Magnetism and Matter

The property of any object by virtue of which it can attract a piece of iron or steel is called **magnetism.**

Natural Magnet

A natural magnet is an ore of iron (Fe_3O_4), which attracts small pieces of iron, cobalt and nickel towards it.

Magnetite or lodestone is a natural magnet.

Artificial Magnet

A magnet which is prepared artificially is called an artificial magnet, *e.g.* a bar magnet, an electromagnet, a magnetic needle, a horse-shoe magnet etc.

According to molecular theory, every molecule of magnetic substance (whether magnetised or not) is a complete magnet itself.

The poles of a magnet are the two points near but within the ends of the magnet, at which the entire magnetism can be assumed to be concentrated.

Properties of Magnet

(i) A freely suspended magnet always aligns itself into North-South direction.

(ii) Like magnetic poles repel and unlike magnetic poles attract each other.

(iii) Magnetic poles exist in pair and they are of equal strength.

Magnetic Field Lines

These are the imaginary lines which continuously represent the direction of the magnetic field.

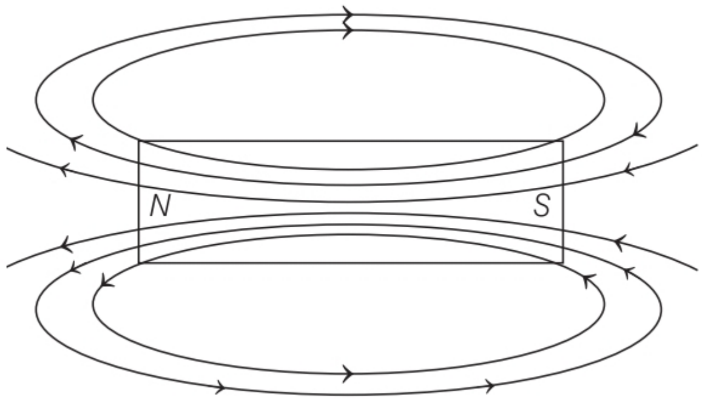
Following are the properties of magnetic field lines

(i) These lines forms closed continuous loops.

(ii) The tangent at any point of a field line represents the direction of net magnetic field.

(iii) These lines do not intersect each other.

(iv) Direction of field lines is from *N* to *S*, if they are outside the magnet and from *S* to *N*, if they are inside the magnet.



Magnetic Dipole

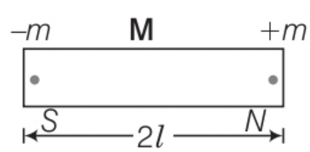
Magnetic dipole is an arrangement of two unlike magnetic poles of equal pole strength separated by a very small distance, *e.g.* a small bar magnet, a magnetic needle, a current carrying loop etc.

Pole Strength

It can be defined as the strength of magnetic pole to attract magnetic material towards itself. It is a scalar quantity and its SI unit is ampere-metre (A-m).

Magnetic Dipole Moment

The product of the distance ($2l$) between the two poles and the pole strength of either pole is called magnetic dipole moment.

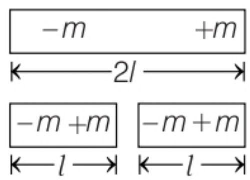
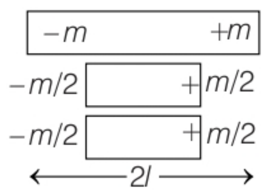
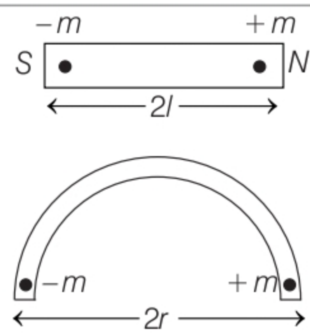
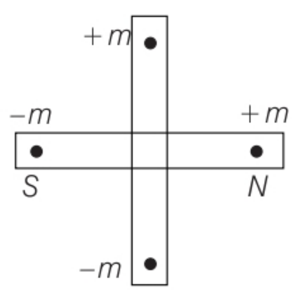
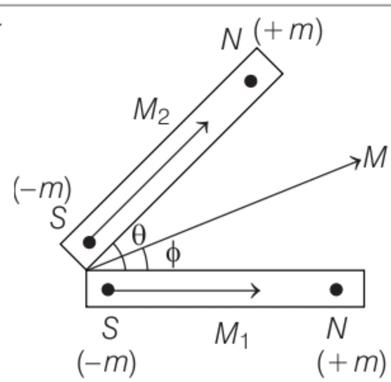


Magnetic dipole moment, $\mathbf{M} = \mathbf{m}(2l)$

Its SI unit is joule/tesla (J/T) or ampere-metre^2 (A-m^2).

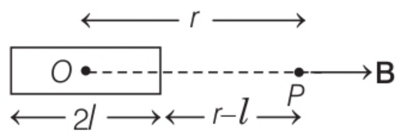
Its direction is from South pole towards North pole.

Pole Strength and Magnetic Dipole Moment in Special Cases

Special Cases	Figure	Effect on Pole strength	Formula for new magnetic dipole moment
If bar magnet is cut into two equal pieces such that the length of each piece becomes half		Remains unchanged	$M' = m \cdot \frac{2l}{2} = \frac{M}{2}$ (becomes half)
If bar magnet is cut into two equal pieces such that the width of each piece becomes half		Pole strength of each piece becomes half	$M' = \left(\frac{m}{2}\right)(2l) = \frac{M}{2}$ (becomes half)
If bar magnet is bent in the form of semi-circle		Remains unchanged	$M' = m(2r)[\because 2l = \pi r]$ $M' = m \times 2\left(\frac{2l}{\pi}\right) = \frac{2M}{\pi}$ $\left(\text{becomes } \frac{2}{\pi} \text{ times}\right)$
When two identical bar magnets are joined perpendicular to each other		Remains unchanged	$M = \sqrt{M_1^2 + M_2^2} = \sqrt{2}M$
When two bar magnets are inclined at an angle θ.		Remains unchanged	Resultant magnetic moment, $M' = \sqrt{M_1^2 + M_2^2 + 2M_1M_2\cos\theta}$ Angle made by resultant magnetic moment (M) with M_1 is given by, $\tan\phi = \frac{M_2 \sin\theta}{M_1 + M_2\cos\theta}$

Magnetic Field Due to a Magnetic Dipole

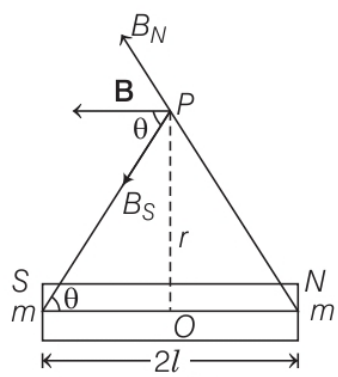
(i) **On Axial Line**



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

If $r >> l$, then $$B = \frac{\mu_0}{4\pi} \frac{2M}{r^3}$$

(ii) **On Equatorial Line**



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

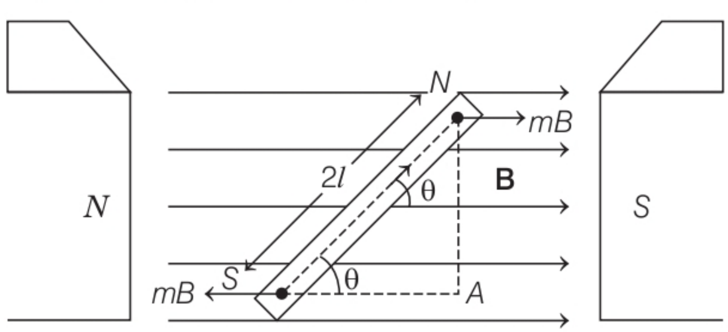
If $r >> l$, then $$B = \frac{\mu_0}{4\pi} \frac{M}{r^3}$$

(iii) On a line making an angle θ with axis of dipole

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

Torque Acting on a Magnetic Dipole

When a magnetic dipole (**M**) is placed in a uniform magnetic field (**B**), then a torque acts on it, which is given by



$$\tau = \mathbf{M} \times \mathbf{B}$$

or $$\tau = MB \sin \theta$$

where, θ is the angle between the dipole axis and magnetic field.

Potential Energy of a Magnetic Dipole in a Uniform Magnetic Field

The work done in rotating the dipole against the action of the torque is stored as potential energy of the dipole.

Potential energy, $U = W = -MB \cos \theta = -\mathbf{M} \cdot \mathbf{B}$

Coulomb's Law

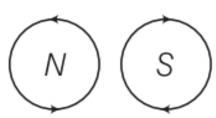
The force of interaction acting between two magnetic poles is directly proportional to the product of their pole strengths and inversely proportional to the square of the distance between them.

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

where, $m_1, m_2 =$ pole strengths, $r =$ distance between poles and $\mu_0 =$ permeability of free space.

Current Carrying Loop

A current carrying loop behaves as a magnetic dipole. If we look the upper face of the loop and current is flowing anti-clockwise, then it has a North polarity and if current is flowing clockwise, then it has a South polarity.



Magnetic dipole moment of a current carrying loop is given by

$$M = IA$$

For N such turns, $M = NIA$

where, $I =$ current and $A =$ area of cross-section of the coil.

When in an atom any electron revolve in an orbit it is equivalent to a current loop. Therefore, atom behaves as a magnetic dipole.

Magnetic Moment of an Atom

Magnetic moment of an atom, $M = \frac{1}{2} e\omega r^2$

where, e = charge on an electron,

ω = angular velocity of electron

and r = radius of orbit.

or $$M = n\frac{eh}{4\pi m}$$

where, h = Planck's constant and m = mass of an electron

and $\frac{eh}{4\pi m} = \mu_B$ called Bohr's magneton and its value is 9.27×10^{-24} A-m^2.

Magnetic Dipole Moment of a Revolving Electron in an Atom

The circular motion of an electron around the positively charged nucleus of an atom can be treated as a current loop producing a magnetic field. Hence, it behaves like a magnetic dipole.

The magnitude of the magnetic dipole moment **M** associated with the revolving electron is

$$\mathbf{M} = IA = \frac{ev}{2\pi r} \times \pi r^2 = \frac{evr}{2}$$

The magnitude of the orbital angular momentum **L** of electron,

$$L = m_e vr \quad \text{...(ii)}$$

$$\therefore \quad \frac{M}{L} = \frac{e}{2m_e} \quad \text{... (iii)}$$

The vector form of Eq. (iii) can be written as

$$\mathbf{M} = -\left(\frac{e}{2m_e}\right)\mathbf{L}$$

Angular momentum, $L = m_e vr = \frac{nh}{2\pi}$ ...(iv)

Now, from Eqs. (iii) and (iv), we get

$$\frac{M}{nh/2\pi} = \frac{e}{2m_e}$$

$$\Rightarrow \quad M = \frac{neh}{4\pi m_e} \quad \text{...(v)}$$

When $n = 1$, $M = \mu$ (the elementary magnetic dipole moment), thus

$$\therefore \quad \mu = \frac{eh}{4\pi m_e} \quad \text{...(vi)}$$

The elementary magnetic moment of a revolving electron is also known as **Bohr magneton** (μ).

Now, substituting $e = 1.6 \times 10^{-19}$ C, $h = 6.626 \times 10^{-34}$ J-s, $\pi = 3.14$ and $m_e = 9.01 \times 10^{-31}$ kg in Eq. (vi), we get,

$$\mu = \frac{1.6 \times 10^{-19} \times 6.626 \times 10^{-34}}{4 \times 3.14 \times 9.01 \times 10^{-31}} \text{ A - m}^2$$

$$= 9.27 \times 10^{-27} \text{ A - m}^2$$

$\therefore$ 1 Bohr magneton $= 9.27 \times 10^{-27}$ A-m^2

Oscillations of a Freely Suspended Magnet

When a small bar magnet of magnetic moment **M** is placed in a uniform magnetic field **B** such as it is free to vibrate in a horizontal plane of magnetic field **B** about a vertical axis passing through its centre of mass. This bar magnet oscillates. The restoring torque in this case will be,

$$\tau = -MB\theta \quad (\because \text{ For small oscillation, } \sin\theta \simeq \theta)$$

The deflecting torque on the magnet is

$$\tau = I\alpha = I\frac{d^2\theta}{dt^2}$$

In equilibrium, deflecting torque = Restoring torque

or $$\frac{d^2\theta}{dt^2} = \frac{-MB\theta}{I} = -\omega^2\theta, \qquad \text{where } \omega = \sqrt{\frac{MB}{I}}$$

The period of vibration is given by

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

Magnetic field B can be calculated from above equation and is given as

$$B = \frac{4\pi^2 I}{MT^2}$$

Gauss's Law in Magnetism

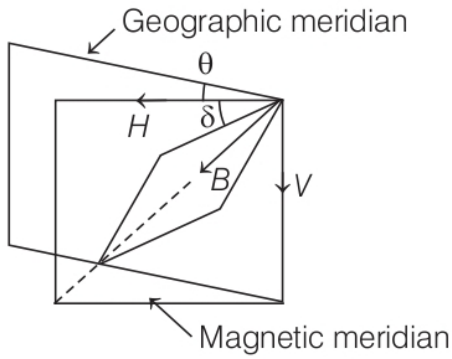
Surface integral of magnetic field over any closed surface is always zero.

$$\oint_S \mathbf{B} \cdot d\mathbf{S} = 0$$

This law tells that the net magnetic flux through any closed surface is always zero.

Earth's Magnetism

Earth behaves like a huge magnet. The value of magnetic field on the surface of earth is a few of tenths of a gauss. Its strength varies from place to place on the earth's surface.



Magnetic Meridian

A vertical plane passing through the magnetic axis is called magnetic meridian.

Geographic Meridian

A vertical plane passing through the geographic axis is called geographic meridian.

Elements of Earth's Magnetism

(i) **Magnetic Declination** (θ) The smaller angle subtended between the magnetic meridian and geographic meridian is called magnetic declination.

(ii) **Magnetic Inclination or Magnetic Dip** (δ) The smaller angle subtended between the magnetic axis and horizontal line is called magnetic inclination or magnetic dip.

Angle of dip is zero at magnetic equator and 90° at poles.

(iii) **Horizontal and Vertical Component of Earth's Magnetic Field** If B is the intensity of earth's magnetic field, then horizontal component of earth's magnetic field $H = B\cos\delta$

It acts from South to North direction.

Vertical component of earth's magnetic field,

$$V = B\sin\delta$$

$$\therefore \quad B = \sqrt{H^2 + V^2}$$

and

$$\tan\delta = \frac{V}{H}$$

Magnetic Map

Magnetic map is obtained by drawing lines on the surface of earth, which passes through different places having same magnetic elements.

The main lines drawn on earth's surface are given below

(i) **Isogonic Line** A line joining places of equal declination is called an isogonic line.

(ii) **Agonic Line** A line joining places of zero declination is called an agonic line.

(iii) **Isoclinic Line** A line joining places of equal inclination or dip is called an isoclinic line.

(iv) **Aclinic Line** A line joining places of zero inclination or dip is called an aclinic line.

(v) **Isodynamic Line** A line joining places of equal horizontal component of earth's magnetic field (H) is called an isodynamic line.

Magnetic Latitude

(i) If at any place, the angle of dip is δ and magnetic latitude is λ, then $\tan \delta = 2 \tan \lambda$.

(ii) The total intensity of earth's magnetic field

$$I = I_0 \sqrt{1 + 3 \sin^2 \lambda}$$

where,
$$I_0 = \frac{M}{R^3}$$

It is assumed that a bar magnet of earth has magnetic moment M and radius of earth is R.

Neutral Points

Neutral point of a bar magnet is a point at which the resultant magnetic field of a bar magnet and horizontal component of earth's magnetic field are zero.

When North pole of a bar magnet is placed towards South pole of the earth, then neutral point is obtained on axial line.

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

If $r >> l$, then
$$B = \frac{\mu_0}{4\pi} \frac{2M}{r^3} = H$$

When North pole of a bar magnet is placed towards North pole of the earth, then neutral point is obtained on equitorial line.

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

If $r >> l$, then
$$B = \frac{\mu_0}{4\pi} \frac{M}{r^3} = H$$

Tangent Law

It states that, if a magnet is placed in two magnetic fields right angle to each other, then it will be acted upon by two couples tending to rotate it in opposite directions. It will be deflected through an angle θ, such that two couples balance each other.

Also,
$$\tan \theta = \frac{B_1}{B_2}$$

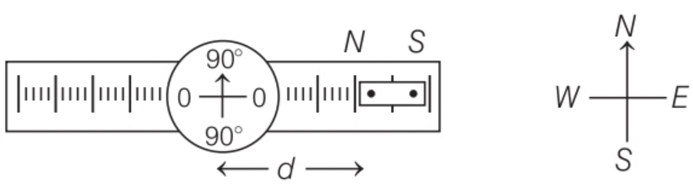
where, θ is the angle between magnet and magnetic field B_2

Deflection Magnetometer

It is a device used to determine M and H. Its working is based on tangent law.

Deflection magnetometer can be used into two settings

(i) **Tangent *A* setting** In this setting, the arms of the magnetometer are along East-West and magnet is parallel to the arms.



In equilibrium,

$$B = H \tan \theta$$

$$\frac{\mu_0}{4\pi} \cdot \frac{2M}{d^3} = H \tan \theta$$

(ii) **Tangent *B* setting** In this setting, the arms of the magnetometer are along North-South and magnet is perpendicular to these arms.

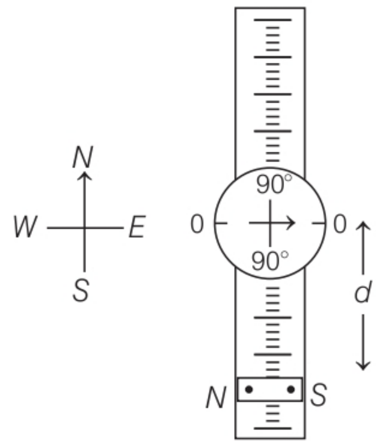
In equilibrium,

$$B = H \tan \theta$$

$$\frac{\mu_0}{4\pi} \cdot \frac{M}{d^3} = H \tan \theta$$

In above setting, the experiment can be performed in two ways

(a) **Deflection method** In this method, one magnet is used at a time and deflection in galvanometer is observed.



Ratio of magnetic dipole moments of the magnets

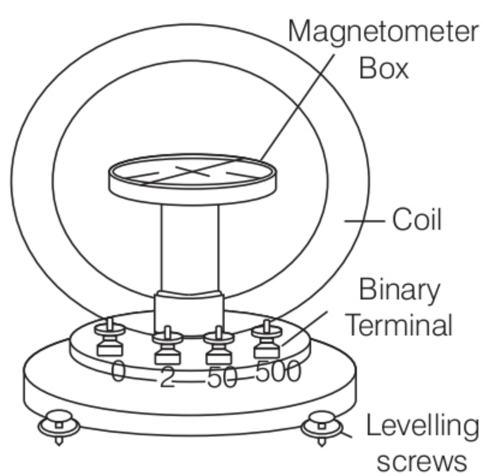
$$\frac{M_1}{M_2} = \frac{\tan \theta_1}{\tan \theta_2}$$

where, θ_1 and θ_2 are mean values of deflection for two magnets.

(b) **Null method** In this method, both magnets are used at a time and no deflectioin condition is obtained. If magnets are at distances d_1 and d_2, then $\frac{M_1}{M_2} = \left(\frac{d_1}{d_2}\right)^3$

Tangent Galvanometer

It is a device used for detection and measurement of low electric currents. Its working is based on tangent law.



If θ is the deflection produced in galvanometer when I current flows through it, then

$$I = \frac{2R}{N\mu_0} H \tan\theta = \frac{H}{G} \tan\theta = K \tan\theta$$

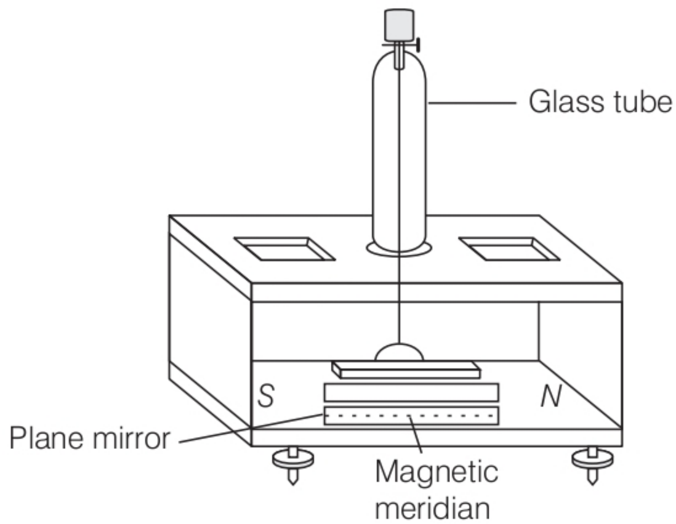
where, $G = \frac{N\mu_0}{2R}$ is called **galvanometer constant** and $K = \frac{H}{G}$ is called **reduction factor** of tangent galvanometer.

Here, N is number of turns in the coil and R is radius of the coil.

Tangent galvanometer is also called moving magnet type galvanometer.

Vibration Magnetometer

It is based on simple harmonic oscillations of a magnet suspended in uniform magnetic field.



Time period of vibrations is given by, $T = 2\pi\sqrt{\frac{I}{MH}}$

where, I = moment of inertia of the magnet,

M = magnetic dipole moment of the magnet

and H = horizontal component of earth's magnetic field.

When two magnets of unequal size are placed one above the other and North poles of both magnets are towards geographic North, then time period of oscillations is given by, $T_1 = 2\pi\sqrt{\frac{I_1 + I_2}{(M_1 + M_2) H}}$

If North pole of first magnet and South pole of second magnet is towards geographic North, then time period of oscillations is given by

$$T_2 = 2\pi\sqrt{\frac{(I_1 + I_2)}{(M_1 - M_2) H}}$$

Then, $$\frac{M_1}{M_2} = \frac{T_2^2 + T_1^2}{T_2^2 - T_1^2}$$

Important Terms used to Describe the Properties of Magnetic Materials

To describe the magnetic properties of materials, following terms are required

(i) **Magnetic Permeability** It is the ability of a material to permit the passage of magnetic lines of force through it.

Magnetic permeability $(\mu) = \frac{B}{H}$

where, B is magnetic induction and H is magnetising force or magnetic intensity.

(ii) **Magnetising Force or Magnetic Intensity** The degree up to which a magnetic field can magnetise a material is defined in terms of magnetic intensity.

$$\text{Magnetic intensity } (H) = \frac{B}{\mu}$$

(iii) **Intensity of Magnetisation** The magnetic dipole moment developed per unit volume of the material is called intensity of magnetisation.

Intensity of magnetisation $(\mathbf{I}) = \frac{\mathbf{M}}{V} = \frac{m}{A}$

where, V = volume and A = area of cross-section of the specimen.

Magnetic induction, $B = \mu_0 (H + I)$.

(iv) **Magnetic Susceptibility (χ_m)** The ratio of the intensity of magnetisation (I) induced in the material to the magnetising force (H) applied is called magnetic susceptibility.

$$\text{Magnetic susceptibility } (\chi_m) = \frac{I}{H}$$

Relation between magnetic permeability and susceptibility is given by

$$\mu = \mu_0 (1 + \chi_m)$$

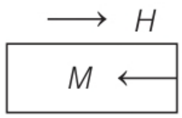
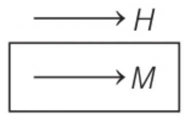
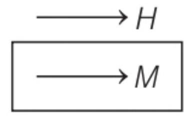
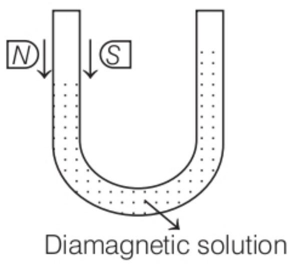
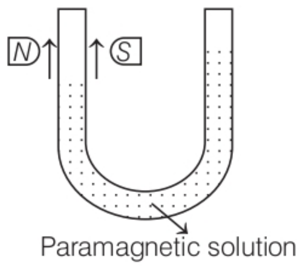
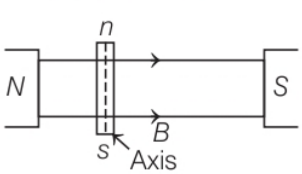
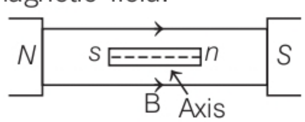
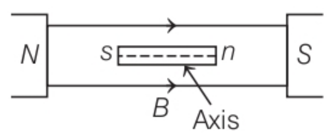
Classification of Magnetic Materials

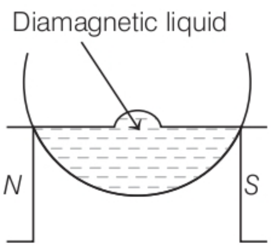
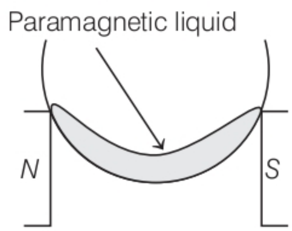
On the basis of their magnetic properties magnetic materials are divided into three categories

(i) Diamagnetic substances

(ii) Paramagnetic substances

(iii) Ferromagnetic substances

S. No.	Diamagnetic substances	Paramagnetic substances	Ferromagnetic substances
1.	These substances when placed in a magnetic field, acquire feeble magnetism opposite to the direction of the magnetic field. 	These substances when placed in a magnetic field, acquire feeble magnetism in the direction of the magnetic field. 	These substances when placed in a magnetic fields are strongly magnetised in the direction of the field. 
2.	These substances are repelled by a magnet.	These substances are feebly attracted by a magnet.	These substances are strongly attracted by a magnet.
3.	When a diamagnetic solution is poured into a U- tube and one arm is placed between the poles of strong magnet, the level of solution in that arm is lowered. 	The level of the paramagnetic solution in that arm rises. 	No liquid is ferromagnetic.
4.	If a rod of diamagnetic material is suspended freely between two magnetic poles, its axis becomes perpendicular to the magnetic field. 	Paramagnetic rod becomes parallel to the magnetic field. 	Ferromagnetic rod also becomes parallel to the magnetic field. 
5.	In non-uniform magnetic field, the diamagnetic substances are attracted towards the weaker fields, *i.e.* they move from stronger to weaker magnetic field.	In non-uniform magnetic field, they move from weaker to stronger part of the magnetic field slowly.	In non-uniform magnetic field, they move from weaker to stronger magnetic field rapidly.
6.	Their permeability is less than one ($\mu < 1$).	Their permeability is slightly greater than one ($\mu > 1$).	Their permeability is much greater than one ($\mu >> 1$).

S. No.	Diamagnetic substances	Paramagnetic substances	Ferromagnetic substances
7.	Their susceptibility is small and negative. Their susceptibility is independent of temperature.	Their susceptibility is small and positive. Their susceptibility is inversely proportional to absolute temperature.	Their susceptibility is large and postitve. They also follow Curie's law.
8.	Shape of diamagnetic liquid in a glass crucible and kept over two magnetic poles. 	Shape of paramagnetic liquid in a glass crucible and kept over two magnetic poles. 	No liquid is ferromagnetic.
9.	In these substances, the magnetic lines of force are farther than in air.	In these substances, the magnetic lines of force are closer than in air.	In these substances, magnetic lines of force are much closer than in air.
10.	The resultant magnetic moment of these substances is zero.	These substances have a permanent magnetic moment.	These substances also have a permanent magnetic moment.

In a ferromagnetic substance, there are several tiny regions called **domains**. Each domain contain approximately 10^{10} atoms.
Each domain is a strong magnet as all atoms or molecules in a domain have same direction of magnetic moment.

Curie Law in Magnetism

The magnetic susceptibility of a paramagnetic substance is inversely proportional to its absolute temperature.

$$\chi_m \propto \frac{1}{T} \Rightarrow \chi_m T = \text{constant}$$

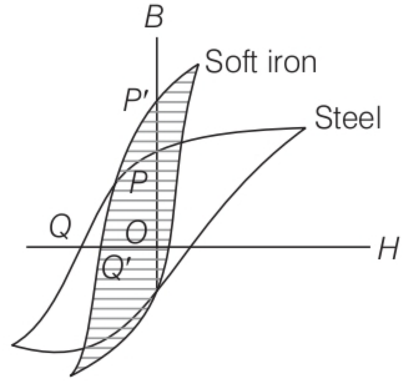
where, χ_m = magnetic susceptibility of a paramagnetic substance and

T = absolute temperature.

At Curie temperature, ferromagnetic substances changes into paramagnetic substances.

Hysteresis

The lagging of intensity of magnetisation (I) or magnetic induction (B) behind magnetising field (H), when a specimen of a magnetic substance is taken through a complete cycle of magnetisation is called hysteresis.



Retentivity or Residual Magnetism

The value of the intensity of magnetisation of a material, when the magnetising field is reduced to zero is called retentivity or residual magnetism of the material.

Coercivity

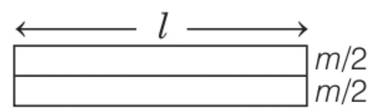
The value of the reverse magnetising field that should be applied to a given sample in order to reduce its intensity of magnetisation or magnetic induction to zero is called coercivity.

Important Points

- Magnetic length $= \frac{5}{6} \times$ Geometric length of magnet.
- About 90% of magnetic moment is due to spin motion of electrons and remaining 10% of magnetic moment is due to the orbital motion of electrons.
- When a magnet having magnetic moment M is cut into two equal parts.

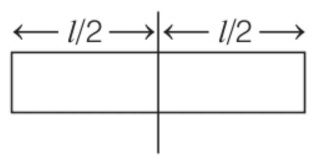
(i) Parallel to its length

$$M' = \frac{m}{2} \times l = \frac{M}{2}$$

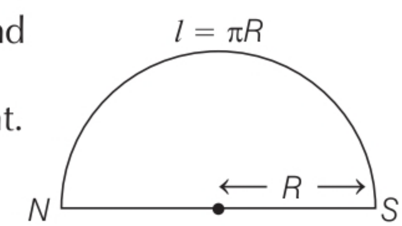


(ii) Perpendicular to its length

$$M' = m \times \frac{l}{2} = \frac{M}{2}$$



- When a magnet of length l, pole strength m and of magnetic moment M is turned into a semicircular arc, then it new magnetic moment.

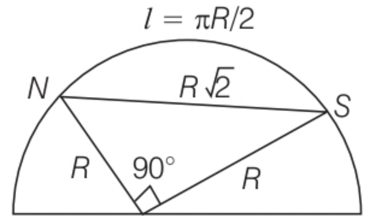


$$M' = m \times 2R = m \times 2 \times \frac{l}{\pi} \quad (\pi R = l)$$

$$= \frac{2M}{\pi} \quad (\because M = m \times l)$$

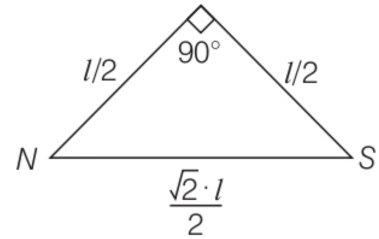
- A thin magnet of moment M is turned into an arc of 90°, then new magnetic moment

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



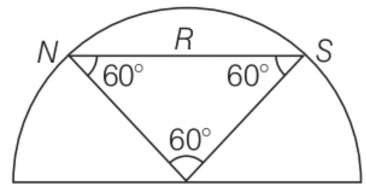
- A thin magnet of moment M is turned at mid-point 90°, then new magnet moment

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



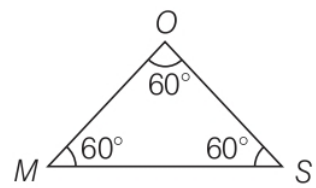
- A thin magnet of moment M is turned into an arc of 60°, then new magnetic moment

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



- A thin magnet of moment M is bent at mid point at angle 60°, then new magnetic moment

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



- Original magnet MOS is bent at O, the mid-point at 60°. All sides are equal.
- The mutual interaction force between two small magnets of moments M_1 and M_2 is given by

$$F = K\frac{6M_1M_2}{d^4} \text{ in end-on position.}$$

Here, d denotes the separation between magnets.
- Cause of diamagnetism is orbital motion and cause of paramagnetism is spin motion of electrons. Cause of ferromagnetism lies in formation of domains.
- The perpendicular bisector of magnetic axis is known as neutral axis of magnet. Magnetism at neutral axis is zero and at poles is maximum.
- For steel coercivity is large. However, retentivity is comparatively smaller in case of steel, so steel is used to make permanent magnets.
- For soft iron, coercivity is very small and area of hysteresis loop is small. So, soft iron is an ideal material for making electromagnets.