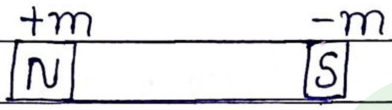
# Magnetism & Matter

* **Magnet :-** A magnet is a rock or a piece of metal that can pull certain types of metal toward itself.

* **Bar Magnet :-** A bar magnet is a rectangular magnet. it has two poles - North pole and South pole.




~~were~~ where m is the pole strength.

## Properties of bar magnet :-

- It is a permanet magnet.
- Like poles repel each other, unlike poles attract each other.
- when freely suspended, north pole of magnet points towards north pole of the earth.
- They are permanent magnets. They do not lose their magnetism.
- when a bar magnet is cut along a transverse axis there is no effect on pole strength but dipole moment reduces to half.

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- Magnetic field is maximum at the poles, and minimum as we go towards the center.
- Monopole of a magnet never exit.

## Basic properties of Magnet :-

- Attractive property — Magnet attracts ferro-magnetic materials like iron, cobalt and nickel.

- Repulsive properties — Like magnetic poles repel each other and unlike magnetic poles ~~each~~ attract each other.

- Directive property — A freely suspended magnet always point in a north-south direction.

- Magnet poles always exist in pair.

- Magnetic Induction — A magnet induces magnetism in a magnetic substance placed near it. This phenomenon is called magnetic induction.

→ Repulsion is the surer test of magnetism:
A magnet can attract another magnet. Also it can attract magnetic substance like iron, nickel, cobalt etc. However, a

magnet can repel another magnet only. So, repulsion is surer test of magnetism.

## Magnetic Dipole :-

An arrangement of two equal and opposite magnetic poles separated by a small distance is called a magnetic dipole.

## Magnetic Dipole moment :-

Magnetic dipole moment is defined as the product of its pole.

## Coulomb's Law Of Magnetic Force :-

The force (repulsion or attraction) between two magnetic poles (in a medium) is directly proportional to the product of their poles strength and inversely proportional to the square of the distance between them.

i.e,

$$F \propto m m_0$$

$$F \propto \frac{1}{r^2}$$

$$F \propto \frac{m m_0}{r^2}$$

magnetic length = $\frac{5}{6}$ Geometric length.

$$\boxed{F = \frac{\mu_0}{4\pi} \frac{m m_0}{r^2}}$$

Strength and magnetic length —

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It is a vector quantity. directed from S-pole to N-pole.

$$\boxed{\vec{M} = m \times 2l} \quad \vec{M} = I \cdot \vec{A}$$

where m is the pole strength and $2\vec{l}$ is the magnetic length.

SI unit : $Am \times m = Am^2$

## * Magnetic Field :-

An area around a magnet or materials that behave like a magnet. where there is a force that will attract some metals towards it.

## Magnetic line of Force :-

These are imaginary lines which comes out from north pole and enters into South pole.

### ↳ Properties of Magnetic lines —

(i) The tangent drawn to the magnetic field lines gives the direction of the magnetic field.

(ii) The closeness or density of the field lines is directly proportional to the strength of the field.

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(iii) Magnetic field lines appear to emerge or start from the north pole and merge or terminate at the south pole.

(iv) Inside the magnet, the direction of the magnectic field lines is form the south pole to the north pole.

(v) Magnetic field lines never intersect with each other.
Reason : If they intersect each other there will be two direction of magnetic field at one point which is not possible.

(vi) Magnetic field lines from a closed-loop.

↳ Magnetic Field Intensity :-

It is defined as the force experienced by a unit positive charge moving with unit velocity in a direction perpendicular to the magnetic field.

$$B = \frac{F}{m_0}$$

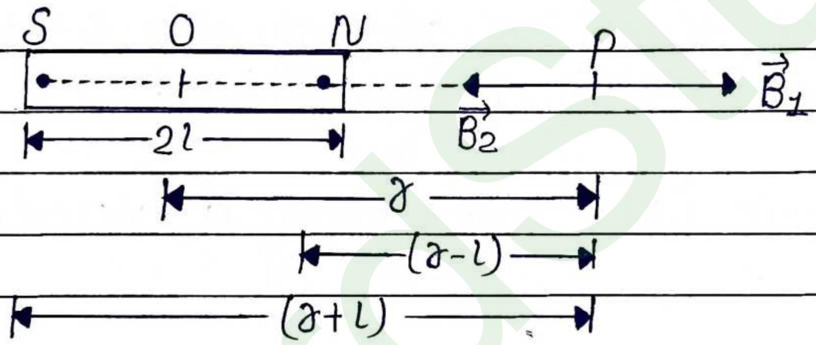
$$B = \frac{\mu_0}{4\pi} \frac{m \cancel{m_0}}{r^2 \cancel{m_0}}$$

$$\boxed{B = \frac{\mu_0 m}{4\pi r^2}}$$

unit ⇒ $\frac{Am}{m^2} = \frac{A}{m}$ or $Am^{-1}$.

## — Magnetic Field Intensity due to a dipole on axial line :-

Let we have a bar magnet NS having length 2l. O is the mid-point of the magnetic dipole. Let m = pole strength of each pole of the magnet (magnetic dipole). Let P is any point on the axial line of magnet at a distance r from the centre of magnetic dipole.




Let OP = r, ∴ NP = (r-l) and SP = (r+l)

Let a unit north pole is placed at P. then magnetic field at P due to N-pole of magnet.

$$\vec{B_1} = \frac{\mu_0}{4\pi}\frac{m}{(NP)^2} = \frac{\mu_0}{4\pi}\frac{m}{(r-l)^2} \text{ along } \vec{NP}$$

or $\vec{B_1} = \frac{\mu_0}{4\pi}\frac{m}{(r-l)^2}$ along $\vec{NP}$ (produced)

Magnetic field at P due to S-Pole of the magnet.

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$$\vec{B_2} = \frac{\mu_0}{4\pi}\frac{m}{(SP)^2} \text{ along } \vec{PS}$$

or $$\vec{B_2} = \frac{\mu_0}{4\pi}\frac{m}{(r+l)^2} \text{ along } \vec{PS}$$

As $|\vec{B_1}| > |\vec{B_2}|$

$\therefore$ Magnetic field at P due to bar magnet

$B = B_1 - B_2$ [in magnitude]

$$B = \frac{\mu_0}{4\pi}\left[\frac{m}{(r-l)^2} - \frac{m}{(r+l)^2}\right]$$

$$B = \frac{\mu_0 m}{4\pi}\left[\frac{(r+l)^2-(r-l)^2}{(r^2-l^2)^2}\right]$$

$$B = \frac{\mu_0 m}{4\pi}\frac{4rl}{(r^2-l^2)^2} = \frac{\mu_0}{4\pi}\frac{2r(m\cdot 2l)}{4\pi(r^2-l^2)^2} \quad [\because m(2l) = M]$$

$$\therefore B = \frac{\mu_0}{4\pi}\cdot\frac{2Mr}{(r^2-l^2)^2} \text{ along NP produced.}$$

For a short magnet or a small magnetic dipole : i.e, when $l^2 << r^2$

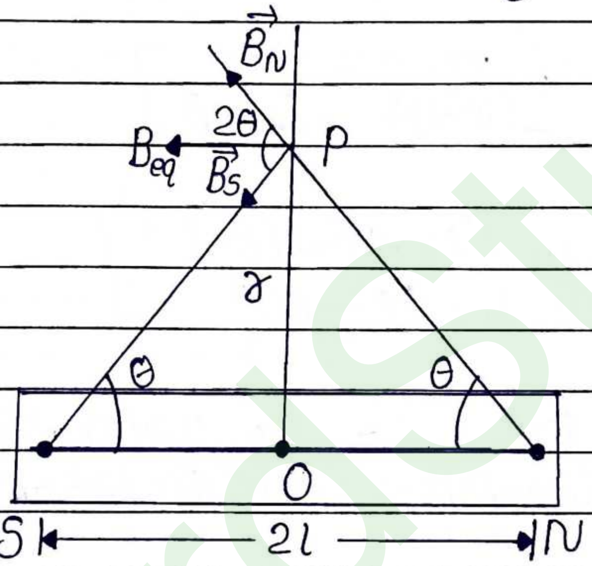
Then, $$\vec{B} = \frac{\mu_0 2\vec{M}}{4\pi(r^2)^2}$$

$$\vec{B} = \frac{\mu_0}{4\pi}\frac{2\vec{M}r}{(r^2)^2}$$

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

## — Magnetic Field Intensity due to a dipole On equatorial line :-

Consider a bar magnet of length $2l$. Let P be the point on the equatorial line at a distance $r$ from the centre of the magnet. Let $m$ be the pole strength of each pole.




Magnetic field at point P due to north pole,

$$B_N = \frac{\mu_0}{4\pi} \cdot \frac{m}{(r^2+l^2)} \quad \text{......(i)}$$

Magnetic field at point P due to south pole.

$$B_S = \frac{\mu_0}{4\pi} \cdot \frac{m}{(r^2+l^2)} \quad \text{......(ii)}$$

From (i) and (ii)

$$B_S = B_N$$

Since $B_N$ and $B_S$ are inclined at angle $2\theta$. Therefore,

$$B_{eq} = \sqrt{B_N^2 + B_S^2 + 2 B_N B_S \cos 2\theta}$$

$$B_{eq} = \sqrt{B_N^2 + B_S^2 + 2B_N B_N \cos 2\theta} \quad [\because B_N = B_S]$$

$$= \sqrt{2B_N^2 + 2B_N^2 \cos 2\theta} = \sqrt{2B_N^2(1+\cos 2\theta)}$$

$$= \sqrt{2B_N^2 \times 2\cos^2\theta} \quad [\therefore 1+\cos 2\theta = 2\cos^2\theta]$$

$$B_{eq} = 2B_N \cos\theta$$

Using eq$^n$. (i), we get

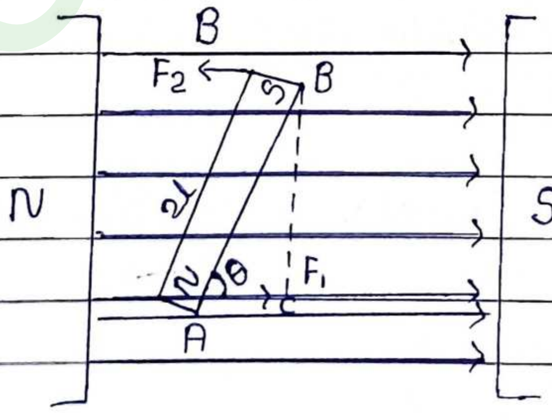
$$B_{eq} = 2 \times \frac{\mu_0}{4\pi} \cdot \frac{m}{(r^2+l^2)} \cos\theta$$

$$= 2 \times \frac{\mu_0}{4\pi} \cdot \frac{m}{(r^2+l^2)} \frac{1}{\sqrt{r^2+l^2}} \quad \left[\therefore \cos\theta = \frac{1}{\sqrt{r^2+l^2}}\right]$$

$$B_{eq} = \frac{\mu_0}{4\pi} \cdot \frac{M}{(r^2+l^2)^{3/2}} \quad [\therefore m \times 2l = M]$$

If $l << r$, then $B_{eq} = \frac{\mu_0}{4\pi} \cdot \frac{M}{r^3}$.

## Torque acting on a dipole in uniform magnetic field :-




Consider a dipole of pole strength '+m' and '-m' separated by a distance 2l is placed in uniform magnetic field B.

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$F_1 = mB$ $\quad\quad [B = \frac{F}{m}]$

$F_2 = mB$

These are equal and opposite and parallel forces, so, they form torque.

$\tau$ = either force × perpendicular distance

$\tau = mB \times Be$

In $\Delta$ ABC

$\sin\theta = \frac{P}{H} = \frac{BC}{2l}$

$BC = 2l \sin\theta$

$\because \tau = mB \times 2l \sin\theta$ $\quad\quad [\because M = m \times 2l]$

$\tau = MB \sin\theta$

or

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

SI unit is joule per tesla ($JT^{-1}$).

Special cases :-

(i) If $\theta = 0°$

$\because \tau = 0°$ (stable Equilibrium)

(ii) If $\theta = 180°$

$\because \tau = 0$ (unstable Equilibrium)

$\{\sin 180° = 0\}$

(iii) If $\theta = 90°$

$\because \tau = MB \sin 90°$

$\tau = MB$ (Maximum torque)

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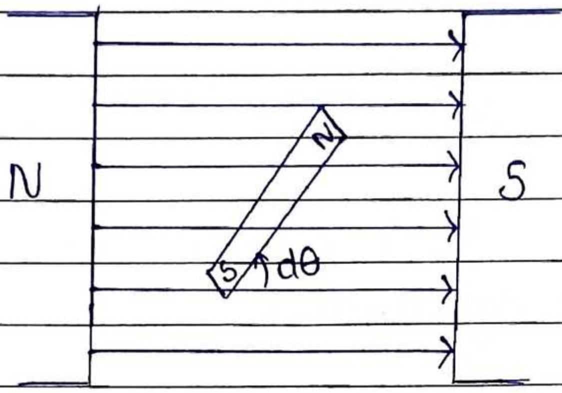
## Potential Energy of a dipole in magnetic field :-




Let dw be the small amount of workdone in rotating a dipole through an angle $d\theta$.

$$dw = \tau \times d\theta$$
$$dw = MB \sin\theta \, d\theta$$

Integrating on both side

$$\int_0^{w} dw = \int_{\theta_1}^{\theta_2} MB \sin\theta \, d\theta$$

$$[w]_0^{w} = MB \int_{\theta_1}^{\theta_2} \sin\theta \, d\theta$$

$$[w - 0] = MB [-\cos\theta]_{\theta_1}^{\theta_2}$$

$$w = -MB [\cos\theta_2 - \cos\theta_1]$$

$$U = w = MB [\cos\theta_1 - \cos\theta_2]$$

The potential energy of the dipole is zero when $\vec{M} \perp \vec{B}$. So, potential energy of dipole in any orientation $\theta$ can be obtained by putting $\theta_1 = 90°$ and $\theta_2 = \theta$ in above equation.

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$$U = MB\,[\cos 90° - \cos\theta]$$
$$U = -MB\cos\theta$$
$$U = -\vec{M}\cdot\vec{B}$$

Special cases :-

(i) If $\theta = 0°$

$\because U = -MB$ (minimum)

(stable Equilibrium)

(ii) If $\theta = 180°$

$\because U = MB$ (Maximum) $\{\cos 180° = -1\}$

(Unstable equilibrium)

(iii) If $\theta = 90°$

$\because U = 0$

* Gauss Law in Magnetism :-

The net magnetic flux ($\phi$) through any closed surface is always zero.

This law suggests that the number of magnetic field lines leaving any closed surface is always equal to the number of magnetic field lines entering it.

$$\phi_m = \oint \vec{B}\cdot d\vec{s} = 0$$

Reason :-

(i) Isolated magnetic poles called monopoles do not exist.

(ii) Magnetic poles always exist in unlike pairs of equal strength.

## Causes Of Earth Magnetism :-

The exact cause of earth's magnetic field is not yet known. However, some important causes in this respect are;

(i) There is a metallic molten charged fluid in the core of the earth. The radius of this fluid is about 3500 km. Due to the motion of this fluid inside the earth, large circulating currents are produced. These currents magnetise the earth.

(ii) In the outer layers of earth's atmosphere, gases are in the ionised state. Due to rotation of earth, these ions also move and hence they constitute the current. These currents may be the reason for magnetism of earth.

(iii) Every substance is made up of protons and electrons. When earth rotates, every substance on the earth or inside the earth will rotate. Hence there is motion of protons and electrons and due to this, currents are produced. This may be the reason of magnetism of earth.

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## Magnetic elements of Earth :-

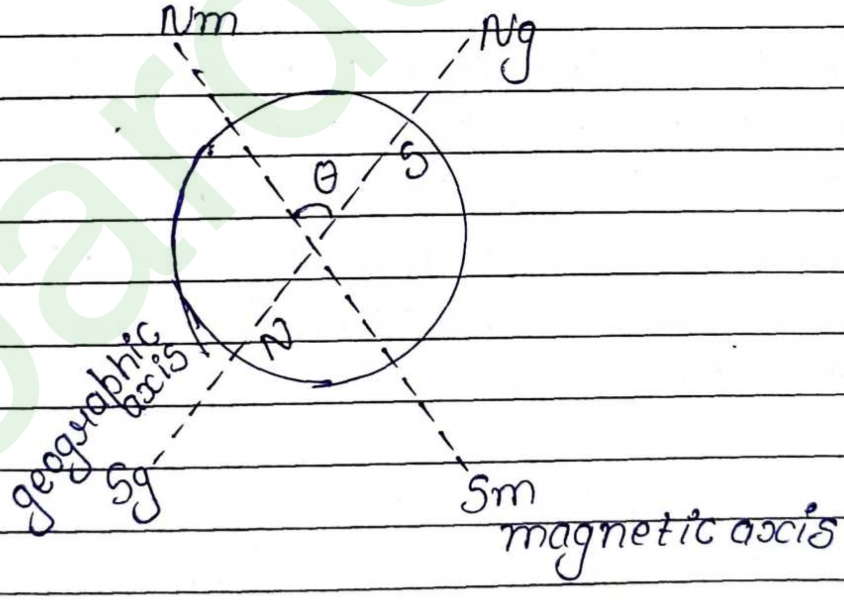
These are the elements which completely specify magnitude and direction of magnetic field at any point on earth.

### There are three magnetic elements :-

(i) Angle of declination ($\theta$).
(ii) Angle of dip or magnetic inclination ($\delta$)
(iii) Horizontal components.

### 1). Magnetic Declination :-

It is defined as the angle between magnetic axis and the geographic axis.




$\theta$ = Magnectic declination.

1. Geographic axis : Line joing N & S pole.
2. Magnetic axis : line joining poles of magnet.
3. Magnetic meridian : Imaginary plane passing through magnetic poles of the earth.

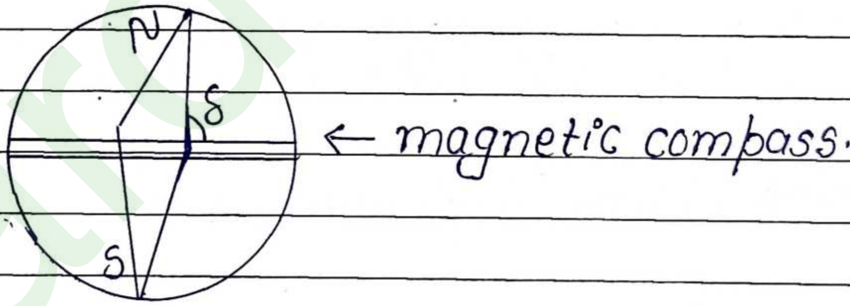
4. Geographical – Imaginary plane passing through geographical axis.

• **Evidence :–**

1. Alignment of bar magnet in N–S direction.
2. Neutral point found near bar magnet.
3. Magnetisation of soft iron inside earth.

## 2.) Magnetic Inclination / Angle of Dip ($\delta$) :–

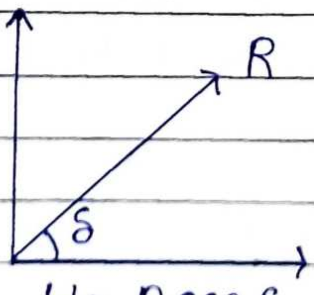
It is defined as the angle between resultant magnetic field of earth and central line in magnetic compass.




## 3.) Horizontal Component :–

It is defined as the component of resultant magnetic field in horizontal direction.

$V = R \sin\delta$




$H = R \cos\delta$

$$H = R\cos\delta \quad \text{--- (1)}$$
$$V = R\sin\delta \quad \text{--- (2)}$$

$\tan\delta = 45°$
$B_V = B_H$

Divide (2) by (1)

$$\frac{V}{H} = \frac{R\sin\delta}{R\cos\delta}$$

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

now, squaring and adding (1) and (2) :-

$$H^2 + V^2 = R^2\cos^2\delta + R^2\sin^2\delta$$
$$H^2 + V^2 = R^2(\cos^2\delta + \sin^2\delta)$$
$$\sqrt{H^2 + V^2} = R$$

$$\because \quad \boxed{R = \sqrt{H^2 + V^2}}$$

## Some important term in magnetism :-

(i) **Magnetic permeability —**

Magnetic permeability (denoted as $\mu$) is defined as the ratio of the magnetic induction B (the magnetic flux density) developed in a material to the strength of the magnetic field H (the magnetic field intensity) that produces it.

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

$$\mu_r = \frac{B}{B_0}$$

$$\mu_r = \frac{\mu}{\mu_0}$$

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Where $B$ = magnetic field line in material
and $B_0$ = magnetic field line in vaccum.

(ii) Magnetic Field Strength or Magnetic field Induction :-

It is equal to the force experienced by unit positive charge moving with unit velocity perpendicular to the direction of magnetic field.

$$\because F = qBV \sin\theta$$
$$F = qBV \quad [q \text{ and } V = 1]$$
$$\boxed{F = B}$$

(iii) Magnetising force or Magnetising Intensity :-

SI unit = $Am^{-1}$

It is defined as the number of ampere turn flowing per unit length in taroid or solenoid.

$$\boxed{H = nI} \quad \left[\because n = \frac{N}{l}\right]$$

Also, we know that -

$$B = \mu nI$$
$$\boxed{B = \mu H} \quad [\because nI = H]$$

For vaccum,

$$\boxed{B_0 = \mu_0 H}$$

OR the capability of MF to magnetise the substance is measured in terms of magnetic intensity of the field.

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(iv) Intensity of Magnetisation :-
It is defined as a magnetic moment developed per unit volume of the material, when placed in a uniform magnetic field.

$$I = \frac{M}{V}$$

$$I = \frac{m \times \cancel{2l}}{A \times \cancel{2l}}$$

$$\boxed{I = \frac{m}{A}}$$ where m = pole strength
A = Area.

(v) Magnetic Susceptibility :- It is defined as the ratio of intensity of magnetisation to the magnetising force.

$$\boxed{\chi_m = \frac{I}{H}}$$ Scalar quantity.

* Difference between the magnetic materials :-

Paramagnetic Substance —

1. The substances are weakly attracted by the magnetic field.
2. Magnetic field lines become denser inside parmagnetic substances.
3. These substances when placed in magnetic field acquire magnetism in the direction of magnetic field.

4. The level of paramagnetic solution in that arm is rise. (U-tube arm)

5. They move from weaker to stronger magnetic fields slowly.
6. There permeability is slightly greater than 1.
7. Susceptibility is small and positive.
E.g – Aluminium, sodium etc.

## Diamagnetic Substance –

1. Magnet repel them.
2. They move from the stronger to the weaker part of the magnetic field when suspended freely in a non-uniform magnetic field.

3. These substance when placed in a magnetic field acquire magnetism opposite in the direction of M.F.

4. when diamagnetic material (solution) is filled in U-tube and one arm is placed between the poles of a strong magnet the level of solution is that arm is lowered.

5. There permeability is less than 1.
6. Susceptibility is small and negative.

7. Their susceptibility is independent of temperature.
8. The resultant magnetic moment is zero.
E.g – water, NaCl, Si, Cu, Gold.

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## Ferromagnetic Substance –

1. Ferromagnetic substances are strongly attracted by the field. so, in a nonuniform field, they tend to sick at the poles where the field is strongest.

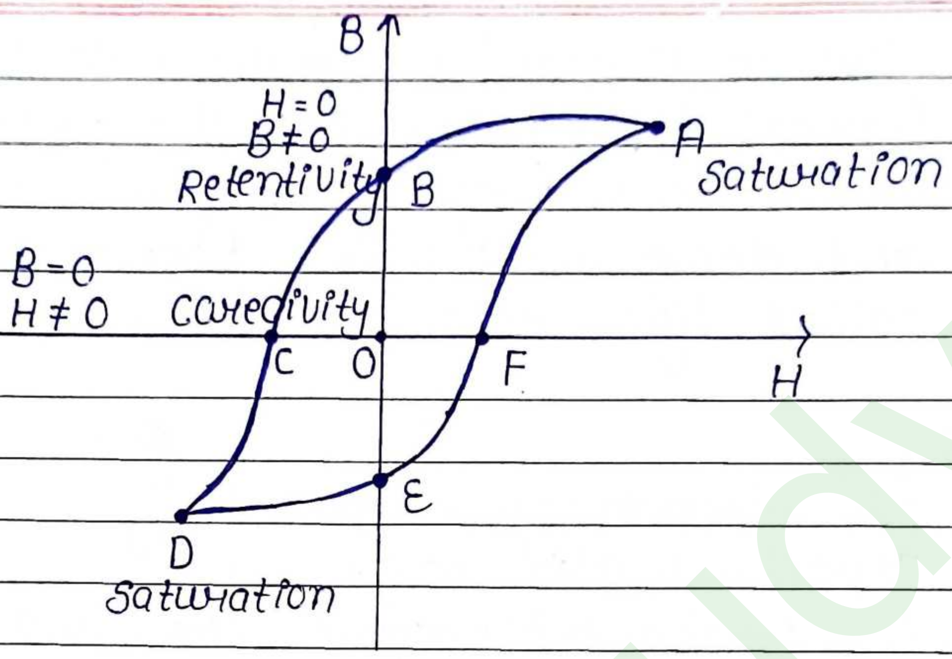
2. Ferromagnetic substances atoms have permanent dipole moment in domains.

3. No liquid is ferromagnetic solution.
4. They move from weaker to stronger magnetic field rapidly.

5. The magnetic susceptibility is very large, positive.
6. There permeability is much greater than 1.
E.g: Iron, cobalt, Nickel.

## * B-H curve or Hysteresis curve :–

This hysteresis curve represent the relation between magnetic induction 'B' of a ferromagnetic material with magnetising intensity 'H'.




From the curve, we observed these points —

(i) An unmagnetised sample is placed in a solenoid and current through the solenoid is increased, then magnetic field B in material rises and saturates in the curve OA called saturation.

(ii) If H is decreased and reduces to zero then at $H = 0$, $B \neq 0$ . i.e. curve AB. The value of B at $H = 0$ is retentivity.

(iii) Now the current in the solenoid is reversed and slowly increased then at C, $B = 0$ and $H \neq 0$. The value of H at $B = 0$ is corecivity.

(iv) when again current is slowly increased we again obtain saturation in the reverse direction at D. i.e. curve CD.

(v) Now the current is reduced to DE then increased to curve EA. The cycle repeats itself hence magnetic material magnetises and demagnetises. This phenomenon is called Hysteresis.

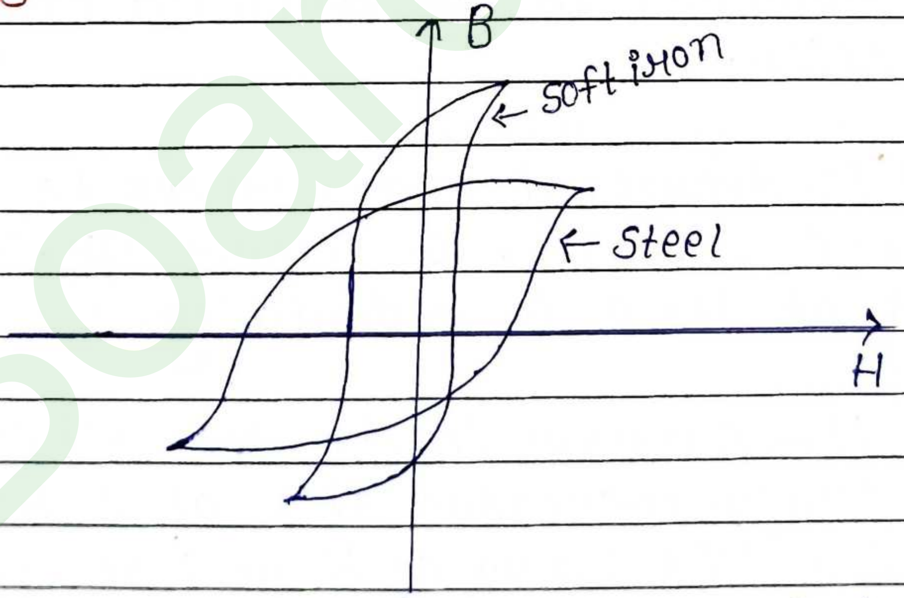
Note :-

(i) For electromagnet retentivity is low and corecivity also low.

(ii) For permanent magnet, the retentivity is high and corecivity is also high.

(iii) Lesser the area under B-H curve less will be the losses and vice-versa.

→ Hysteresis Curve of soft Iron and steel :-




Hysteresis loop for soft iron is large and narrow where as Hysteresis loop for steel is short and wide.

→ Retentivity of soft iron is greater than steel.

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→ Soft iron is more strongly magnetised than steel.

→ Carecivity of soft iron is less than steel.

## * Curie's Law in Magnetism :-

According to curie's law, the magnetisation M developed in a paramagnetic material is directly proportional to the applied magnetic field $B_0$ and inversely proportional to the absolute temperature T. i.e.

$$M \propto \frac{B_0}{T} \quad \text{or} \quad M = C\frac{B_0}{T}$$

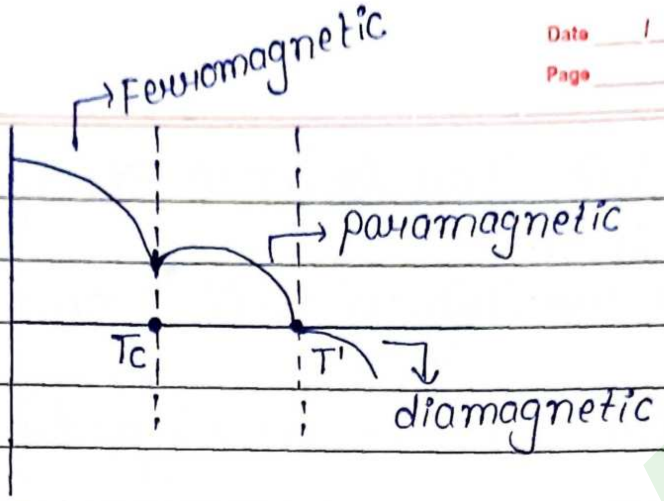
Where C is a constant for given material and is know as curie's constant. As a temperature of a paramagnetic material is reduced the magnetisation vector increases.

In terms of magnetic susceptibility $\chi$, curie's law for paramagnetic materials may be expressed as:

$$\chi = \frac{C}{T}.$$

## Curie Temperature :-

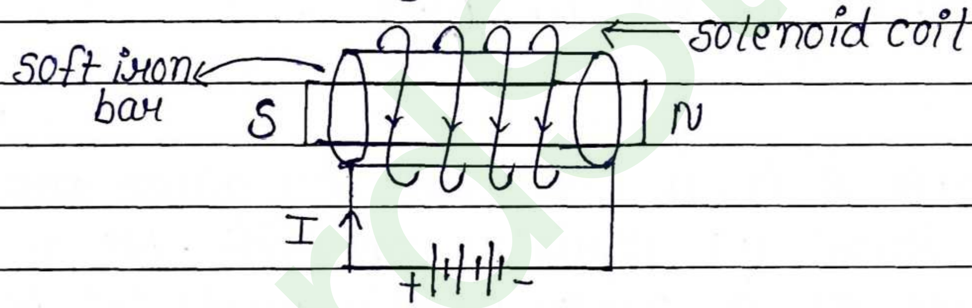
The temperature at which ferromagnetic substance convers in the paramagnetic substance.




Ferromag. $\chi_m >> +1$
Para $\chi_m > +1$
Dia $\chi_m < 0$

## * ElectroMagnets :–

An electromagnet is a magnet consisting of wire wound around a soft iron core. It is magnetized only when electric current is passed through the coil.




→ The core of electromagnet is made up of ferromagnetic material which have high permeability and low retentivity and low corecivity.

→ Soft iron is suitable material of electromagnet.

→ When a current is passed through the solenoid coil, the iron bar is magnetised under the influence of a strong magnetic field produced inside the solenoid. The magnetisation of soft iron bar lasts

So long as current is flowing in solenoid is switched off the iron bar magnet immediately loss its magnetism due to low carecivity of soft iron.

## Uses of electromagnets :-

- The electromagnets are used in the manufacture of electric bells.
- Electromagnets are used in Headphones and loudspeakers.
- The electromagnets are an important part of the data storage devices such as VCRs, tape recorders, hard discs, etc.....
- The electromagnet are even used in the medical field, for the MRI machines used to diagnose the patient.

## Factor affecting the strength of an electromagnet:

- The number of turns in the coil
- The current flowing in the coil
- Nature of the core of electromagnet.

## * ~~Param~~ Permanent magnets :-

A permanent magnet is a type of material that has its own magnetic properties and creates its own magnetic field.

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The material chosen should have —

→ High permeability so that it can be magnetised easily.

→ High retentivity so that the magnet is strong.

→ High corecivity so that the magnetisation is not erased by temperature fluctuation or mechanical damage.

→ Steel is preferred for making permanent magnets though retentivity of steel is slightly smaller than that of soft iron, yet its corecivity is much larger than that of soft iron.

→ Some suitable material for making permanent magnet are cobalt, steel, carbon steel etc.