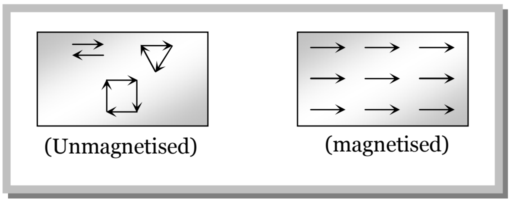
Magnetism

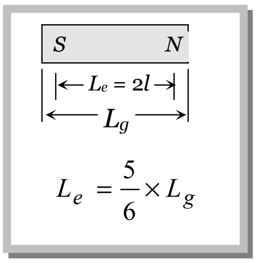
Every molecule of a substance is a complete magnet in itself. However, in an **magnetised** substance the molecular magnets are randomly oriented to give zero net magnetic moment. On magnetising, the molecular magnets are realigned in a specific direction leading to a net magnetic moment.

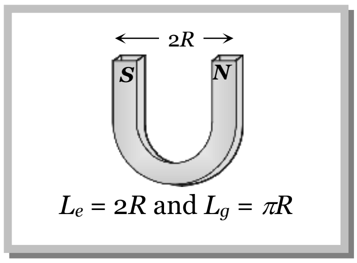


Note : ❑ On heating/hammering the magnetism of magnetic substance reduces.

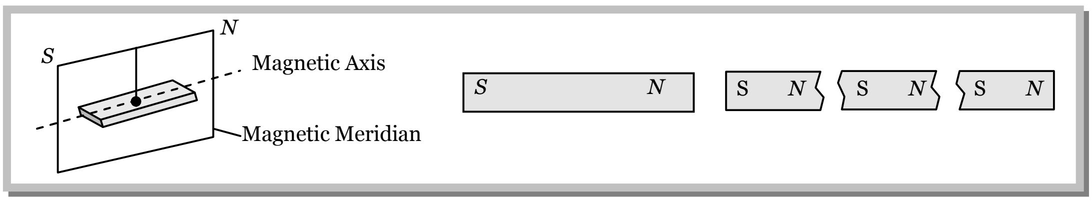
Bar magnet

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).

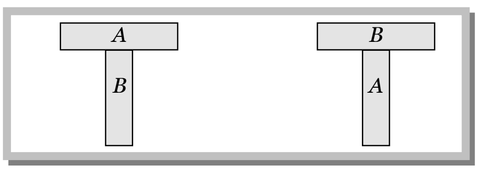




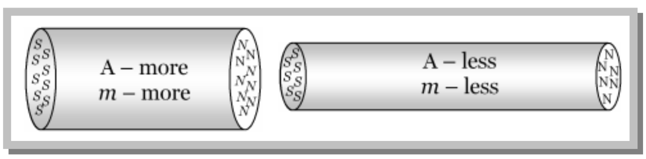
(1) When a magnet suspended freely it stays in the earth's *N-S* direction (in magnetic meridian). Also magnet poles exist in pair (*i.e.*, ultimate individual unit of magnetism in any magnet is called dipole).



(2) 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.

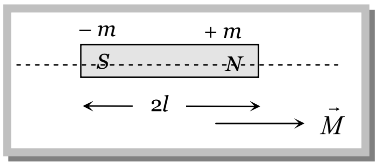


(3) **Pole strength (*m*) :** Also called magnetic charge ($\pm$ *m*). It is a scalar quantity it's SI unit is *Amp-m* or *N*/*Tesla* and CGS unit is *dyne/gauss*. It's dimensional formula [*m*] = [*AL*]. It depends on nature of material of

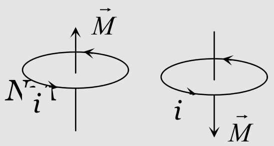
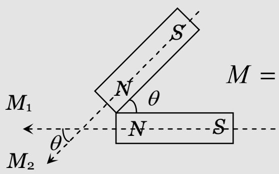
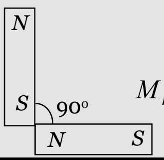
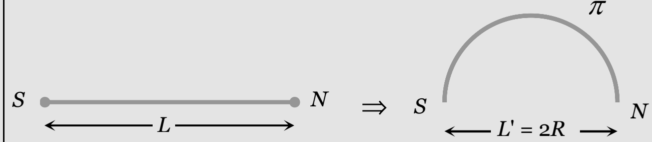


magnet and area of cross-section and not on the length of the magnet.

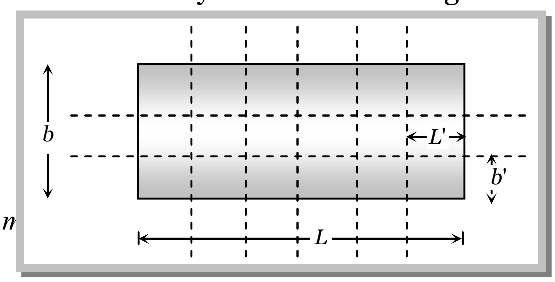
(4) **Magnetic dipole moment ($\vec{M}$) :** It represents strength of magnet. It is a vector quantity having SI unit *Amp-m*^{2} and dimensional formula $[M] = [AL^2]$. $\vec{M} = m \times 2\vec{l}$ (direction from $S \rightarrow N$)



(5) **Magnetic moment in various other situations :**

(i) Current carrying coil  Magnetic moment M = N = number of turns	(ii) Revolving charge : When a charge particle having charge q revolves in a circular path of radius r then corresponding magnetic moment $M = q\nu A = \frac{q\omega r^2}{2} = \frac{1}{2} qvr$; ω - angular speed, v – linear sped, ν - frequency
(iii) Combination of two bar magnet  $M = \sqrt{M_1^2 + M_2^2 + 2M_1M_2\cos\theta}$ Common condition  $M_{net} = \sqrt{2}\,M$	(iv) A magnetic wire (length L, magnetic moment M) is bent in the form of semicircle of radius R then new magnetic moment $M' = \frac{2M}{\pi}$  If a semicircular magnetic wire of magnetic moment M is stretched in a straight wire. What will be it's New magnetic moment $M' = \frac{M\pi}{2}$.

(6) **Cutting of a bar magnet :** Suppose we have a rectangular bar magnet having length, breadth and mass are L, b and w respectively if it is cut in n equal parts along the length as well as perpendicular to the length simultaneously as shown in the figure then –



n

Length of each part $L' = \frac{L}{\sqrt{n}}$, breadth of each part $b' = \frac{b}{\sqrt{n}}$

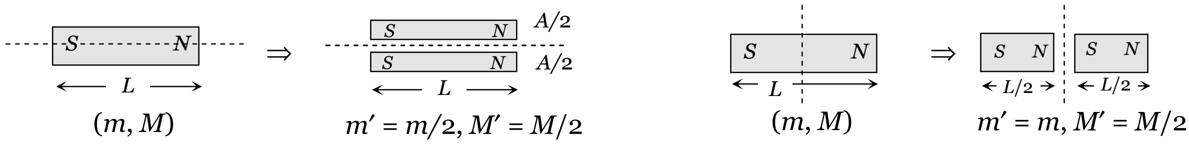
Mass of each part $w' = \frac{w}{n}$, pole strength of each part

Magnetic moment of each part $M' = m'L' = \frac{m}{\sqrt{n}} \times \frac{L}{\sqrt{n}} = \frac{M}{n}$

If initially moment of inertia of bar magnet about the axes passing from centre and perpendicular to it's length is $I = w\left(\frac{L^2 + b^2}{12}\right)$ then moment of inertia of each part $I' = \frac{I}{n^2}$

Note : ❑ For short bar magnet $b = 0$ so $L' = \frac{L}{n}, w' = \frac{w}{n}, \; m' = m, M' = \frac{M}{n}$ and $I' = \frac{I}{n^3}$

❑ Commonly asked question



❑ If angular momentum of the electron (mass = m) is $\vec{J}$ then the magnitude of the magnetic momentum will be $\frac{eJ}{2m}$.

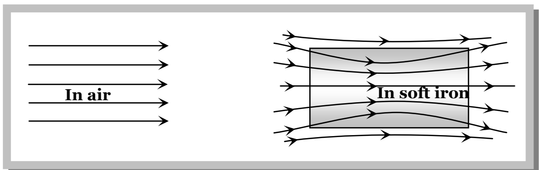
❑ Magnetic moment of atomic neon is zero.

Coulomb's Law in Magnetism

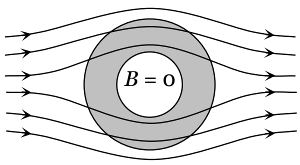
Force between two imaginary and isolated pole at a distance r is given by $\vec{F} = \frac{\mu_0}{4\pi} \frac{m_1 m_2}{r^2} \hat{r} \, N$ (in SI units) $= \frac{m_1 m_2}{r^2} \hat{r}$ *dynes* (in CGS units)

(1) **Permeability :** Characteristic of a medium with which it allows magnetic flux (magnetic lines of forces) to pass through it is called permeability of medium.

Permeability of soft iron is 1000 times greater than that of air.



Note : ❑ For protecting a sensitive equipment from the external magnetic field it should be placed inside an iron cane.



(2) **Magnetic lines of force**

(i) Imaginary lines (straight or curved) on which a unit north pole moves. (ii) Closed continuous. (Out side magnet $N \rightarrow S$, inside $S \rightarrow N$). (iii) Tangent drawn at any point on the magnetic line gives direction of $\vec{B}$. (iv) In a region where there is no field, no line will exist and thin region called neutral region. (v) No two lines can cross. (vi) Uniform magnetic field is represented by parallel and equidistant lines.

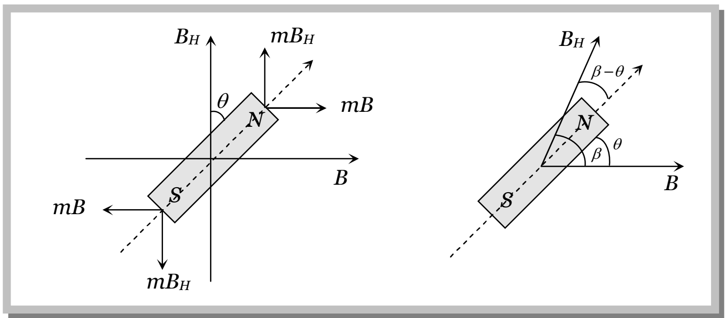
Magnetic Field/Magnetic Induction or Magnetic Flux Density

Magnetic field due to an isolated, imaginary pole of pole strength m at a distance r is $\vec{B} = \frac{\mu_0}{4\pi} \frac{m}{r^2} \hat{r}$. It's SI units : $Tesla = Wb/m^2 = \frac{N}{A-m} = \frac{J}{A-m^2} = \frac{volt - sec}{m^2}$, CGS units : Gauss $1T = 10^4 \, Gauss$. Force on an isolated pole (m) in magnetic field (B) is $\boldsymbol{F = mB}$, north pole experience force in the direction of field while south pole experience force in the direction opposite to the field.

Note : ❑ **Magnetic field due to a magnetic dipole (bar magnet) and it's behaviour in magnetic field :** We already discussed in electrostatics.

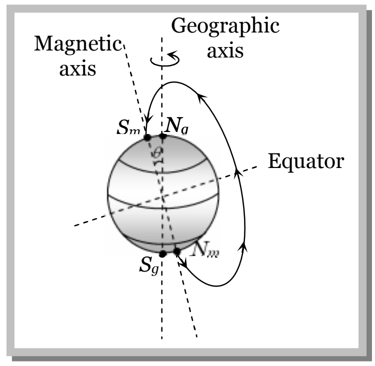
Tangent Law

Under equilibrium, torque due to two mutually perpendicular fields will be equal and opposite and in equilibrium $B = B_H \tan\theta$. If field's are not mutually perpendicular then $\frac{B}{B_H} = \frac{\sin(\beta - \theta)}{\sin\theta}$



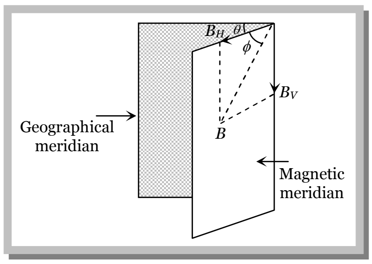
Earth's magnetic Field (Terrestrial Magnetism)

As per the most establised 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. Earth is assumed to be a large bar magnet with its south pole near to geographic north and vice-versa.



(1) **Magnetic declination (θ) :** The magnetic meridian is a vertical *N*-*S* plane. The magnetic field due to the earth lies in this plane. The angle made by the magnetic meridian at a point with the geographical meridian is called the declination at that point. Knowledge of declination fixes the vertical plane in which the earth's magnetic field lies.

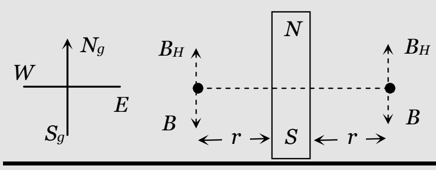
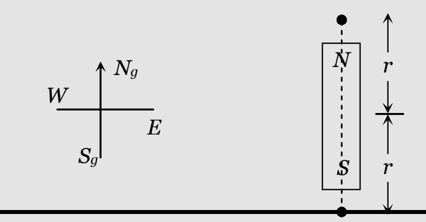
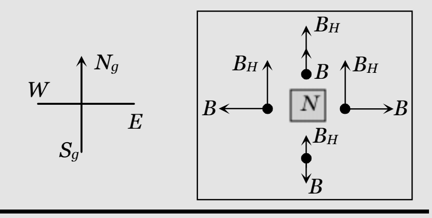
(2) **Magnetic inclination or dip (ϕ) :** Angle made by earth's magnetic field with the horizontal direction in magnetic meridian. At the poles, $\phi = 90^o$, at the equator $\phi = 0^o$



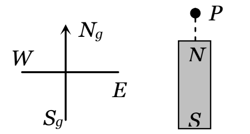
(3) **Horizontal component of earth's magnetic field**

$$B_H = B\cos\phi, B_V = B\sin\phi \quad \text{hence } \tan\phi = \frac{B_V}{B_H} \text{ and } B = \sqrt{B_H^2 + B_V^2}$$

(4) **Neutral points (*NP*) :** Points where net magnetic field due to a magnet and earth is zero.

(i) **when *N*-pole of a bar magnet is towards north of earth :** Neutral point will be on perpendicular bisector and at *NP* $B_H = B = \frac{\mu_0}{4\pi}\frac{M}{r^3}$	(ii) **When *S*-pole of magnet is towards geographic north :** Neutral point will be on axial line $B = B_H = \frac{\mu_0}{4\pi}\frac{2M}{r^3}$	(iii) **When magnet is kept vertical in horizontal plane :** One neutral point will be obtained
		

Note : ❑ A short bar magnet with it's N-pole facing N_g-pole of earth form a NP at point P. If the magnet is rotated by 90° in horizontal plane the net magnetic induction at P is $\sqrt{5}\, B_H$. (Where B_H-horizontal component of earth's magnetic field).



Instruments Based on Magnetism

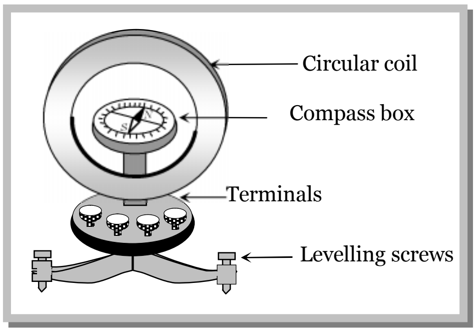
(1) **Dip circle :** Determines

(i) Plane of magnetic meridian (ii) Angle of dip or inclination.

True dip : When dip circle is in the plane of magnetic meridian $\tan\phi = \frac{B_V}{B_H}$.

Apparent dip : If dip circle is at an angle α to the meridian, dip circle will not read the actual value of dip. Say it reads ϕ'. Actual dip is given by $\tan\phi = \tan\phi' \cos\alpha$

(2) **Tangent 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 $\boldsymbol{B = B_H \tan\theta}$



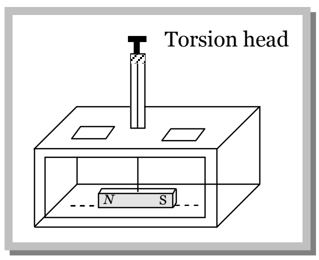
where $B = \frac{\mu_0 ni}{2r}$; n = number of turns, r = radius of coil, i = the current to be measured, θ = angle made by needle from the direction of B_H in equilibrium. Hence $\frac{\mu_0 N_i}{2i} = B_H \tan\theta \Rightarrow i = K\tan\theta$ where $K = \frac{2rB_H}{\mu_0 N}$ is called reduction factor.

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

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

❑ This instrument is also called moving magnet type galvanometer.

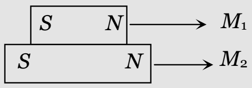
(3) **Oscillation or vibration magnetometer :** The magnet is made to oscillate in a horizontal plane where the restoring force is provided by the horizontal component of earth's magnetic field. $T = 2\pi\sqrt{\frac{I}{MB_H}}$



At the poles B_H = 0 so $T \to \infty$. It is used for determination of 'M', determination of B_H and comparison of two magnetic moments.

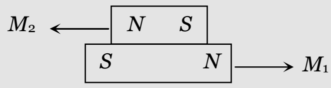
Comparison of two magnetic moment by sum and difference method : Two bar magnet oscillate simultaneously in earth's magnetic field.

Sum position : Magnetic moments are additive



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

Difference position : Magnetic moments are subtractive



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

Note : ❑ Remember $T_d > T_s$ and $\frac{M_1}{M_2} = \frac{T_d^2 + T_s^2}{T_d^2 - T_s^2} = \frac{\nu_s^2 + \nu_d^2}{\nu_s^2 - \nu_d^2}$

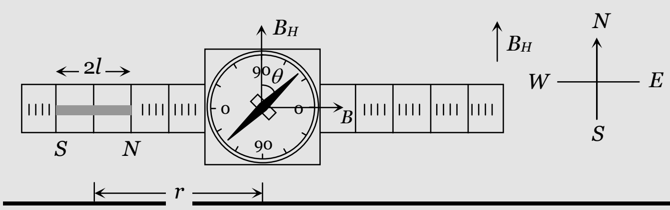
❑ If a rectangular bar magnet is cut in n equal part then time period of each part will be $\frac{1}{\sqrt{n}}$ times that of complete magnet (*i.e.* $T' = \frac{T}{\sqrt{n}}$) while for short magnet $T' = \frac{T}{n}$. If nothing is said then bar magnet is treated as short magnet.

❑ 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.

(4) **Deflection magnetometer :** Used to find 'B_H' or 'M'

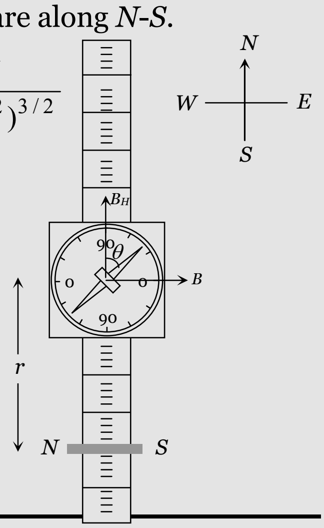
Tan-*A* position : Arms of magnetometer are along *E-W*. The needle of the compass is under the action of two mutually perpendicular field – One due to B_H and the other due to magnet at its axial position.

$$B = B_H \tan\theta = \frac{\mu_0}{4\pi}\frac{2Mr}{(r^2 - l^2)^2}$$



Tan-*B* position : Arms are along *N-S*.

$$B = B_H \tan\theta = \frac{\mu_0}{4\pi}\frac{M}{(r^2 + l^2)^{3/2}}$$



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.

Magnetic Materials

(1) **Various terms involved in magnetism**

(i) Magnetic permeability (μ) : It measures the degree to which a magnetic material can be penetrated or permeated by the magnetising field, $\mu = \frac{B}{H}$. It's SI unit is $\frac{H}{m}$. It is scalar.

(ii) Relative permeability (μ_r) : The ratio of permeability of a medium to that of free space is called relative permeability $\mu_r = \frac{\mu}{\mu_0}$. It is unitless, dimensionless and scalar.

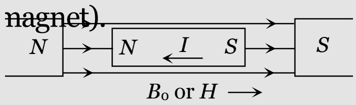
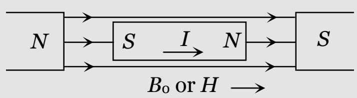
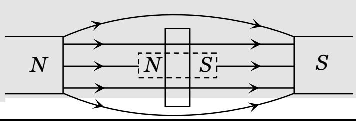
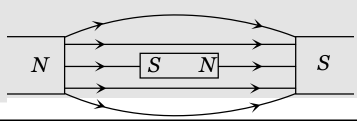
(iii) Intensity of magnetic field (H) : In a magnetising field the ratio of magnetising field (B_o) to the permeability (μ_o) of free space is called intensity of magnetising field, $H = \frac{B_0}{\mu_0}$. It's SI unit is *Amp/m*. CGS unit is *Oersted* ($1\ Oersted \simeq 80\ Am^{-1}$). It is vector.

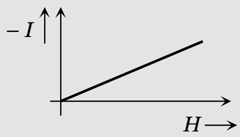
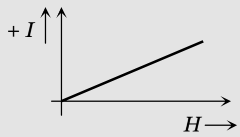
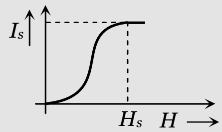
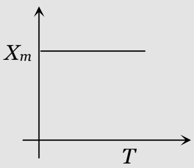
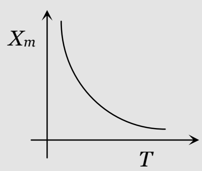
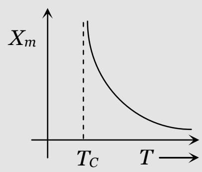
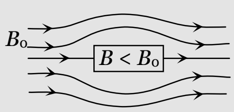
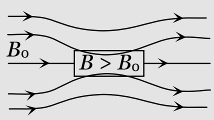
(iv) Intensity of magnetisation (I) : The induced dipole-moment per unit volume in the specimen is called intensity of magnetisation $I = \frac{M}{V} = \frac{m}{A}$. It's SI unit is *Amp/m*. It is vector.

(v) Magnetic susceptibility (χ_m) : The ratio of magnitude of intensity of magnetisation to that of magnetising field is called magnetic susceptibility, (large value of χ_m implies that the material is more susceptible to the field and hence can be easily magnetised). $\chi_m = \frac{I}{H}$, $\chi_m = (\mu_r - 1)$. It is unitless and scalar

Note : ❑ In a magnetising field, inside the magnetic material field is the resultant of the magnetising field B_o and the induced field B_i *i.e.*, B = (B_o + B_i). Remember in SI system $\vec{B} = \mu_0(\vec{H} + \vec{I})$ and $\mu_r = (1 + \chi_m)$ while in CGS $\vec{B} = \vec{H} + 4\pi\vec{I}$ and $\mu_r = (1 + 4\pi\chi_m)$

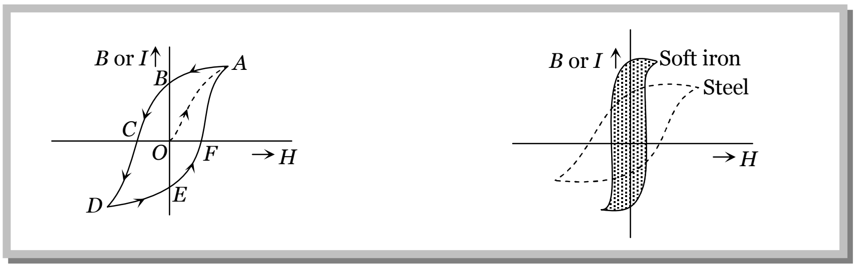
(2) **Classification of magnetic materials**

S.No.	**Diamagnetic substance**	**Paramagnetic substance**	**Ferromagnetic substance**
(i)	These substances feebly magnetised in a direction opposite to the magnetising field (feebly repelled by the magnet). 	These substances feebly magnetised in the direction of magnetising field. (feebly attracted by the magnet). 	These substances strongly magnetised in the direction of field (strongly attracted by the magnet).
(iii)	In a non-uniform field these have a tendency to move from strong to weak field. (A diamagnetic rod sets itself perpendicular to the field if free to rotate between the poles of a magnet) 	In a non-uniform field these have a tendency to move from weaker to strong field. (A paramagnetic rod sets itself parallel to the field if free to rotate between the poles of a magnet) 	In a non-uniform field these stick to the poles, where the field is strongest.

(ii)	Their atoms do not have any permanent dipole moment	Atoms have permanent dipole moments which are randomly oriented.	Atoms have permanent dipole moments which are organised in domains.
(iv)	Intensity of magnetisation (I) is small, negative and varies linearly with field. 	Intensity of magnetisation (I) is small, positive and varies linearly with field. 	Intensity of magnetisation (I) is very large positive and varies non-linearly with field. 
(v)	Magnetic susceptibility χ_m is small, negative and temperature independent. 	Magnetic susceptibility χ_m is small, positive and varies inversely with temperature *i.e.*, $\boxed{\chi_m \propto (1/T)}$ (This is Curies law). It is independent of the field. 	Magnetic susceptibility χ_m very large, positive and varies with temperature in a complex way. Above Curie temperature (for iron it is 770°C) they behaves as paramagnetic. 
(vi)	Relative permeability μ_r is slightly lesser than unity, *i.e.*, $\mu < \mu_0$ ($B < B_0$) so diamagnetic substances have a tendency to expel lines of force when placed in a field. 	Relative permeability μ_r is slightly greater than unity, *i.e.*, $\mu > \mu_0$ ($B > B_0$) so paramagnetic substances have a tendency to 'pull in' lines of force when placed in a field. 	μ_r is much greater than unity, *i.e.*, $\mu_r >> \mu_0$ In it lines of force are pulled in strongly by the substance, *i.e.*, $B >> B_0$
(vii)	Exhibited by solids, liquids and gases. e.g. *Bi*, *Cu*, *Ag*, *Hg*, *Pb*, water hydrogen. *He*, *Ne*, etc. are diamagnetic. A super conductor exhibits perfect diamagnetism	Exhibited by solids, liquids and gases e.g. *Na*, *K*, *Mg*, *Mn*, *Al*, *Cr*, *Sn* and liquid oxygen are paramagnetic	Exhibited by solids only, that too crystalline e.g. *Fe*, *Co*, *Ni* and their alloys are ferromagnetic.

(3) **Hysterisis curve :** I or B lags H for ferromagnetic substances. $OB = OE$ represent retentivity of the material. The loss of energy per unit volume of the specimen per cycle of magnetisation in CGS unit is equal to area of the I-H loop or $\frac{1}{4\pi}$ time the area of B-H loop of the specimen. The study of these characteristics enables us to select suitable materials for different purposes.

A comparative study of hysteresis loops of soft iron and steel, fig. shown that



(i) Retentivity of soft iron is larger compared to that of steel.

(ii) Coercivity of steel is greater than that of soft iron.

(iii) Area of hysterisis loop of steel is greater than that of soft iron, indicating higher energy loss in case of steel.

On the basis of these properties, we prefer to make electromagnets of soft iron, permanent magnets of steel and transformer cores of soft iron.