

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 lode stone 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 molecular 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.

The poles always occur in pairs and they are of equal strength. Like poles repel and unlike poles attract.

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.

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.

$$F = \mu_0 / 4\pi \cdot m_1 m_2 / r^2$$

where m_1, m_2 = pole strengths, r = distance between poles and μ_0 = permeability of free space.

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.

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

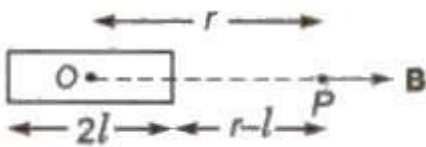
$$M = m (2l)$$

Its SI unit is 'joule/tesla' or 'ampere-metre²'.

Its direction is from south pole towards north pole.

Magnetic Field Due to a Magnetic Dipole

(1) On Axial Line

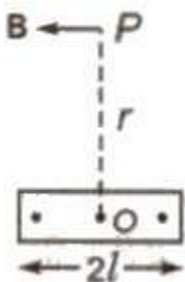


$$B = \frac{\mu_0}{4\pi} \frac{2Mr}{(r^2 - l^2)^2}$$

If $r \gg l$, then

$$B = \mu_0 / 4 \pi 2M / r^3$$

(ii) On Equatorial Line



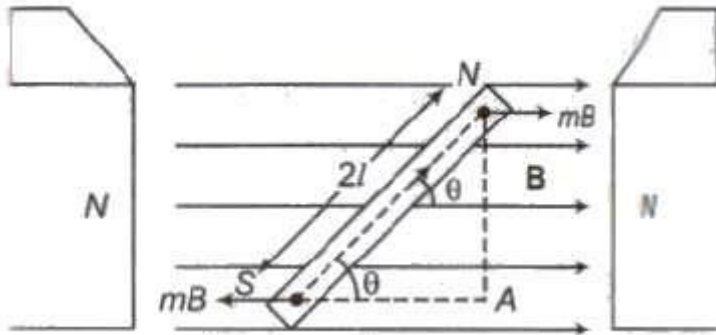
$$B = \mu_0 / 4 \pi M / (r^2 + l^2)^{3/2}$$

If $r \gg l$, then

$$B = \mu_0 / 4 \pi 2M / r^3$$

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



$$\tau = M \times B$$

$$\text{or } \tau = MB \sin \theta$$

Where θ is 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.

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

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

$$M = IA$$

$$\text{For } N \text{ such turns } M = NIA$$

Where I = current and A = area of cross-section of the coil.

Gauss's Law in Magnetism

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

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

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

[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 $M = \frac{1}{2} e\omega r^2$

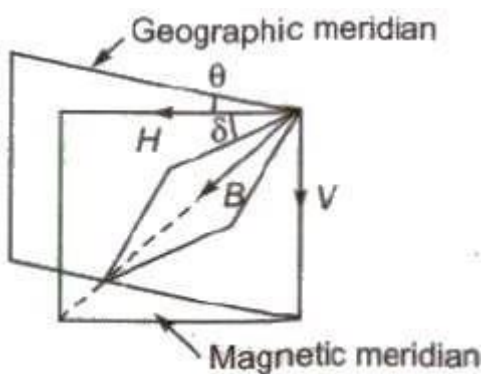
where e = charge on an electron, ω = angular velocity of electron and r = radius of orbit.

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 magneton and its value is $9.27 \times 10^{-24} \text{ A}\cdot\text{m}^2$.

Earth's Magnetism

Earth is a huge magnet. There are three components 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 is called magnetic inclination or magnetic dip.

(iii) Horizontal Component of Earth's Magnetic Field (H) 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

$$V = B \sin \delta$$

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

$$\text{and } \tan \delta = V / H$$

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

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.

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 acclinic 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

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

$$\text{where } I_0 = M / R^3$$

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

(Magnetic maps are maps obtained by drawing lines passing through different places on the surface of earth, having the same value of a magnetic element.)

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.

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

$$\text{If } r \gg l, \text{ then } B = \mu_0 / 4\pi 2M / r^3 = H$$

When north pole of a bar magnet is placed towards north pole of the earth, then neutral point is obtained on equatorial line

$$B = \mu_0 / 4\pi 2Mr / (r^2 + l^2)^2 = H$$

$$\text{If } r \gg l, \text{ then } B = \mu_0 / 4\pi 2M / r^3 = H$$

Tangent Law

When a bar magnet is freely suspended under the combined effect of two uniform magnetic fields of intensities B and H acting at 90° to each other, then it bar magnet comes to rest making an angle θ with the direction of H , then

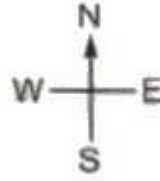
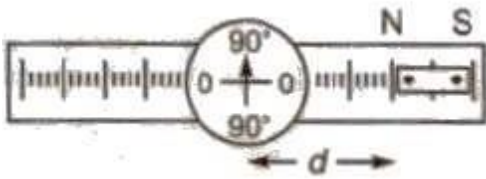
$$B = H \tan \theta$$

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.

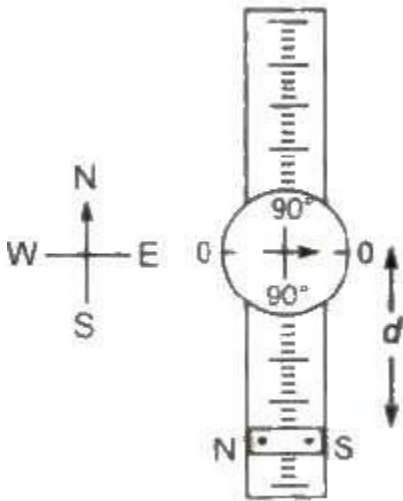


In equilibrium

$$B = H \tan \theta$$

$$\mu_0 / 4\pi 2M / d^3 = H \tan \theta$$

(ii) **Tangent B setting** In this setting the arms of the magnetometer are along north-south and magnet is perpendicular to these arm in equilibrium



$$\mu_0 / 4\pi M / d^3 = H \tan \theta$$

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

$$M_1 / M_2 = \tan \theta_1 / \tan \theta_2$$

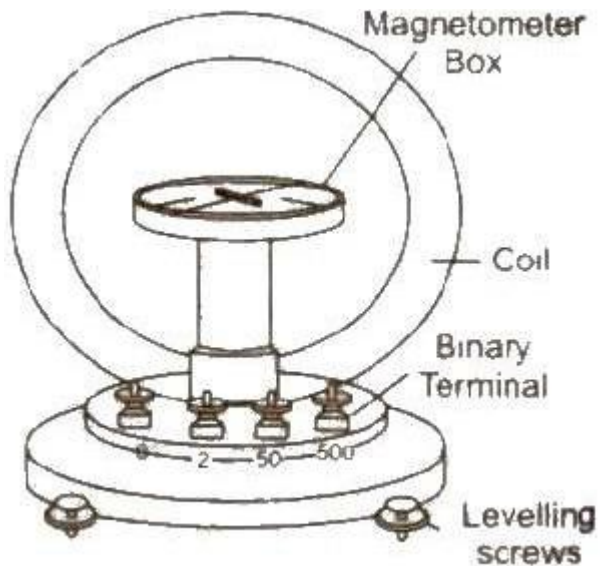
where θ_1 and θ_2 are mean values of deflection for two magnets.

(b) **Null method** In this method both magnets are used at a time and no deflection condition is obtained. If Magnets are at distance d_1 and d_2 then

$$M_1 / M_2 = (d_1 / d_2)^3$$

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



$$I = 2R / N\mu_0 H \tan \theta = H / G \tan \theta = K \tan \theta$$

Where $G = N\mu / 2R$ is called galvanometer constant and $K = H / G$, is called reduction factor of tangent galvanometer.

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

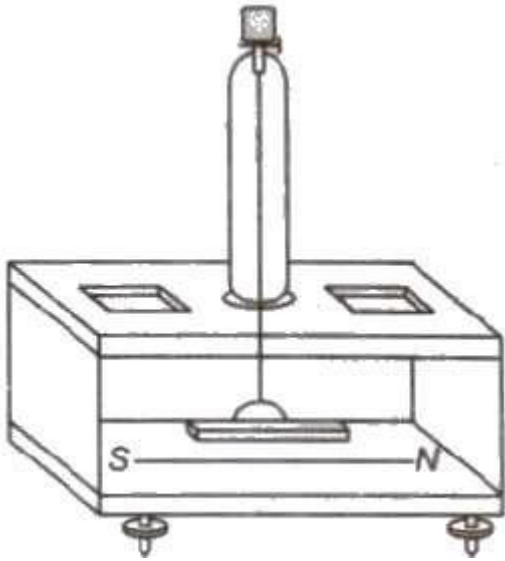
Tangent galvanometer is also called moving magnet type galvanometer.

Vibration Magnetometer

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

Time period of vibrations is given by

$$T = 2\pi \sqrt{I / MH}$$



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

$$T_1 = 2\pi\sqrt{I_1 + I_2 / (M_1 + M_2) H}$$

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

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

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

Magnetic Flux

The number of magnetic lines of force passing through any surface is called magnetic flux linked with that surface.

$$\text{Magnetic flux } (\phi) = B \cdot A = BA \cos \theta$$

where B is magnetic field intensity or magnetic induction, A is area of the surface.

Its unit is 'weber'.

Magnetic Induction

The magnetic flux passing through per unit normal area, is called magnetic induction.

$$\text{Magnetic induction (B)} = \phi / A$$

Its unit is 'waber/metre²' or 'tesla'.

Magnetic of Material

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.

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

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.

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

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

$$\text{Intensity of magnetisation (I)} = M / V = m / A$$

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

$$\text{Magnetic induction } B = \mu_0 (H + I)$$

(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.

$$\text{Magnetic Susceptibility } (\chi_m) = I / H$$

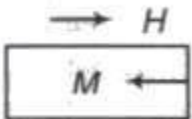
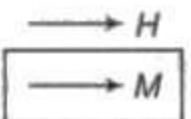
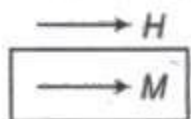
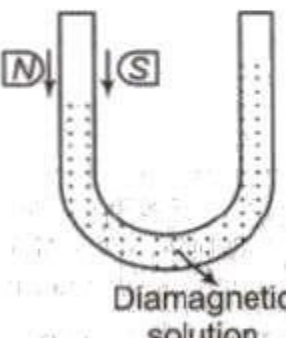
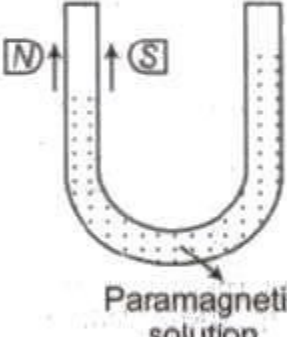
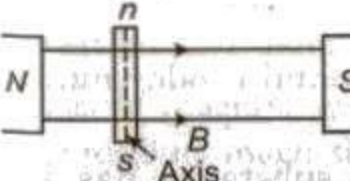
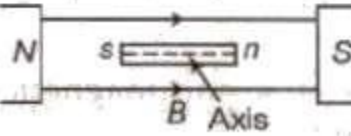
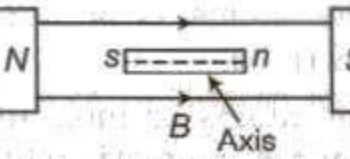
[Relation between Magnetic Permeability and Susceptibility is given by

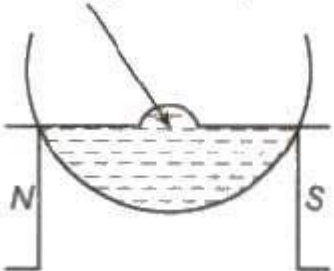
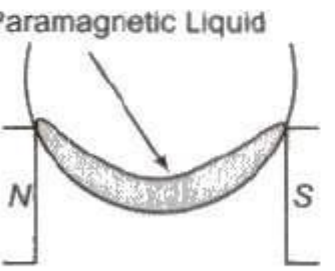
$$\mu = \mu_0 (1 + \chi_m)]$$

Classification of Magnetic Materials

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

Diamagnetic substances, Paramagnetic substances ,Ferromagnetic substances

S. No.	Diamagnetic substances	Paramagnetic substances	Ferromagnetic substances
1.	<p>These substances when placed in a magnetic field, acquire feeble magnetism opposite to the direction of the magnetic field.</p> 	<p>These substances when placed in a magnetic field, acquire feeble magnetism in the direction of the magnetic field.</p> 	<p>These substances when placed in a magnetic field are strongly magnetised in the direction of the field.</p> 
2.	<p>These substances are repelled by a magnet.</p>	<p>These substances are feebly attracted by a magnet.</p>	<p>These substances are strongly attracted by a magnet.</p>
3.	<p>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.</p> 	<p>The level of the paramagnetic solution in that arm rises.</p> 	<p>No liquid is ferromagnetic.</p>
4.	<p>If a rod of diamagnetic material is suspended freely between two magnetic poles, its axis becomes perpendicular to the magnetic field.</p> 	<p>Paramagnetic rod becomes parallel to the magnetic field.</p> 	<p>Ferromagnetic rod also becomes parallel to the magnetic field.</p> 

S. No.	Diamagnetic substances	Paramagnetic substances	Ferromagnetic substances
5.	In non-uniform magnetic field, the diamagnetic substances are attracted towards the weaker fields, <i>i.e.</i> , 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 ($\mu >> 1$).
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 which is Curie's law, <i>i.e.</i> , $\chi \propto 1/T$	Their susceptibility is large and positive. They also follow Curie law. <i>i.e.</i> , ($\chi \propto 1/T$). At Curie temperature ferromagnetic substances change into paramagnetic substances.
8.	Shape of diamagnetic liquid in a glass crucible and kept over two magnetic poles. Diamagnetic Liquid 	Shape of paramagnetic liquid in a glass crucible and kept over two magnetic poles. Paramagnetic Liquid 	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 the 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.

The atoms of a paramagnetic substance contain even number of electrons.

The atoms or molecules of a paramagnetic substance do not possess any net magnetic moment.

The atoms of a paramagnetic material contain odd number of electrons.

Every atom or molecule of a paramagnetic substance has its own magnet moment, i.e., its each atom or molecule is a tiny magnet.

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

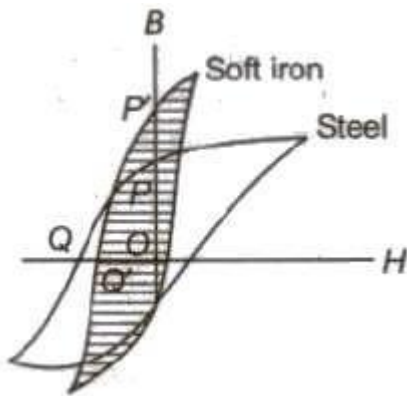
The magnetic susceptibility of a paramagnetic substance is inversely proportional to its absolute temperature.

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

where χ_m = magnetic susceptibility of a para magnetic substance and T = absolute temperature.

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.

Permanent Magnets

Commonly steel is used to make a permanent magnet because steel has high residual magnetism and high coercivity.

Electromagnets

Electromagnets are made of soft iron because area of hysteresis loop for soft iron is small. Therefore, energy loss is small for a cycle of magnetisation and demagnetisation.

(Permanent magnets are made by the materials such as steel, for which residual magnetism as well as coercivity should be high. Electromagnets are made by the materials such as soft iron for which residual magnetism is high, coercivity is low and hysteresis loss is low).

Important Points

- Magnetic length = $5 / 6$ * 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

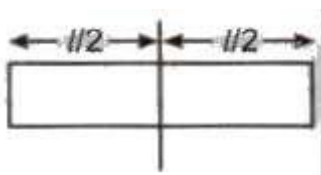
(i) Parallel to its length

$$M' = m / 2 * l = M / 2$$



(ii) Perpendicular to its length

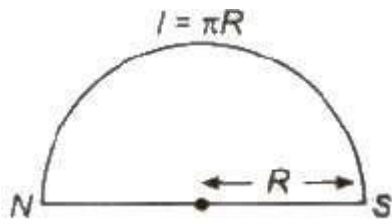
$$M' = m * l / 2 = M / 2$$



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

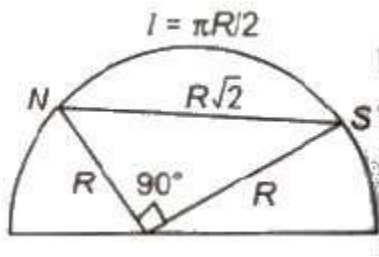
$$M' = m * 2R = m * 2 * l / \pi (\pi R = l)$$

$$= 2M / \pi (M = m * l)$$



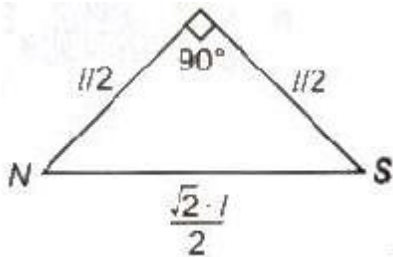
- A thin magnet of moment M is turned into an arc of 90° . Then new magnetic moment

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



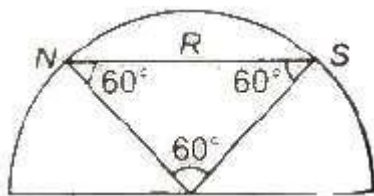
- A thin magnet of moment M is turned at mid point 90° . Then new magnet moment

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



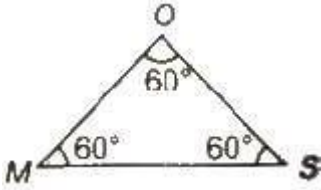
- A thin magnet of moment M is turned into an arc of 60° . Then new magnetic moment

$$M' = 3M / \pi$$



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

$$M' = M / 2$$



- 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

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

Here, d denotes the separation between magnets.

- Magnetic length = $\frac{5}{6}$ * geometric length of magnet.
- 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.