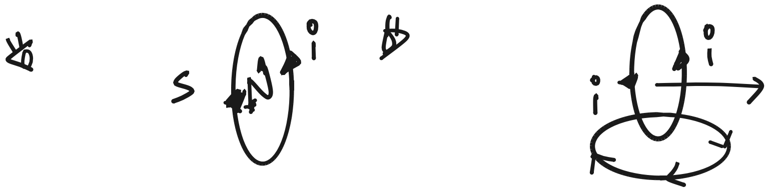
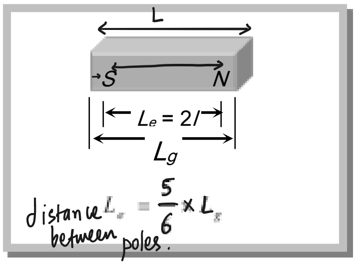
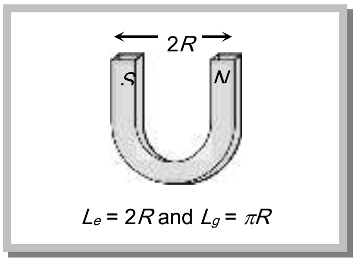


$\overrightarrow{\text{Magnetic Moment}} = N i \vec{A}$

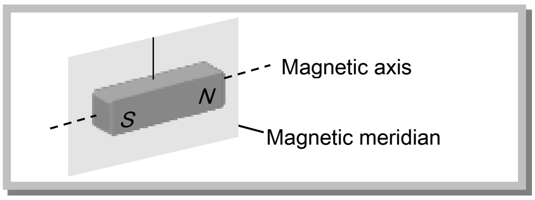
I. Bar Magnet

A bar magnet consist of two equal and opposite magnetic pole separated by a small distance. Poles are not exactly at the ends. The shortest distance between two poles is called effective length (L_e) and is less then its geometric length (L_g).

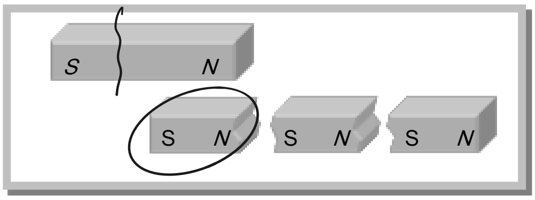




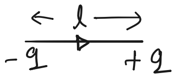
(1) **Directive properties** : When a magnet suspended freely it stays in the earth's *N-S* direction (in magnetic meridian).



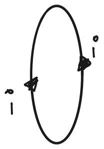
(2) **Monopole concept** : If a magnet is Broken into number of pieces, each piece becomes a magnet. This in turn implies that monopoles do not exist. (*i.e.*, ultimate individual unit of magnetism in any magnet is called dipole).



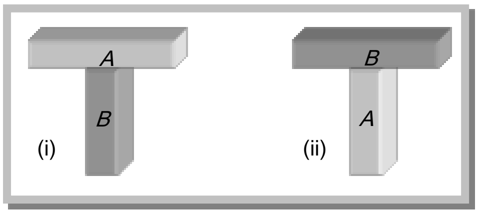
(3) For two rods as shown, if both the rods attract in case (i) and doesn't attract in case (ii) then, *B* is a magnetic and *A* is simple iron rod. Repulsion is sure test of magnetism.



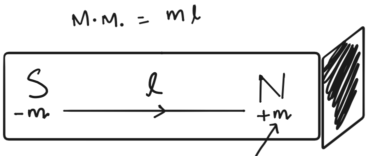
$P = ql$



M.M. = NIA



M.M. = ml



Pole strength

pole strength is proportional to Area of cross section of magnet.

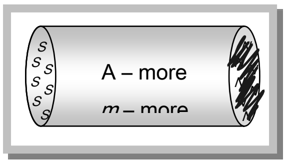
(4) **Pole strength (*m*) :** The strength of a magnetic pole to attract magnetic materials towards itself is known as pole strength.

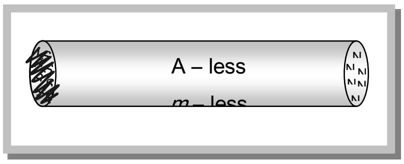
(i) It is a scalar quantity.

(ii) Pole strength of *N* and *S* pole of a magnet is conventionally represented by +*m* and –*m* respectively.

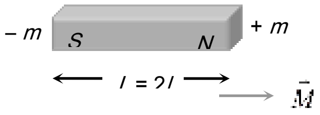
(iii) It's SI unit is *amp* × *m* or *N*/*Tesla* and dimensions are [*LA*].

(iv) Pole strength of the magnet depends on the nature of material of magnet and area of cross section. It doesn't depends upon length.





(5) **Magnetic moment or magnetic dipole moment** $(\vec{M})$ **:** It represents the strength of magnet. Mathematically it is defined as the product of the strength of either pole and effective length. *i.e.* $\vec{M} = m(2\vec{l})$

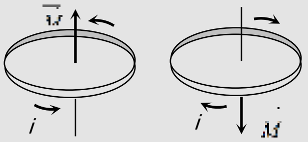


(i) It is a vector quantity directed from south to north.

(ii) It's S.I. unit *amp*×m^2 or *N-m*/*Tesla* and dimensions [AL^2]

(iii) Magnetic moment in various other situations.

Current carrying coil

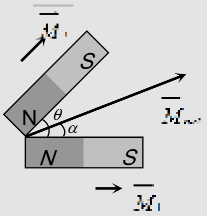


Magnetic moment $M = NiA$

N = number of turns,

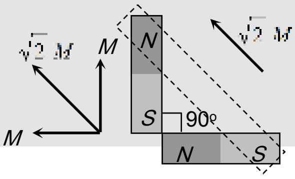
i= current through the coil, A= Area of the coil

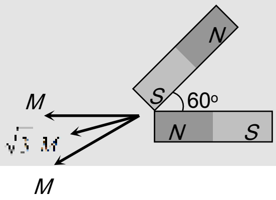
Combination of bar magnet

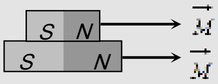


$$M_{net} = \sqrt{M_1^2 + M_2^2 + 2M_1M_2\cos\theta}$$ ✓

$$\tan\alpha = \frac{M_2\sin\theta}{M_1 + M_2\cos\theta}$$ ✓







$M_{net} = 2M$

Revolving charge

(a) Orbital electron : In an atom electrons revolve around the nucleus in circular orbit and it is equivalent to the flow of current in the orbit. Thus the orbit of electrons is considered as tiny current loop with magnetic moment.

$M = e\nu A = \frac{e\omega r^2}{2} = \frac{1}{2}evr = \frac{e}{2m}L = \frac{eh}{4\pi m}$; where, ω = angular speed, ν = frequency, v = linear speed and L= Angular moment $I\omega$.

(b) For geometrical symmetrical charged rotating bodies : The magnetic moment given by $M = \frac{QL}{2m} = \frac{QI\omega}{2m}$; where

m = mass of rotating body, Q = charge on body, I = moment of inertia of rotating body about axis of rotation.

$I = \frac{mR^2}{2}$, $M = \frac{1}{4}Q\omega R^2$ $\quad$ $I = MR^2$, $M = \frac{1}{2}Q\omega R^2$ $\quad$ $I = \frac{mL^2}{12}$, $M = \frac{1}{24}Q\omega L^2$

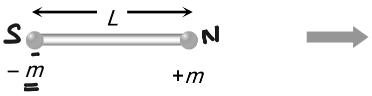
Note : ☐ Bohr magneton $\mu_B = \frac{eh}{4\pi m}$ = 9.27×10^{-24} A/m^2 . It serves as natural unit of magnetic moment.

Bohr magneton can be defined as the orbital magnetic moment of an electron circulating in inner most orbit.

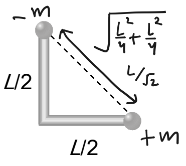
☐ Magnetic moment of straight current carrying wire is zero.

☐ Magnetic moment of toroid is zero.

☐ If a magnetic wire of magnetic moment (M) is bent into any shape then it's M decreases as it's length (L) always decreases and pole strength remains constant.



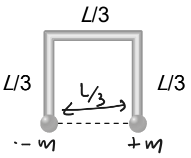
$M = mL$



$M' = M/\sqrt{2}$

$M' = \frac{\boxed{mL}}{\sqrt{2}}$

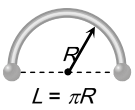
$M' = \frac{M}{\sqrt{2}}$



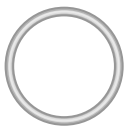
$M' = M/3$

$M' = \frac{mL}{3}$

$M' = \frac{M}{3}$



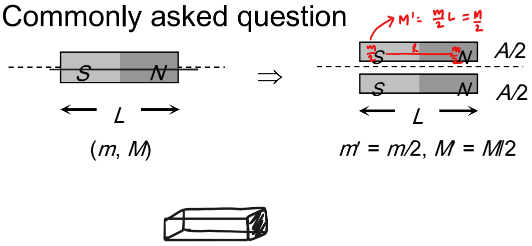
$M' = 2M/\pi$

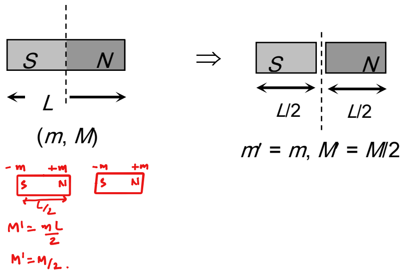


$M = 0$

(6) **Cutting of a bar magnet**

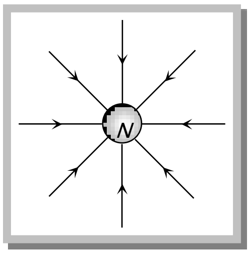
☐ Commonly asked question



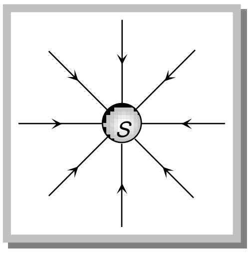


Various Terms Related to Magnetism

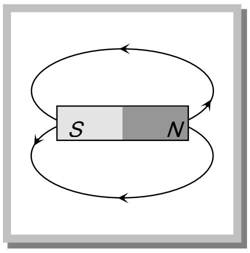
(1) **Magnetic field and magnetic lines of force :** Space around a magnetic pole or magnet or current carrying wire within which it's effect can be experienced is defined magnetic field. Magnetic field can be represented with the help of a set of lines or curves called magnetic lines of force.



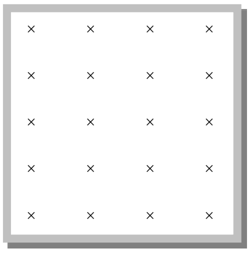
Isolated north pole



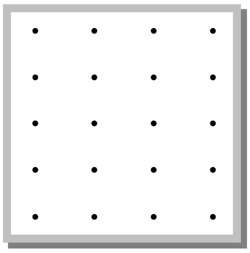
Isolated south pole



Magnetic dipole



Inward magnetic field



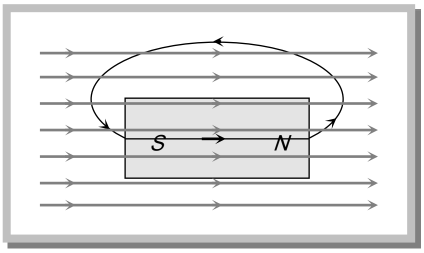
Outward magnetic field

(2) **Magnetic flux (ϕ) and flux density (B)**

(i) The number of magnetic lines of force passing normally through a surface is defined as magnetic flux (ϕ). It's S.I. unit is *weber* (*wb*) and CGS unit is *Maxwell*.

Remeber 1 *wb* = 10^8 *maxwell*.

(ii) When a piece of a magnetic substance is placed in an external magnetic field the substance becomes magnetised. The number of magnetic lines of induction inside a magnetised substance crossing unit area normal to their direction is called magnetic induction or magnetic flux density $(\vec{B})$. It is a vector quantity.



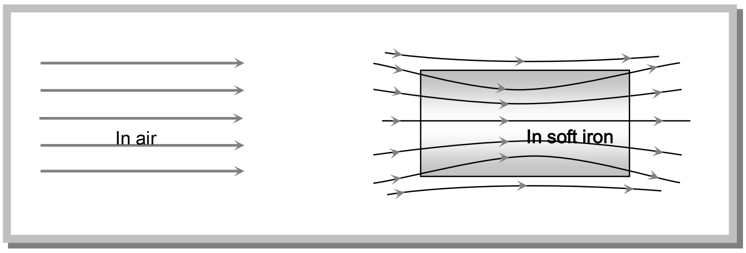
It's SI unit is *Tesla* which is equal to $\frac{wb}{m^2} = \frac{N}{amp \times m} = \frac{J}{amp \times m^2} = \frac{volt \times \sec}{m^2}$

and CGS unit is *Gauss*. Remember 1 *Tesla* = 10^4 *Gauss*.

Note : ❑ Magnetic flux density can also be defined in terms of force experienced by a unit north pole placed in that field *i.e.* $B = \frac{F}{m_0}$.

(3) **Magnetic permeability :** It is the degree or extent to which magnetic lines of force can enter a substance and is denoted by μ. or

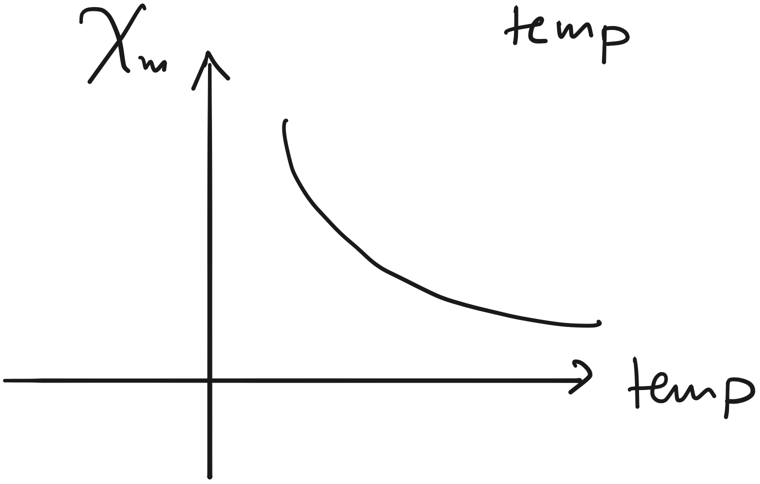
Characteristic of a medium which allows magnetic flux to pass through it is called it's permeability. *e.g.* permeability of soft iron is 1000 times greater than that of air.



Also μ = $\mu_0\ \mu_r$; where μ_0 = absolute permeability of air or free space = $4\pi \times 10^{-7}\ tesla \times m / amp$.

and μ_r = Relative permeability of the medium = $\frac{B}{B_0} = \frac{\text{flux density in material}}{\text{flux density in vacuum}}$.

Curie law $\chi_m \propto \frac{1}{temp}$ For paramagnetic Substance



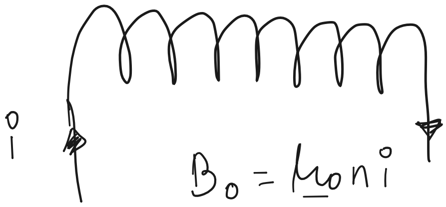
$$H = \frac{B}{\mu}$$

H is independent From medium.

(4) **Intensity of magnetising field $(\vec{H})$ (magnetising field)** : It is the degree or extent to which a magnetic field can magnetise a substance. Also $H = \frac{B}{\mu}$.

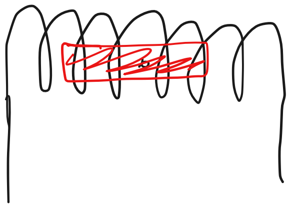
It's SI unit is $A/m = \frac{N}{m^2 \times Tesla} = \frac{N}{wb} = \frac{J}{m^3 \times Tesla} = \frac{J}{m \times wb}$ It's CGS unit is *Oersted*. Also 1 *oersted* = 80 *A*/*m*

$B = \mu n i, \quad \frac{B}{\mu} = ni$



$B_0 = \mu_0 n i$

$H = \frac{B_0}{\mu_0} = ni$



$\frac{B}{\mu} = H$

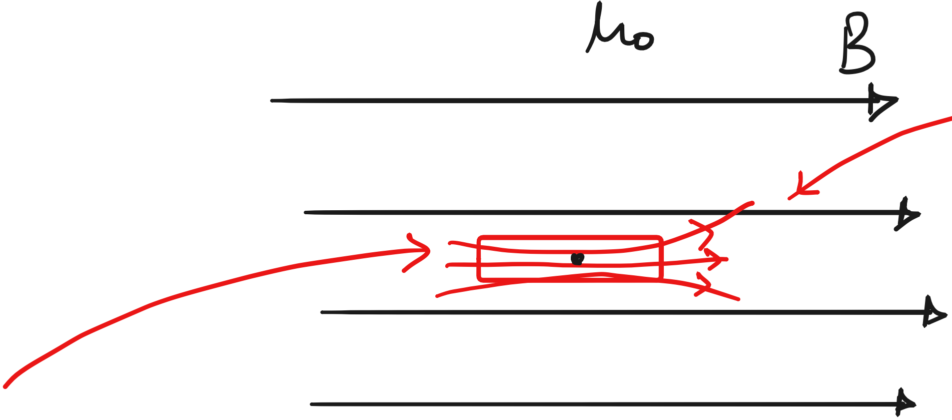
(5) **Intensity of magnetisation (*I*)** : It is the degree to which a substance is magnetised when placed in a magnetic field.

It can also be defined as the pole strength per unit cross sectional area of the substance or the induced dipole moment per unit volume.

Hence $I = \frac{m}{A} = \frac{M}{V}$. It is a vector quantity, it's S.I. unit is *Amp*/*m*.

$$I = \frac{M_{induced}}{Vol_o}$$

✓ $H = \frac{B}{\mu_o}$



$$I = \frac{B_i}{\mu_o}$$

Ferromagnetic Substance $B_{Net} = B_0 + B_i$

(6) **Magnetic susceptibility (χ_m) :** It is the property of the substance which shows how easily a substance can be magnetised. It can also be defined as the ratio of intensity of magnetisation (*I*) in a substance to the magnetic intensity (*H*) applied to the substance, *i.e.* $\chi_m = \frac{I}{H}$. It is a scalar quantity with no units and dimensions.

$$\chi_m = \frac{I}{H}$$

I ← induced Magnetization

H ← external field strength.

(7) **Relation between permeability and susceptibility :** Total magnetic flux density B in a material is the sum of magnetic flux density in vacuum B_0 produced by magnetising force and magnetic flux density due to magnetisation of material B_m. *i.e.* $B = B_0 + B_m$

$\Rightarrow B = \mu_0 H + \mu_0 I = \mu_0 (H + I) = \mu_0 H(1 + \chi_m)$. Also $\mu_r = (1 + \chi_m)$

$$B_{Net} = B_0 + B_i$$

$$= \mu_0 H + \mu_0 I$$

$$\mu \cancel{H} = \mu_0 \cancel{H}\left(1 + \frac{I}{H}\right)$$

$$\frac{\mu}{\mu_0} = 1 + \chi$$

$$\boxed{\mu_r = 1 + \chi_m}$$

Note : ☐ In CGS $B = H + 4\pi I$ and $\mu = 1 + 4\pi\chi_m$.

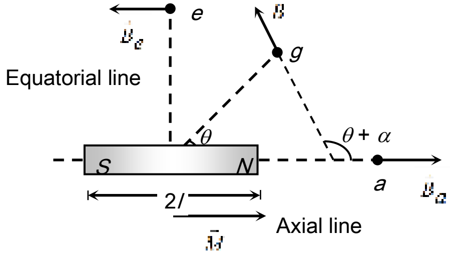
Force and Field

(1) **Coulombs law in magnetism** : The force between two magnetic poles of strength m_1 and m_2 lying at a distance r is given by $F = k.\frac{m_1 m_2}{r^2}$. In S.I. units $k = \frac{\mu_0}{4\pi} = 10^{-7} wb / Amp \times m$, In CGS units $k = 1$

(2) **Magnetic field**

(i) Magnetic field due to an imaginary magnetic pole (Pole strength *m*) : Is given by $B=\frac{F}{m_0}$ also $B=\frac{\mu_0}{4\pi}\cdot\frac{m}{d^2}$

(ii) Magnetic field due to a bar magnet : At a distance *r* from the centre of magnet



(a) On axial position

$$B_a=\frac{\mu_0}{4\pi}\frac{2Mr}{(r^2-l^2)^2};$$

If *l*<<*r* then $B_a=\frac{\mu_0}{4\pi}\frac{2M}{r^3}$

(b) On equatorial position : $B_e=\frac{\mu_0}{4\pi}\frac{M}{(r^2+l^2)^{3/2}}$; If *l*<<*r*; then $B_e=\frac{\mu_0}{4\pi}\frac{M}{r^3}$

(c) General position : In general position for a short bar magnet $B_g=\frac{\mu_0}{4\pi}\frac{M}{r^3}\sqrt{(3\cos^2\theta+1)}$

(3) **Bar magnet in magnetic field** : When a bar magnet is left free in an uniform magnetic field, if align it self in the directional field.

(i) Torque : $\tau = MB\sin\theta \Rightarrow \vec{\tau}=\vec{M}\times\vec{B}$

(ii) Work : $W = MB(1-\cos\theta)$

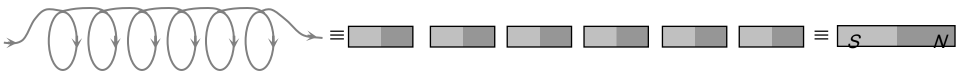
(iii) Potential energy : $U = MB\cos\theta = -\vec{M}.\vec{B}$; (θ = Angle made by the dipole with the field)

Note : ❑ For more details see comparative study of electric and magnetic dipole in electrostatics.

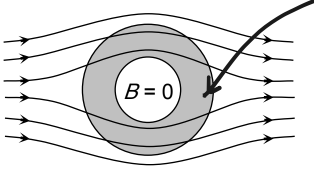
(4) **Gauss's law in magnetism** : Net magnetic flux through any surface is always zero *i.e.* $\oint \vec{B}.\vec{ds} = 0$

Concepts

- *The property of magnetism is materials is on account of magnetic moment in the material.*
- *Atoms which have paired electron have the magnetic moment zero.*
- *Magnetostriction : The length of an iron bar changes when it is magnetised, when an iron bar magnetised it's length increases due to alignment of spins parallel to the field. This increase is in the direction of magnetisation. This effect is known as magnetostriction.*
- *A current carrying solenoid can be treated as the arrangement of small magnetic dipoles placed in line with each other as shown. The number of such small magnetic dipoles is equal to the number of such small magnetic dipoles is equal to the number of turns in the in the solvent*



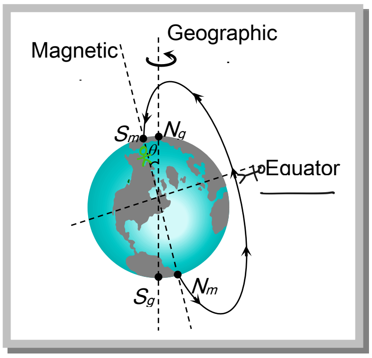
- *When a magnetic dipole of moment M moves from unstable equilibrium to stable equilibrium position in a magnetic field B, the kinetic energy by it will be 2 MB.*
- *Intensity of magnetisation (I) is produced in materials due to spin motion of electrons.*
- *For protecting a sensitive equipment from the external magnetic field it should be placed inside an iron cane. (magnetic shielding)*



pefect Diamagnetic material

Earth's magnetic Field (Terrestrial Magnetism)

As per the most established theory it is due to the rotation of the earth where by the various charged ions present in the molten state in the core of the earth rotate and constitute a current.



(1) The magnetic field of earth is similar to one which would be obtained if a huge magnet is assumed to be buried deep inside the earth at it's centre.

(2) The axis of rotation of earth is called geographic axis and the points where it cuts the surface of earth are called geographical poles (N_g, Sg). The circle on the earth's surface perpendicular to the geographical axis is called equator.

(3) A vertical plane passing through the geographical axis is called geographical meridian.

(4) The axis of the huge magnet assumed to be lying inside the earth is called magnetic axis of the earth. The points where the magnetic axis cuts the surface of earth are called magnetic poles. The circle on the earth's surface perpendicular to the magnetic axis is called magnetic equator.

(5) Magnetic axis and Geographical axis don't coincide but they makes an angle of 17.5° with each other.

(6) Magnetic equator divides the earth into two hemispheres. The hemisphere containing south polarity of earth's magnetism is called northern hemisphere while the other, the southern hemisphere.

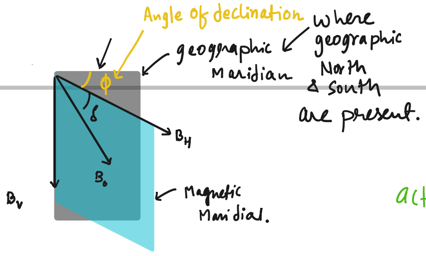
(7) The magnetic field of earth is not constant and changes irregularly from place to place on the surface of the earth and even at a given place in varies with time too.

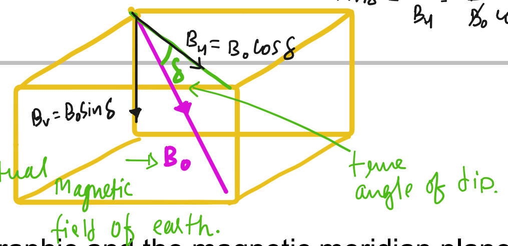
(8) Direction of earth's magnetic field is from S (geographical south) to N (Geographical north).

Elements of Earth's Magnetic Field

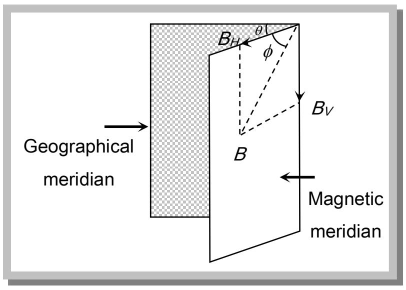
The magnitude and direction of the magnetic field of the earth at a place are completely given by certain. quantities known as magnetic elements.

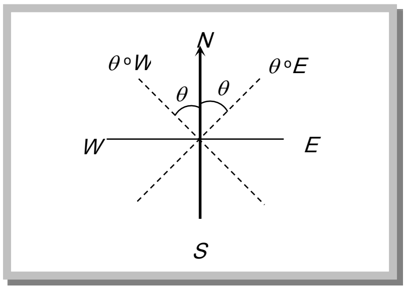
$\tan\delta = \frac{B_v}{B_H} = \frac{\cancel{B_0}\sin\delta}{\cancel{B_0}\cos\theta} = \tan\delta$





(1) **Magnetic Declination (θ) :** It is the angle between geographic and the magnetic meridian planes.





Declination at a place is expressed at $\theta^o E$ or $\theta^o W$ depending upon whether the north pole of the compass needle lies to the east or to the west of the geographical axis.

(2) **Angle of inclination or Dip (ϕ) :** It is the angle between the direction of intensity of total magnetic field of earth and a horizontal line in the magnetic meridian.

(3) **Horizontal component of earth's magnetic field (B_H) :** Earth's magnetic field is horizontal only at the magnetic equator. At any other place, the total intensity can be resolved into horizontal component (B_H) and vertical component (B_V).

Also $B_H = B\cos\phi$ ...... (i) and $B_V = B\sin\phi$ .... (ii)

By squaring and adding equation (i) and (ii) $B = \sqrt{B_{H^2} + B_{V^2}}$

Dividing equation (ii) by equation (i) $\tan\phi = \frac{B_V}{B_H}$

Note : ❑ At equator $\theta = 0 \Rightarrow B_H = B, B_V = 0$ while at poles $\phi = 90^o \Rightarrow B_H = 0,\ B_V = B.$

Magnetic Maps and Neutral Points (1) Magnetic maps (*i.e.* Declination, dip and horizontal component) over the earth vary in magnitude from place to place. It is found that many places have the same value of magnetic elements. The lines are drawn joining all place on the earth having same value of a magnetic elements. These lines forms magnetic map.

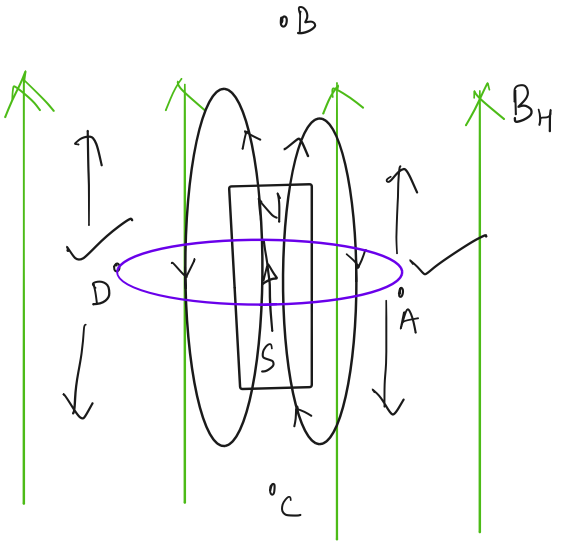
(i) Isogonic lines: These are the lines on the magnetic map joining the places of equal declination.

(ii) Agonic line: The line which passes through places having zero declination is called agonic line.

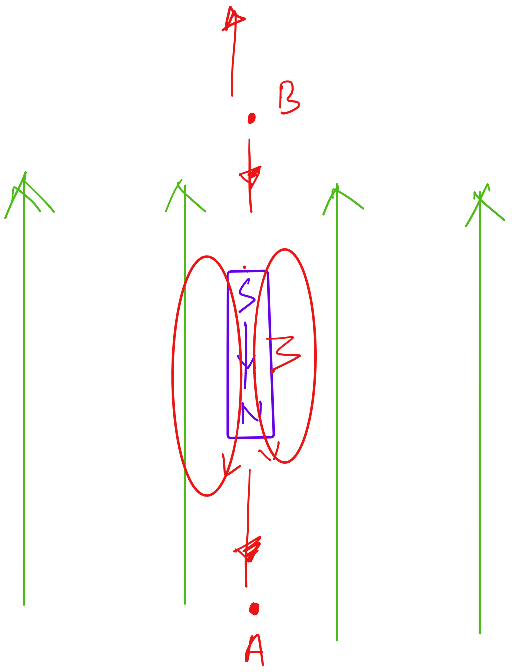
(iii) Isoclinic lines : These are the lines joining the points of equal dip or inclination.

(iv) Aclinic line : The line joining places of zero dip is called aclinic line (or magnetic equator)

(v) Isodynamic lines : The lines joining the points or places having the same value of horizontal component of earth's magnetic field are called isodynamic lines.

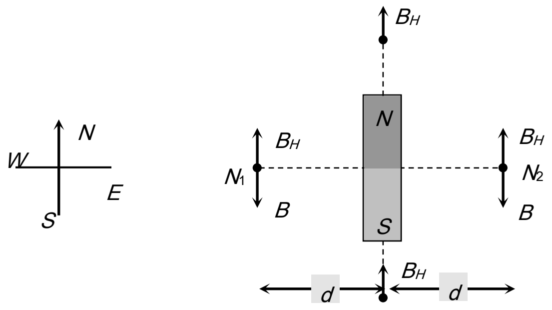
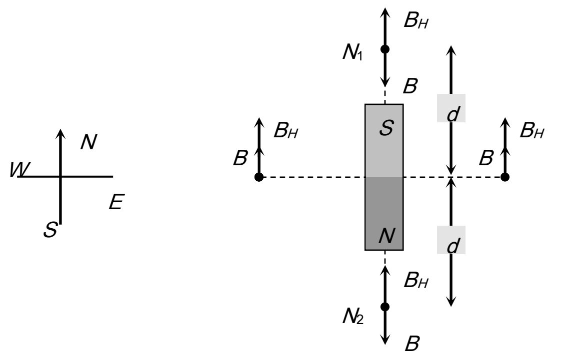


∞ Neutral points.



2 Neutral point.

(2) **Neutral points :** At the neutral point, magnetic field due to the bar magnet is just equal and opposite to the horizontal component of earth's magnetic field.

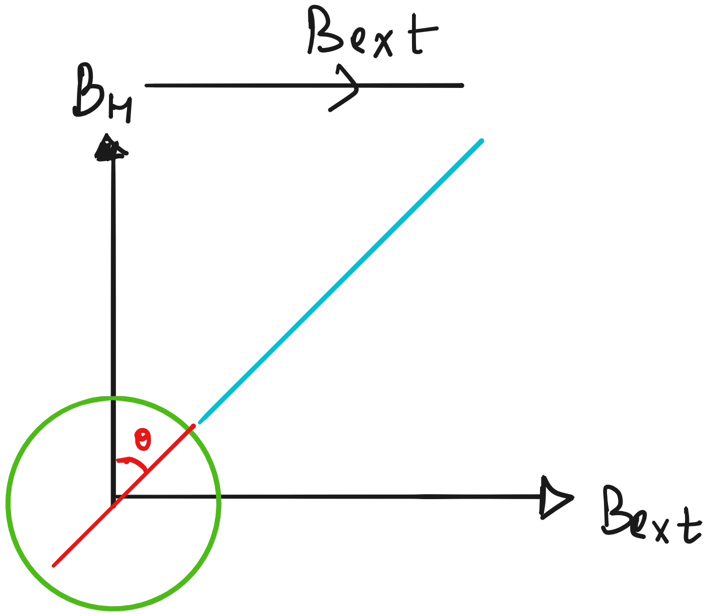
(i) **Magnet is placed horizontally in a horizontal plane.**	
N- pole of magnet is facing N- pole of earth	N - pole of magnet is facing N- pole of earth
	
Two neutral points N_1 and N_2 are obtained on equatorial line of bar magnet as shown and at Neutral points $B = B_H \Rightarrow \frac{\mu_0}{4\pi}\frac{M}{d^3} = B_H$	Two neutral points N_1 and N_2 are obtained on axial line of B or magnet and at neutral points $B = B_H$ i.e. $\frac{\mu_0}{4\pi}.\frac{2M}{d^3} = B_H$

* tangent law

$$\tan\theta = \frac{B_{ext}}{B_H}$$

$\boxed{S \rightarrow N}$

$$\boxed{B_{ext} = B_H \tan\theta}$$



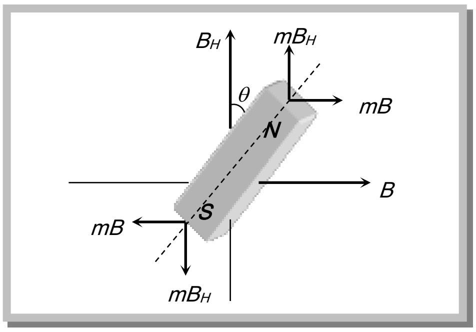
tangent law

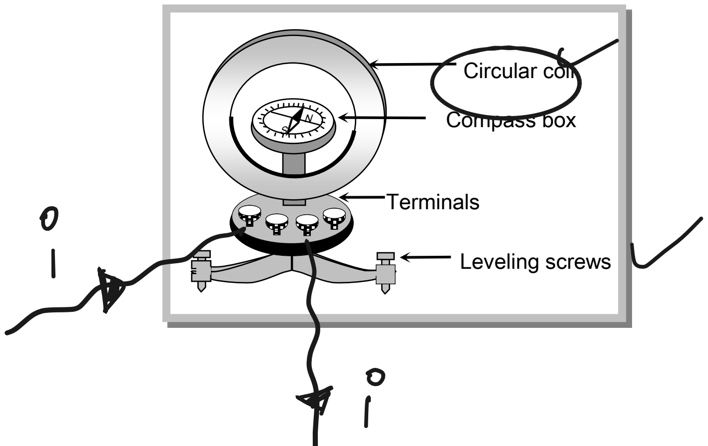
condition $B_H \perp B_{ext}$

$B_{ext} = \frac{\mu_0 i}{2r} N$

Tangent Law and it's Application

When a small magnet is suspended in two uniform magnetic fields B and B_H which are at right angles to each other, the magnet comes to rest at an angle θ with respect to B_H such that $B = B_H \tan\theta$. This is called tangent law.





Tangent galvanometer : It is an instrument which can detect/measure very small electric currents. It is also called as moving magnet galvanometer. It consists of three circular coils of insulated copper wire wound on a vertical circular frame made of nonmagnetic material as ebonite or wood. A small magnetic compass needle is pivoted at the centre of the vertical circular frame. This needle rotates freely in a horizontal plane inside a box made of nonmagnetic material. When the coil of the tangent galvanometer is kept in magnetic meridian and current passes through any of the coil then the needle at the centre gets deflected and comes to an equilibrium position under the action of two perpendicular field : one due to horizontal component of earth and the other due to field set up by the coil due to current (B).

In equilibrium $\boldsymbol{B = B_H \tan\theta}$ where $B = \frac{\mu_0 ni}{2r}$; n = number of turns, r = radius of coil, i = the current to be measured, θ = angle made by needle from the direction of B_H in equilibrium.

Hence $\frac{\mu_0 Ni}{2r} = B_H \tan\theta \Rightarrow i = k\tan\theta$ where $k = \frac{2rB_H}{\mu_0 N}$ is called reduction factor.

$B_{ext} = B_H \tan\theta$

$\frac{N \mu_0 i}{} = B_H \tan\theta$

K (reduction factor)

$2r$

$$i = \boxed{\frac{B_H 2r}{\mu_0 N}} \tan\theta$$

$$\boxed{i = k\tan\theta}$$

moving
coil
galvenometer

Note : ❑ Principle of moving coil galvanometer is $i \propto \tan\theta$. Since $i \propto \tan\theta$ so it's scale is not uniform.

❑ When $\theta = 45^o$, reduction factor equals to current flows through coil.

❑ Sensitivity of this galvanometer is maximum at $\theta = 45^o$.

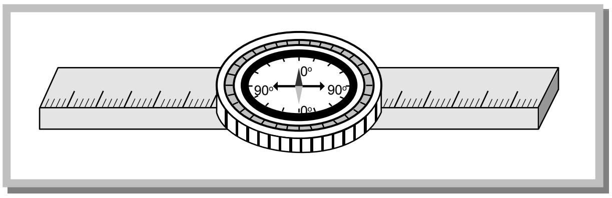
❑ This instrument is also called moving magnet type galvanometer.

Magnetic Instruments

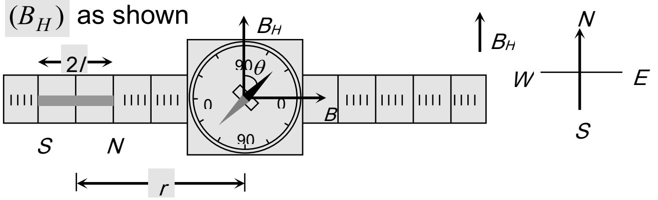
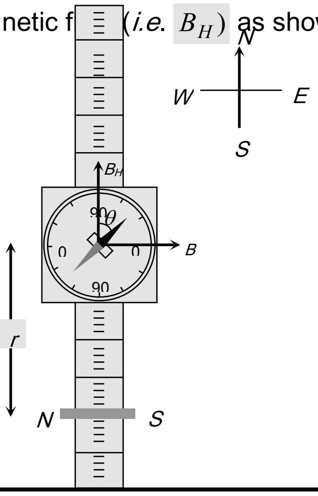
Magnetic instruments are used to find out the magnetic moment of a bar magnet, find out the horizontal component of earth's magnetic field, compare the magnetic moments of two bar magnets.

(1) **Deflection magnetometer**

It's working is based on the principle of tangent law. It consist of a small compass needle, pivoted at the centre of a circular box. The box is kept in a wooden frame having two meter scale fitted on it's two arms. Reading of a scale at any point directly gives the distance of that point from the centre of compass needle.



Different position of deflection magnetometer : Deflection magnetometer can be used according to two following positions.

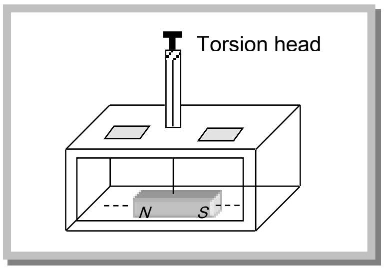
Tan A position	Tan B position
Arms of magnetometer are placed along *E*-*W* direction such that magnetic needle is acted upon by only horizontal component of earth's magnetic field (B_H) as shown  	Arms of magnetometer are placed along *N*-*S* direction such that magnetic needle align itself in the direction of earth's magnetic f (*i.e.* B_H) as shown. 

It a bar magnet is placed on one arm with it's length parallel to arm, so magnetic needle comes under the influence of two mutual perpendicular magnetic field (i) B_H and (ii) Axial magnetic field of experimental bar magnet. In equilibrium $B = B_H \tan\theta \Rightarrow \frac{\mu_0}{4\pi}\frac{2M}{r^3} = B_H \tan\theta$ (M= Magnetic moment of experimental bar magnet)	If a bar magnet is placed on one arm with it's length perpendicular to arm, so magnetic needle comes under the influence of two mutual perpendicular magnetic fields (i) B_H and (ii) equatorial magnetic field of experimental bar magnet. In equilibrium $B = B_H$ and $\Rightarrow \frac{\mu_0}{4\pi}.\frac{M}{r^3} = B_H \tan\theta$

Note : ☐ Deflection magnetometer also used to compare the magnetic moments either by deflection method or by null deflection method. **Deflection method :** $\frac{M_1}{M_2} = \frac{\tan\theta_1}{\tan\theta_2}$, **Null deflection method :** $\frac{M_1}{M_2} = \left(\frac{d_1}{d_2}\right)^3$ where d_1 and d_2 are the position of two bar magnet placed simultaneously on each arm.

(2) **Vibration magnetometer**

Vibration magnetometer is used for comparison of magnetic moments and magnetic fields. This device works on the principle, that whenever a freely suspended magnet in a uniform magnetic field, is disturbed from it's equilibrium position, it starts vibrating about the mean position.



Time period of oscillation of experimental bar magnet (magnetic moment *M*) in earth's magnetic field (B_H) is given by the formula. $T = 2\pi\sqrt{\frac{I}{MB_H}}$

Where, $I =$ moment of inertia of short bar magnet $= \frac{wL^2}{12}$ (*w* = mass of bar magnet)

(3) **Use of vibration magnetometer**

(i) Determination of magnetic moment of a magnet :

The experimental (given) magnet is put into vibration magnetometer and it's time period *T* is determined.

Now $T = 2\pi\sqrt{\frac{I}{MB_H}} \Rightarrow M = \frac{4\pi^2 I}{B_H.T^2}$

(ii) Comparison of horizontal components of earth's magnetic field at two places.

$T = 2\pi\sqrt{\frac{I}{MB_H}}$; since *I* and *M* the magnet are constant, so $T^2 \propto \frac{1}{B_H} \Rightarrow \frac{(B_H)_1}{(B_H)_2} = \frac{T_2^2}{T_1^2}$

(iii) Comparison of magnetic moment of two magnets of same size and mass.

$T = 2\pi\sqrt{\frac{I}{M.B_H}}$; Here *I* and B_H are constants. So $M \propto \frac{1}{T^2} \Rightarrow \frac{M_1}{M_2} = \frac{T_2^2}{T_1^2}$

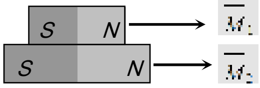
(iv) Comparison of magnetic moments of two magnets of unequal sizes and masses (by sum and difference method) :

In this method both the magnets vibrate simultaneously in two following position.

Sum position : Two magnets are placed such that their magnetic moments are additive

Net magnetic moment $M_s = M_1 + M_2$

Net moment of inertia $I_s = I_1 + I_2$



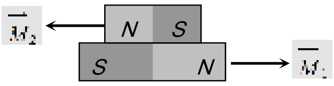
Time period of oscillation of this pair in earth's magnetic field (B_H)

$$T_s = 2\pi\sqrt{\frac{I_s}{M_s B_H}} = 2\pi\sqrt{\frac{I_1 + I_2}{(M_1 + M_2)B_H}} \quad .....(i)$$

Frequency $\nu_s = \frac{1}{2\pi}\sqrt{\frac{M_s(B_H)}{I_s}}$

Difference position : Magnetic moments are subtractive

Net magnetic moment $M_d = M_1 + M_2$



Net moment of inertia $I_d = I_1 + I_2$

and $T_d = 2\pi\sqrt{\frac{I_d}{M_d B_H}} = 2\pi\sqrt{\frac{I_1 + I_2}{(M_1 - M_2)B_H}}$ ....(ii)

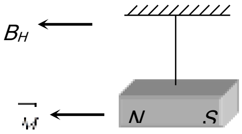
and $\nu_d = \frac{1}{2\pi}\sqrt{\frac{(M_1 + M_2)B_H}{(I_1 + I_2)}}$

From equation (i) and (ii) we get $\frac{T_s}{T_d} = \sqrt{\frac{M_1 - M_2}{M_1 + M_2}} \Rightarrow \frac{M_1}{M_2} = \frac{T_d^2 + T_s^2}{T_d^2 - T_s^2} = \frac{\nu_s^2 + \nu_d^2}{\nu_s^2 - \nu_d^2}$

(v) To find the ratio of magnetic field : Suppose it is required to find the ratio $\frac{B}{B_H}$ where B is the field created by magnet and B_H is the horizontal component of earth's magnetic field.

To determine $\frac{B}{B_H}$ a primary (main) magnet is made to first oscillate in earth's magnetic field (B_H) alone and it's time period of oscillation (T) is noted.

$$T = 2\pi\sqrt{\frac{I}{M\,B_H}}$$



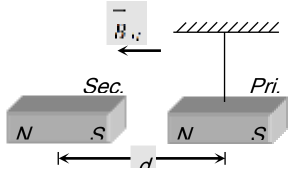
and frequency $\nu = \frac{1}{2\pi}\sqrt{\frac{M\,B_H}{I}}$

Now a secondary magnet placed near the primary magnet so primary magnet oscillate in a new field with is the resultant of B and B_H and now time period, is noted again.

There are two important possibilities for placing secondary magnet

Possibility 1

New field increases so time period of oscillation of primary magnet decreases



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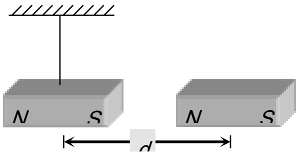

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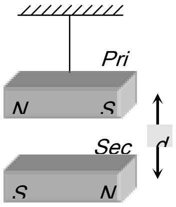
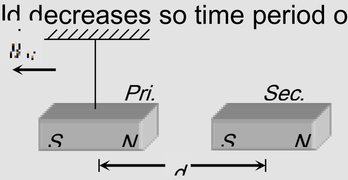


Now time period $T' = 2\pi\sqrt{\dfrac{I}{M(B+B_H)}}$ or new frequency $\nu' = \dfrac{1}{2\pi}\sqrt{\dfrac{M(M+B_H)}{I}}$

Also $\left(\dfrac{\nu'}{\nu}\right)^2 = \sqrt{\dfrac{B+B_H}{B_H}} \Rightarrow \left(\dfrac{\nu'}{\nu}\right)^2 = \dfrac{B}{B_1}+1 \Rightarrow \boxed{\dfrac{B}{B_H} = \left(\dfrac{\nu'}{\nu}\right)^2 - 1}$

Possibility 2

Net field decreases so time period of oscillation of primary magnet increases



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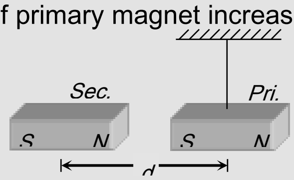

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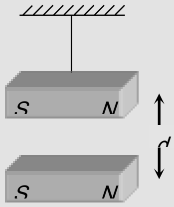


$T' = 2\pi\sqrt{\dfrac{I}{M(B_H - B)}}$ $(B_H > B)$ and $\nu' = \dfrac{1}{2\pi}\sqrt{\dfrac{M(B_H - B)}{I}}$

Also $\left(\dfrac{\nu'}{\nu}\right)^2 = \sqrt{\dfrac{B_H - B}{B_H}} \Rightarrow \left(\dfrac{\nu'}{\nu}\right)^2 = 1 - \left(\dfrac{B}{B_1}\right) \Rightarrow \boxed{\dfrac{B}{B_H} = 1 - \left(\dfrac{\nu'}{\nu}\right)^2}$

Concepts

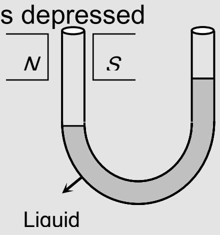
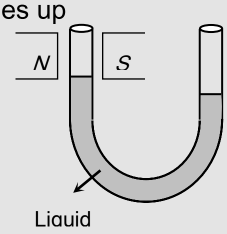
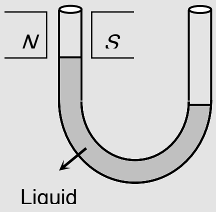
- ☞ *Remember time period of oscillation in difference position is greater than that in sum position* $T_d > T_s$.
- ☞ *If a rectangular bar magnet is cut in n equal parts then time period of each part will be* $\dfrac{1}{\sqrt{n}}$ *times that of complete magnet*

(i.e. $T' = \frac{T}{\sqrt{n}}$) while for short magnet $T' = \frac{T}{n}$. If nothing is said then bar magnet is treated as short magnet.

☞ *Suppose a magnetic needle is vibrating in earth's magnetic field. With temperature rise M decreases hence time period (T) increases but at 770°C (Curie temperature) it stops vibrating.*

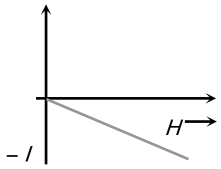
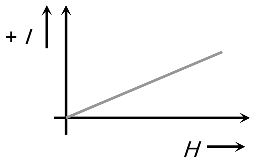
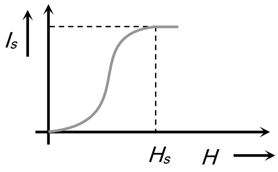
(3) **Comparative study of magnetic materials**

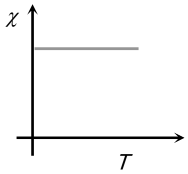
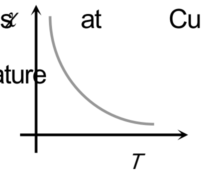
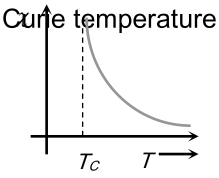
read once → H.W.

Property	**Diamagnetic substances**	**Paramagnetic substances**	**Ferromagnetic substances**
Cause of magnetism	Orbital motion of electrons	Spin motion of electrons	Formation of domains
Explanation of magnetism	On the basis of orbital motion of electrons	On the basis of spin and orbital motion of electrons	On the basis of domains formed
Behaviour In a non-uniform magnetic field	These are repelled in an external magnetic field *i.e.* have a tendency to move from high to low field region.	These are feebly attracted in an external magnetic field *i.e.*, have a tendency to move from low to high field region	These are strongly attracted in an external magnetic field *i.e.* they easily move from low to high field region
State of magnetisation	These are weekly magnetised in a direction opposite to that of applied magnetic field	These get weekly magnetised in the direction of applied magnetic field	These get strongly magnetised in the direction of applied magnetic field
When the material in the form of liquid is filled in the *U*-tube and placed between pole pieces.	Liquid level in that limb gets depressed 	Liquid level in that limb rises up 	Liquid level in that limb rises up very much 

On placing the gaseous materials between pole pieces	The gas expands at right angles to the magnetic field.	The gas expands in the direction of magnetic field.	The gas rapidly expands in the direction of magnetic field
The value of magnetic induction B	$B < B_0$	$B > B_0$	$B >> B_0$

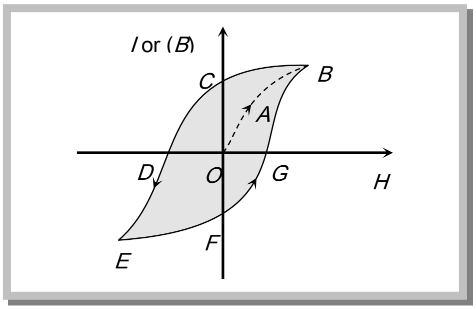
where B_0 is the magnetic induction in vacuum

Magnetic susceptibility χ	Low and negative $\|\chi\| \approx 1$	Low but positive $\chi \approx 1$	Positive and high $\chi \approx 10^2$
Dependence of χ on temperature	Does not depend on temperature (except Bi at low temperature)	Inversely proportional to temperature $\chi \propto \frac{1}{T}$ or $\chi = \frac{C}{T}$. This is called Curie law, where C = Curie constant	$\chi \propto \frac{1}{T - T_c}$ or $\chi = \frac{C}{T - T_c}$ This is called Curie Weiss law. T_c = Curie temperature
Dependence of χ on H	Does not depend independent	Does not depend independent	Does not depend independent
Relative permeability (μ_r)	$\mu_r < 1$	$\mu_r > 1$	$\mu_r >> 1$ $\mu_r = 10^2$
Intensity of magnetisation (I)	I is in a direction opposite to that of H and its value is very low	I is in the direction of H but value is low	I is in the direction of H and value is very high.
I-H curves			

Magnetic moment (M)	The value of M is very low ($\approx$ 0 and is in a direction opposite to H.)	The value of M is very low and is in the direction of H	The value of M is very high and is in the direction of H
Transition of materials (at Curie temperature)	These do not change. 	On cooling, these get converted to ferromagnetic materials at Curie temperature 	These get converted into paramagnetic materials above Curie temperature 
The property of magnetism	Diamagnetism is found in those materials the atoms of which have even number electrons	Paramagnetism is found in those materials the atoms of which have majority of electron spins in the same direction	Ferro-magnetism is found in those materials which when placed in an external magnetic field are strongly magnetised
Examples	Cu, Ag, Au, Zn, Bi, Sb, $NaCl$, H_2O air and diamond *etc.*	Al, Mn, Pt, Na, $CuCl_2$, O_2 and crown glass	Fe, Co, Ni, Cd, Fe_3O_4 *etc.*
Nature of effect	Distortion effect	Orientation effect	Hysteresis effect

(4) **Hysteresis :** For ferromagnetic materials, by removing external magnetic field *i.e.* $H = 0$. The magnetic moment of some domains remain aligned in the applied direction of previous magnetising field which results into a residual magnetism.

The lack of retracibility as shown in figure is called hysteresis and the curve is known as hysteresis loop.



(i) When magnetising field (H) is increased from O, the intensity of magnetisation I increases and becomes maximum. This maximum value is called the saturation value.

(ii) When H is reduced, I reduces but is not zero when $H = 0$. The remainder value OC of magnetisation when $H = 0$ is called the residual magnetism or retentivity.

The property by virtue of which the magnetism (I) remains in a material even on the removal of magnetising field is called Retentivity or Residual magnetism.

(iii) When magnetic field H is reversed, the magnetisation decreases and for a particular value of H, denoted by H_c, it becomes zero *i.e.*, $H_c = OD$ when $I = 0$. This value of H is called the corecivity.

(iv) So, the process of demagnetising a material completely by applying magnetising field in a negative direction is defined Corecivity. Corecivity assesses the softness or hardness of a magnetic material. Corecivity signifies magnetic hardness or softness of substance :

Magnetic hard substance (steel) $\rightarrow$ High corecvity

Magnetic soft substance (soft iron) $\rightarrow$ Low corecivity

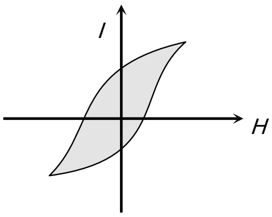
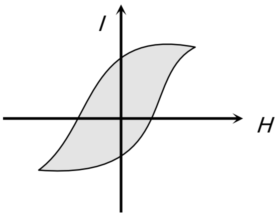
(v) When field *H* is further increased in reverse direction, the intensity of magnetisation attains saturation value in reverse direction (*i.e.* point *E*)

(vi) When *H* is decreased to zero and changed direction in steps, we get the part *EFGB*.

Thus complete cycle of magnetisation and demagnetisation is represented by *BCDEFGB*.

Note : ☐ The energy loss (or hysteresis energy loss) in magnetising and demagnetising a specimen is proportional to the area of hysteresis loop.

(vii) Comparison between soft iron and steel :

Soft iron	Steel
	
The area of hysteresis loop is less (low energy loss)	The area of hysteresis loop is large (high energy loss)
Less relativity and corecive force	More retentivity and corecive force
Magnetic permeability is high	Magnetic permeability is less
Magnetic susceptibility (χ) is high	χ is low
Intensity of magnetisation (I) is high	I is low
It magnetised and demagnetised easily	Magnetisation and demagnetisation is complicated
Used in dynamo, transformer, electromagnet tape recorder and tapes *etc.*	Used for making permanent magnet.

Concepts

- ☞ *An iron cored coil and a bulb are connected in series with an ac generator. If an iron rod is introduced inside a coil, then the intensity of bulb will decrease, because some energy lest in magnetising the rod.*
- ☞ *Hysteresis energy loss = Area bound by the hysteresis loop = VAnt Joule*

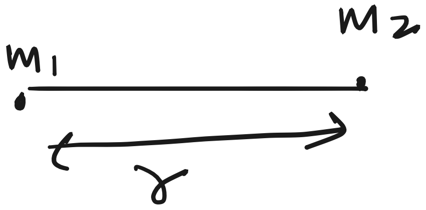
Where , V = Volume of ferromagnetic sample, A = Area of B – H loop P, n = Frequency of alternating magnetic field and t = Time.

Bar Magnets

pole Strength ← Charge

-m
For South pole

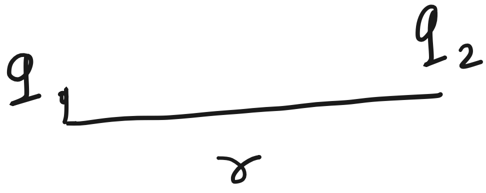
+m
North pole



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

Electrostatics

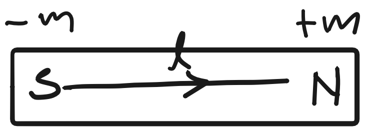
Charge → +q
Charge → -q



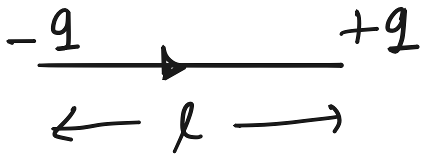
$$F = \frac{q_1 q_2}{4\pi \varepsilon_0 r^2}$$

$\mu_0 \rightarrow \frac{1}{\varepsilon_0}$

Bar Magnet



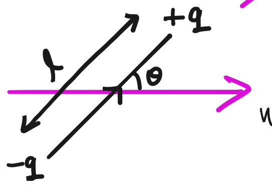
$M = ml$



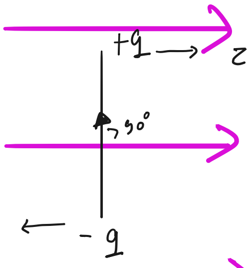
$P = ql$

$\theta << $
$T = 2\pi \sqrt{\frac{I}{PE}}$ S.H.M. M.I. of dipole.

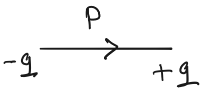
E



$\tau = PE\sin\theta$
$U = -PE\cos\theta$
$W = PE(\cos\theta_1 - \cos\theta_2)$

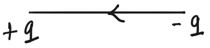


$F_{Net} = 0$
$\tau_{max} = PE$
$U = -PE\cos 90° = 0$



$\tau = 0$
$F_{Net} = 0$
$U = -PE$
equilibirium position

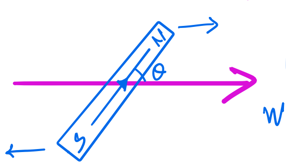
Stable equlibirium



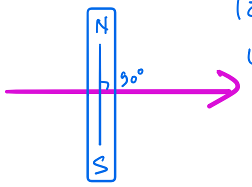
$\theta = 180°$ $F_{Net} = 0$
$\tau_{Net} = 0$
$U = -PE\cos 180°$
$U_{max} = PE$

$\theta << $
$T = 2\pi \sqrt{\frac{I}{MB}}$

B



$F_{Net} = 0$
$\tau_{Net} = MB\sin\theta$
$U = -MB\cos\theta$
$W = MB(\cos\theta_1 - \cos\theta_2)$

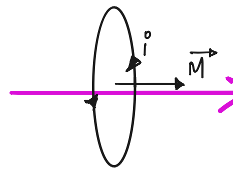


$F = 0$
$(\tau_{Net})_{max} = MB$
$U = 0$

$\theta = 0°$
$F_{Net} = 0$
$\tau_{Net} = 0$
$U = -MB\cos 0°$
$U_{min} = -MB$

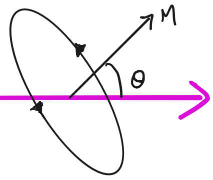
Stable equilibirium

B



$\theta = 0°$
$F_{Net} = 0$
$\tau_{Net} = 0$
$U = -MB\cos 0$
$U_{min} = -MB$

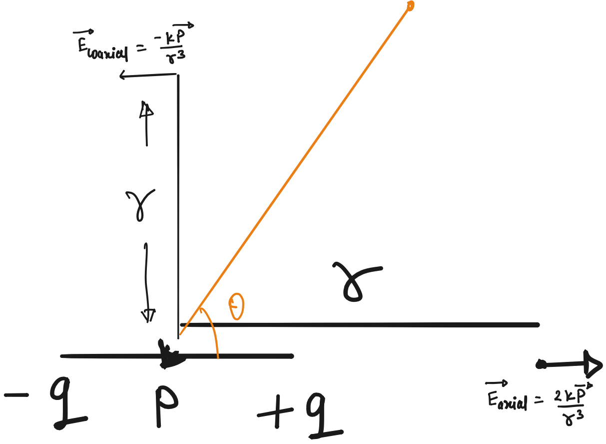
Stable equilibirium.



$F_{Net} = 0$
$\tau_{Net} = MB\sin\theta$
$U = -MB\cos\theta$
$W = MB(\cos\theta_1 - \cos\theta_2)$

unstable equilibrium

$E_{gen} = \frac{kP}{r^3}\sqrt{3\cos^2\theta+1}$

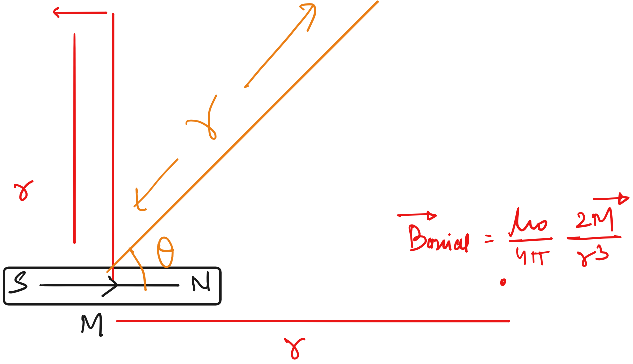


$\vec{E}_{coaxial} = \frac{-k\vec{P}}{r^3}$

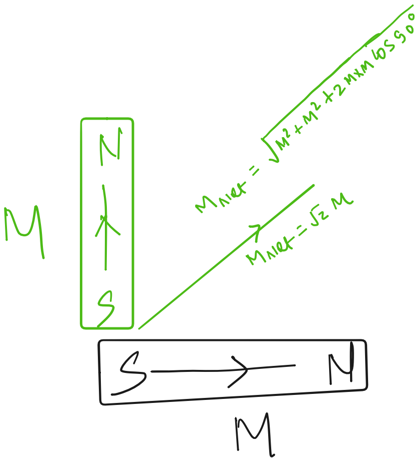
$\vec{E}_{axial} = \frac{2k\vec{P}}{r^3}$

$B = \frac{\mu_0}{4\pi}\frac{M}{r^3}\sqrt{3\cos^2\theta+1}$

$B_{coaxial} = \frac{\mu_0}{4\pi}\frac{M}{r^3}$

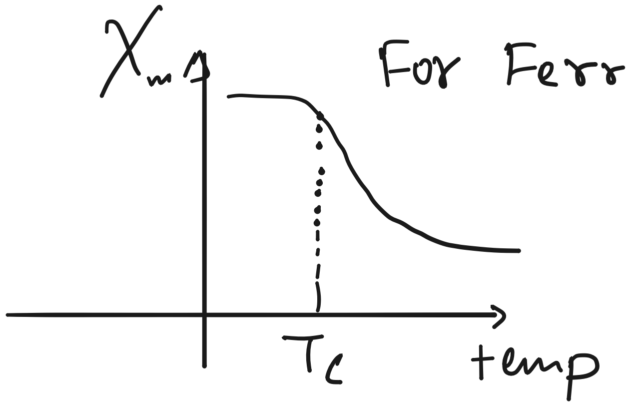


$\vec{B}_{axial} = \frac{\mu_0}{4\pi}\frac{2\vec{M}}{r^3}$



$M_{net} = \sqrt{M^2+M^2+2M\times M\cos 90^\circ}$

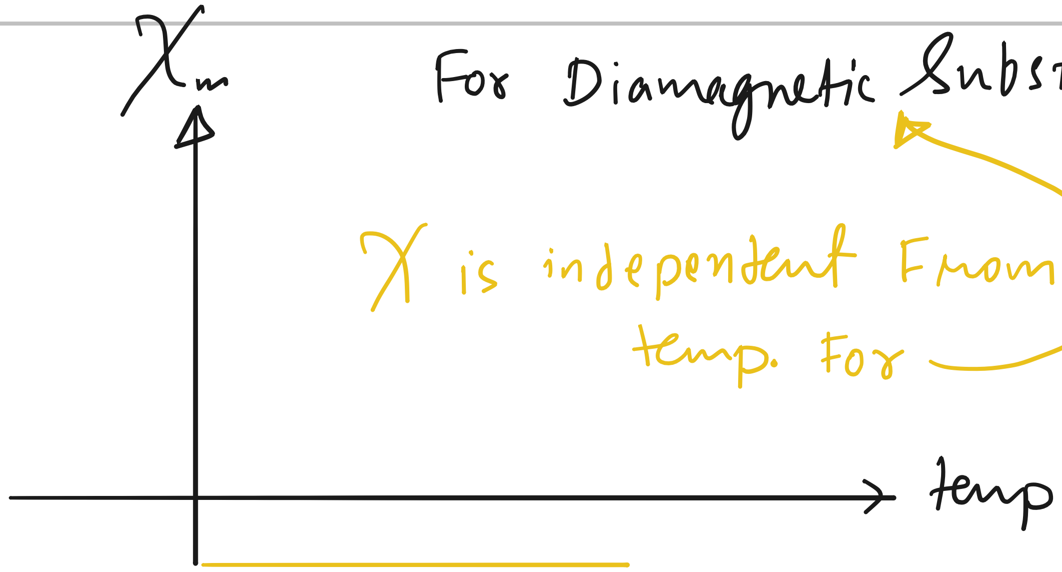
$M_{net} = \sqrt{2}M$



For Ferromagnetic Substance.

$\chi_m = \frac{C}{T-T_c}$

For Diamagnetic Substance



χ is independent From temp. For

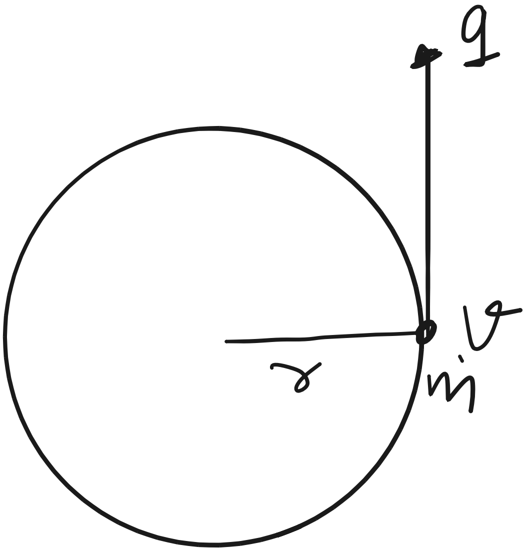
Value χ_m is $-ve$.

Bohr's Magnetron → Angular Momentum

$L = mvr$ —Ⓑ

$v = \frac{2\pi r}{T}$

$T = \frac{2\pi r}{v}$



$i = \frac{q}{T} = \frac{q}{\frac{2\pi r}{v}}$

$\boxed{i = \frac{qv}{}}$

$M.M. = \cancel{\pi} r^{\cancel{2}} \times \frac{qv}{2\cancel{\pi}\cancel{r}}$

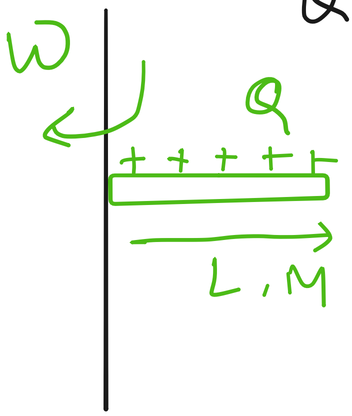
$M.M. = \frac{qvr}{}$ —Ⓐ

$$\frac{\text{Magnetic Moment}}{\text{Angular Momentum}} = \frac{q\cancel{vr}/2}{m\cancel{vr}}$$

$$\boxed{\frac{M.M.}{L} = \frac{q}{2m}}$$

above relationship is always true.

Q Calculate effective Magnetic Moment.



$$\text{Angular Momentum of rod} = I\omega$$

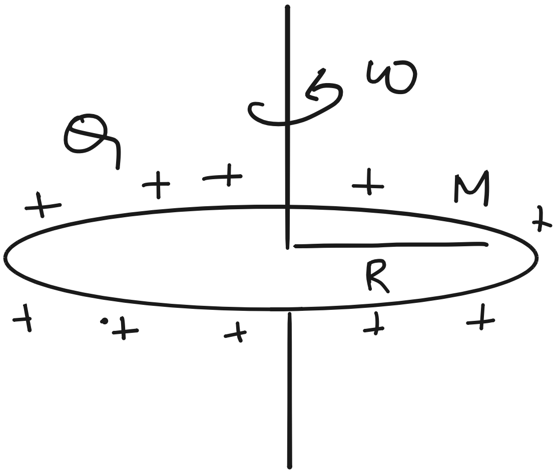
$$= \frac{ML^2}{3}\omega$$

$$\frac{M.M.}{\text{Angular Momentum}} = \frac{Q}{2M}$$

$$M.M. = \frac{Q}{2\cancel{M}} \times \frac{\cancel{M}L^2\omega}{3}$$

$$\frac{ML^2}{3}\omega \qquad 2M$$

$$M.M. = \frac{QL^2\omega}{6}$$



$$M.M. = ?$$

$$M.M. = \frac{Q}{2M} \times L$$

$$= \frac{Q}{2\cancel{M}} \times \cancel{M}R^2\omega$$

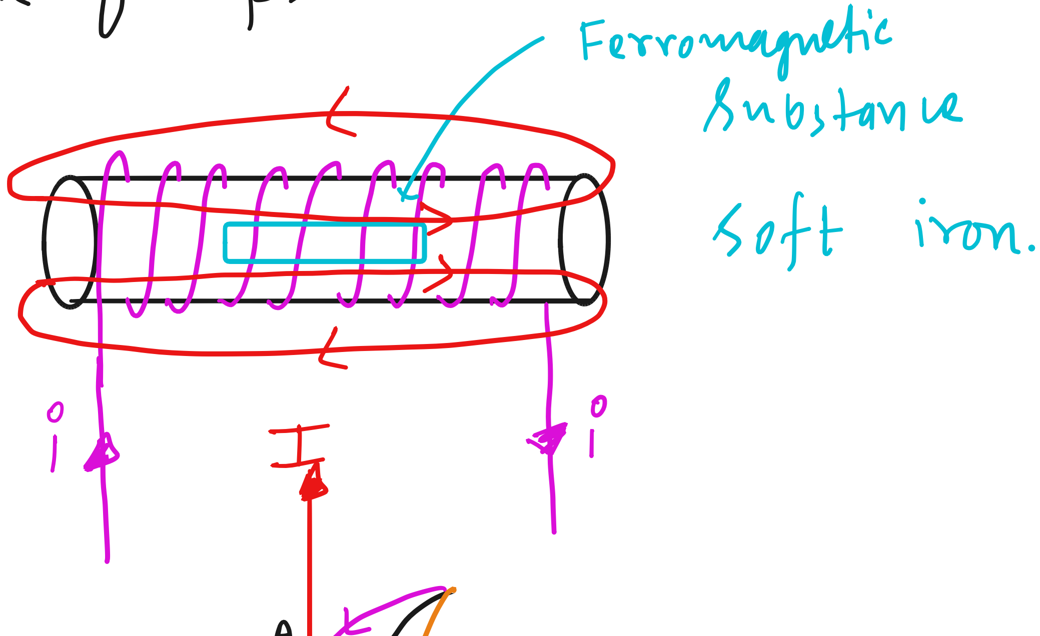
$$L = I\omega = MR^2\omega \qquad \boxed{M.M. = \frac{QR^2\omega}{2}}$$

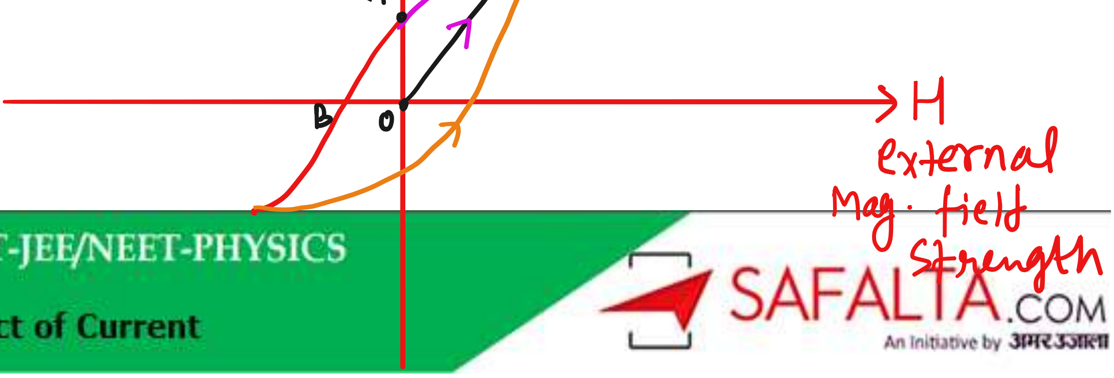
$$\tan\delta' = \frac{\tan\delta}{\cos\phi}$$

$\tan\delta$ ← true angle of dip

ϕ ← angle of declination

δ': App. angle of dip.




B
O
H
external
Mag. field
Strength