -F dx$

$= -\frac{KQq}{x^2} dx$ — (1)

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Now [illegible] charge from ∞ to the point P can be obtained by integration i.e., $W = \int_{0}^{W} dW$

$$= \int_{\infty}^{x} \frac{-k'Qq}{x^2}\, dx$$

$$= -k'Qq \left[-\frac{1}{x} \right]_{\infty}^{x}$$

$$= -k'Qq \left[\frac{1}{x} - \frac{1}{\infty} \right]$$

$$= \frac{k'Qq}{x} \quad \text{— (ii)}$$

Now, the potential at the the point P $V = \frac{W}{+q}$

$$= \frac{k'Qq/x}{+q}$$

$$\Rightarrow \boxed{V = \frac{k'Q}{x}} \quad \text{— (iii)}$$

This is the expression for electric field potential at a point due to a charge +Q at a distance of 'x' from it.

Units

(i) C.G.S system

(a) E.S.U $\rightarrow$ stat volt

$$1 \text{ stat volt} = \frac{1 \text{ erg}}{1 \text{ stat coulomb}}$$

Potential at a point is said to be 1 stat volt if 1 erg of work is done in bringing 1 stat coulomb charge from ∞ to that point against the electric field.

(b) E.M.U → ab volt

$$\boxed{1\text{ ab volt} = \frac{1\text{ erg}}{1\text{ ab coulomb}}}$$

The potential at a point is said to be 1 ab volt if 1 erg of work is done in bringing 1 ab coulomb charge from ∞ to that point against the electric field.

(ii). S.I unit ⇒ volt

$$1\text{ volt} = \frac{1\text{ Joule}}{1\text{ coulomb}}$$

The potential at a point is said to be 1 volt if 1 Joule of work is done in bringing 1 coulomb charge from infinity to that point against the electric field.

<u>Relation between volt and stat volt</u>

$$1\text{ volt} = \frac{1\text{ Joule}}{1\text{ Coulomb}}$$

$$1V = \frac{10^7\text{ erg}}{3\times10^9\text{ stat C}}$$

$$\boxed{1V = \frac{1}{300}\text{ stat volt}}$$

<u>Relation between volt & ab volt</u>

$$1\text{ volt} = \frac{1\text{ Joule}}{1\text{ coulomb}}$$

$$= \frac{10^7\text{ erg}}{\frac{1}{10}\text{ ab Coulomb}}$$

$$\boxed{1V = 10^8\text{ ab volt}}$$

$$V = \frac{W}{+q}$$

$$= \frac{[ML^2T^{-2}]}{[AT]} = [ML^2T^{-3}A^{-1}]$$

Potential difference (V)

The electric field potential at different points within an electric field are different

Let us consider r_A & r_B from the point source charge '+Q'. Then the potential at $V_A = \frac{k'Q}{r_A}$ and at B, $V_B = \frac{k'Q}{r_B}$.

Let $r_A > r_B$

Then, $V_A < V_B$.

The difference $V_B - V_A = \frac{k'Q}{r_B} - \frac{k'Q}{r_A}$

$= k'Q\left[\frac{1}{r_B} - \frac{1}{r_A}\right]$ is called potential difference.

If these two points A & B are connected to each other by a conductor then +ve charge goes from higher potential to lower potential and the negative charge flows from ~~higher~~ lower potential to higher potential.

Electric field → Electric field of an electric charge is the space or region surrounding the charge within which it can influence other charges.

It is a subjective idea or it is qualitative concept.

Electric field intensity ($\vec{E}$) → Electric field intensity at a point within an electric field is defined as the amount of force experienced by a unit positive charge placed at that point. i.e., $\boxed{\vec{E} = \frac{\vec{F}}{+q}}$

It is a vector quantity. The magnitude of electric field intensity $E = \frac{kQq}{r^2} / +q$

$$\boxed{E = \frac{kQ}{r^2}}$$

Unit → (a) In C.G.S → Dyne/statC.
(b) In S.I → Newton/Coulomb

Dimensional formula → $\frac{[MLT^{-2}]}{[AT]} = [MLT^{-3}A^{-1}]$.

Capacitance → Capacitance is the capacity of a capacitor to store charge.

Capacity → Whenever some additional charge is given to a conductor then its potential increase i.e., $Q \propto V$
$\Rightarrow Q = CV$ — (1)

where C is called capacity of the conductor.

From eqn (1) $C = \frac{Q}{V}$

Therefore, capacity of a conductor may be defined as the ratio between the total charge on the conductor to its potential.

Hence, capacity of a conductor may be defined as the amount of additional charge required to raise its potential by 1 unit.

Units

(1) S.I → Farad

$$1 \text{ Farad} = \frac{1 \text{ coulomb}}{1 \text{ volt}}$$

Therefore, capacity of a conductor is said to be 1 Farad if 1 coulomb of additional charge increases its potential by 1 volt.

(2) In C.G.S

(a) Electrostatic unit → stat Farad

$$1 \text{ stat Farad} = \frac{1 \text{ stat coulomb}}{1 \text{ stat volt}}$$

Therefore, capacity of a conductor is said to be 1 stat farad if 1 stat coulomb ~~equally~~ ~~to~~ ~~to someone~~ ~~that~~ ~~sufficient~~ ~~someone~~ of additional charge is sufficient to increase its potential by 1 stat volt.

(b) Electromagnetic unit → ab Farad

$$1 \text{ ab farad} = \frac{1 \text{ ab coulomb}}{1 \text{ ab volt}}$$

Therefore, capacity of a conductor is said to be 1 ab farad if a charge of 1 ab coulomb is sufficient to increase its potential by 1 ab volt.

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

$$= \frac{3\times10^{9}\,\text{stat}C}{\frac{1}{300}\,\text{stat}V}$$

$$= 9\times10^{11}\,\text{stat farad}$$

Relation between farad & ab farad

$$1\,\text{ab farad} = \frac{1C}{1V}$$

$$= \frac{\frac{1}{10}\,abC}{10^{8}\,abV}$$

$$= \frac{1}{10^{9}}\,ab\,V.$$

Dimensional formula of capacity

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

$$= \frac{[AT][AT]}{[ML^{2}T^{-2}]} = [M^{-1}L^{-2}T^{4}A^{2}].$$

Capacitor ⇒ Capacitor is an electrical device which can store charge and increases the capacity of a conductor upto infinite times. Its circuit symbol is ⊣⊢

Principle of capacitor

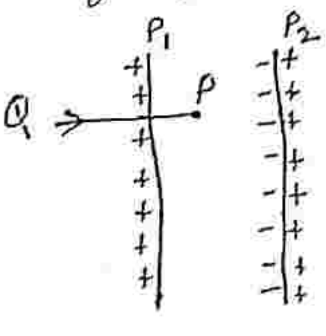


fig:(a)

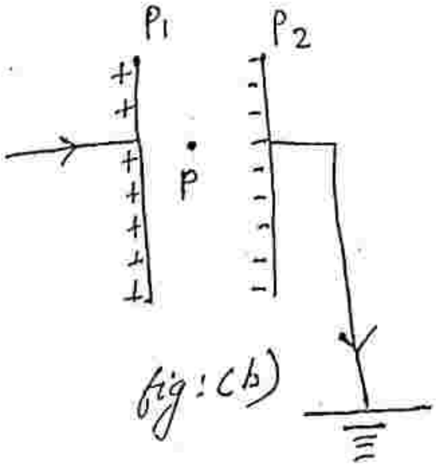


fig:(b)

Consider ~ parallel plates P_1 & P_2. Let P_1 is given charge 'Q' and Let P_2 is neutral.
By the method of induction by -ve charges of the plate P_2 lie towards P_1 (and the -ve charges of the plate P_2 are towards P_1) and the +ve charges of the plate P_2 are on the outer surface.

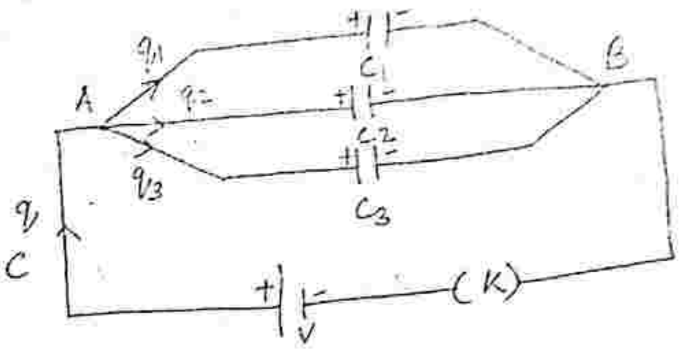
P be a point in between the two plates. Let the potential at the point P is 'V'. The case is shown in the fig: (a)

Now, the plate P_2 is earthed as shown in fig: (b). The +ve charges flows to the earth and the plate P_2 becomes -ve. Now in the presence of this plate, the work done in bringing a unit +ve charge from infinity to the point P will be less. Thus the potential at the point P decreases keeping the charge '+Q' constant.

Since, $C = \frac{Q}{V}$ thus the capacity increases.
This is the principle of the capacitor.

Combination of Capacitors

Parallel combination → Number of capacitors are said to be connected in parallel. If the +ve plates of all the capacitors are connected to one point and the -ve plates of all the capacitors are connected to another point and these two points are connected to the two terminals of source maintained at a P.D of (V).



Consider three capacitors having capacities C_1, C_2 & C_3 connected in parallel to a P.D (V).
Let 'q' amount of charge be drawn from the source and $q_1 \cdot q_2$ q_3 be the charges drawn by the capacitors $C_1; C_2$ & C_3 respectively.

Then, $q = q_1 + q_2 + q_3$ — ①
(According to the law of conservation of charge)
Let C be the net capacity of the combination then, $V = \frac{q}{C}$

$\Rightarrow q = CV$

Since the P.D across each capacitor is same, therefore;

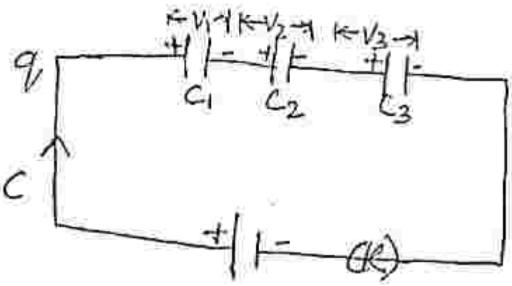
$$V = \frac{q_1}{C_1} = \frac{q_2}{C_2} = \frac{q_3}{C_3}$$

$$\Rightarrow q_1 = VC_1, q_2 = VC_2, q_3 = VC_3$$

substituting in eqn ① $CV = C_1V + C_2V + C_3V \Rightarrow \boxed{C = C_1 + C_2 + C_3}$

Therefore, when number of capacitors are connected in parallel then the net capacity of the combination is always equal to the sum of their individual capacity.

Here ... of capacitors are ... connected in series if the -ve plate of the first capacitor is connected to the +ve plate of the next and so on. It leaves the +ve plate of the first capacitor C_1 the -ve plate of the last capacitor as free terminals. These two plates are connected to the two terminals of the source maintained at some potential difference.



Consider three capacitors having capacities C_1, C_2 & C_3 are connected in series to a source maintained at a potential (V).

Let V_1, V_2, V_3 be the potential differences across the capacitors then, $V = V_1 + V_2 + V_3$ — ①

Let q be the amount of charge drawn from the source 'S' which is same for all the capacitors.

If C be the net capacitors of the combination then, $V = \frac{q}{C}$

Similarly, the P.D across the capacitors $V_1 = \frac{q}{C_1}$, $V_2 = \frac{q}{C_2}$, $V_3 = \frac{q}{C_3}$

substituting in eqn ①

$$\frac{q}{C} = \frac{q}{C_1} + \frac{q}{C_2} + \frac{q}{C_3}$$

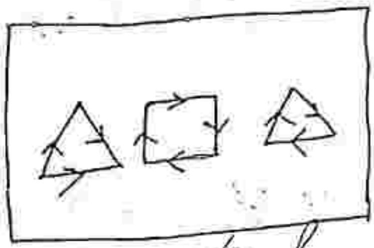
$$\Rightarrow \boxed{\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}}$$

Therefore, if number of capacitors are connected in series then the reciprocal of the resultant capacity is equal to the sum of the reciprocal of the individual capacities of the capacitors.

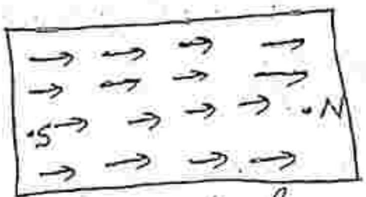
Magnet → The substance which has an ability to attract iron like materials.

In an unmagnetised magnetic substance, the molecular magnets are arranged in the form of a closed chain, neutralizing each other's effect.

A magnet consists of large number of molecular magnets. Each molecular magnet has a north pole and a south pole of equal pole strength. When an unmagnetised magnetic substance is under the influence of an electric field or magnetic field then all the molecular magnets are arranged in such a way that there north-poles are directed in one direction called as north pole of the magnet and the south pole are directed in the opposite direction called as the south pole of the magnet. The number of molecular lines (magnets) directed towards a pole of the magnet gives the strength of the pole called as pole strength & is denoted by (m).



(unmagnetised magnetic substance)



(Magnetised magnetic substance)

Coulomb's law in magnetism →

Like pole repeals each other and unlike poles attract each other. The magnitude of the force of attraction or repulsion between two isolated magnetic poles is given by coulomb's law.

Statement → The magnitude of force of attraction or repulsion between two isolated magnetic poles is directly proportional to the product of their pole strength and inversely proportional to the square of the distance between them.

Expt ÷ Consider two isolated magnetic north poles of pole strengths m_1 & m_2 respectively, seperated by a distance 'x'. The magnitude of force of repulsion between them is given by

(i) $F \propto m_1 m_2$

(ii) $F \propto \frac{1}{x^2}$

Combindly $F \propto \frac{m_1 m_2}{x^2}$

$$F = \frac{\mu_0}{4\pi} \frac{m_1 m_2}{x^2}$$

where $\frac{\mu_0}{4\pi}$ is a constant,

μ_0 is called permeability of free space.

Unit (magnetic pole) → A magnetic pole that, when placed in a vacuum at a distance of one centimeter from an equal and like pole, will repeal it with a force of one dyne.

OR

A unit of magnetic pole strength equal to the strength of a magnetic pole that repeals an identical pole at a distance of one centimeter with a force of one dyne.

Magnetic field

Magnetic field of a magnet is defined as the space or region surrounding the magnet within which it can influence other magnetic materials.

Magnetic field intensity (H)

The magnetic field intensity at a point within a magnetic field is defined as the amount of force experienced by a unit /north pole placed at that point.

The expression for magnetic field intensity can be obtained by substituting $m_1 = 1$ & $m_2 = m$; in the expression for coulomb's force $\boxed{F = \frac{\mu_0}{4\pi} \frac{m}{x^2}}$

Magnetic lines of force

Magnetic lines of force is an imaginary path which may be straight or curved along which a unit north pole would move if it were free to do so in a magnetic field. It's a straight line for a single pole and is a curve for multiple poles.

Properties of magnetic lines of force

① They are directed away from a north pole & towards a south pole.

② They start from a north pole and end at a south pole.

③ The tangent drawn at any point on the magnetic lines of force gives the direction of magnetic field intensity at the point.

(4) Two magnetic lines of force never intersect. If they do so then at the point of intersection two tangents can be drawn which gives two directions of magnetic field intensity.

(5) The number of magnetic lines of force per unit area is directly proportional to the strength of the magnetic field. More concentration of magnetic field lines of force represents a stronger magnetic field.

(6) They tends to contract longitudinally this is why two unlike attract each other.

(7) They tend to exert lateral pressure this is why two like poles repeal each other.

(8) A unit north pole produces 4π lines of force.

Magnetic flux

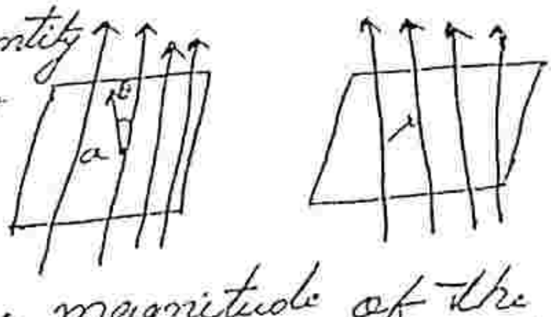
Number of magnetic lines of force crossing through an area produces magnetic flux.

Mathematically, it is the dot product of magnetic field induction and area of vector i.e; $\phi_B = \vec{B} \cdot \vec{a}$

$$= Ba\cos\theta \quad \text{--- (1)}$$

where θ is the smaller angle between $\vec{B}$ & $\vec{a}$.

Magnetic flux is a scalar quantity being the dot product of two vector quantities.

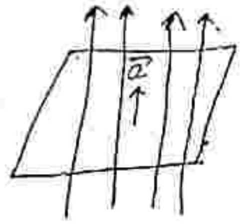


Magnetic flux may also be defined as the product of the magnitude of the magnetic field induction and the component of the area along the direction of magnetic field.

Case ① If $\theta = 0°$, $\cos\theta = 1$

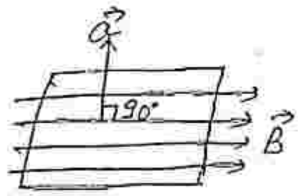
$$\phi_B = Ba \text{ (maximum)}.$$

When the magnetic line of force are crossing the area perpendicularly, the flux is maximum.



Case-② If $\theta = 90°$, $\cos\theta = 0$

$$\phi_B = 0 \text{ (minimum)}$$



i.e; When the magnetic lines of force are parallel to the area, then the flux is zero or minimum.

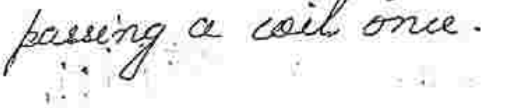
Again, we know the permeability $\mu = B/H$

$$\Rightarrow B = \mu H$$
$$= \mu a H$$

$\therefore$ The $(\phi_B)_{max} = \mu a H$.

If a coil has 'n' no. of turns then, the maximum flux $(\phi_B)_{max} = \mu a n H$.

It is to be noted that a magnetic line of force cutting a coil n-times produces equal flux as 'n' no. of lines of force passing a coil once.



Unit of Magnetic flux

a) In C.G.S → gauss cm^2 or maxwell

b) In S.I → Tesla m^2 or weber

Relation between weber and Maxwell

$$1\,\text{weber} = 1\,\text{Tesla} \times 1\,m^2$$
$$= 10^4\,\text{gauss} \times 10^4\,cm^2$$
$$= 10^8\,\text{maxwell}$$

$$\boxed{1\,\text{weber} = 10^8\,\text{Maxwell}}$$

Dimensional formula of magnetic flux

$$\phi_B = B \cdot a$$
$$= [M T^{-2} A^{-1}][L^2]$$
$$= [M L^2 T^{-2} A^{-1}].$$

Magnetic flux density (B)

It is defined as the sum of the number of magnetic lines of force per unit area of the magnetic field and the number of magnetic lines of force per unit area of the induced magnet.

The number of magnetic lines of force per unit area of the magnetic field is given by H.

A unit pole strength produces 4π lines of force.
Total no. of lines of force produced by the induced magnet $= 4\pi m$.

The no. of lines of force per unit area of the induced magnet $= \frac{4\pi m}{a}$,

According to the statement $B = H + \frac{4\pi m}{a}$

$$\Rightarrow B = H + 4\pi I.$$