PHYSICS

NEET and JEE Main 2020 : 45 Days Crash Course

Magnet and Magnetism

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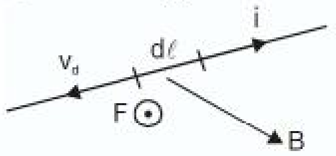
Magnetic Force on a Current Carrying Wire

Suppose a conducting wire, carrying a current i, is placed in a magnetic field $\vec{B}$. Consider a small element $d\ell$ of the wire.



The magnetic force on the wire of length $d\ell$ is

$$\boxed{d\vec{F} = i d\vec{\ell} \times \vec{B}}$$

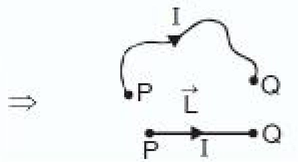
The quantity $i d\vec{\ell}$ is called a *current element.*

$$\overrightarrow{F_{res}} = \int \overrightarrow{dF} = \int i d\vec{\ell} \times \vec{B} = i \int \overrightarrow{d\ell} \times \vec{B}$$ (∵ i is same at all points of the wire)

If $\vec{B}$ is uniform then $\vec{F}_{res} = i(\int \overrightarrow{d\ell}) \times \vec{B}$

$$\boxed{\overrightarrow{F_{res}} = i\vec{L} \times \vec{B}}$$

Here $\vec{L} = \int d\vec{\ell}$ = vector length of the wire = vector connecting the end points of the wire.



Note :

- If a current loop of any shape is placed in a uniform $\vec{B}$ then $\overrightarrow{F_{res}}\big|_{magnetic}$ on it = 0 (∵ $\vec{L}$ = 0).

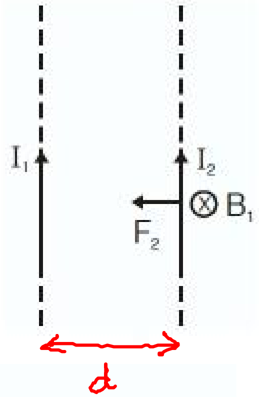
Magnetic Force per unit length between two Long Wires

On (2), B due to (1) is = $\frac{\mu_0 I_1}{2\pi d} \otimes$

$\therefore$ F on (2) on 1m length

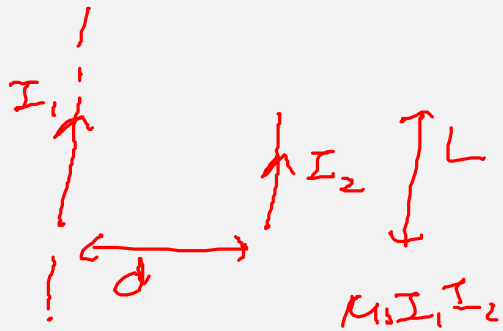
$= I_2 . \frac{\mu_0 I_1}{2\pi d} . 1$ towards left it is attractive

$F/l = \frac{\mu_0 I_1 I_2}{2\pi d}$



Note :

If the currents are in the opposite direction then the magnetic force on the wires will be repulsive.



$F/L = \frac{\mu_0 I_1 I_2}{2\pi d}$

$F = \frac{\mu_0 I_1 I_2 L}{2\pi d}$

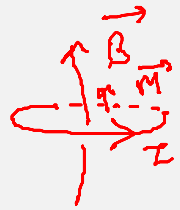
Torque on a Current Carrying Loop

When a current-carrying coil is placed in a uniform magnetic field the net force on it is always zero. However, as its different parts experience forces in different directions so the loop may experience a torque (or couple) depending on the orientation of the loop and the axis of rotation.

$$\boxed{\vec{\tau} = \vec{M} \times \vec{B}} \qquad [\text{with } \vec{M} = I\vec{A} = NIA\vec{n}]$$

$\vec{F}_{net} = 0$

$\tau = MB\sin\theta$



Note :

(1) Torque will be minimum (= 0) when sinθ = min = 0, i.e., θ = 0°, i.e. 180° i.e., the plane of the coil is perpendicular to magnetic field i.e. normal to the coil is collinear with the field.

(2) Torque will be maximum (= BINA) when sinθ = max = 1, i.e., θ = 90° i.e. the plane of the coil is parallel to the field i.e. normal to the coil is perpendicular to the field.

Potential Energy

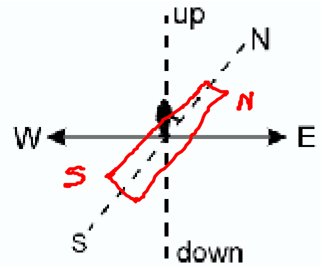
$$U = -\vec{M}.\vec{B} = -MBcos\theta$$

Magnet

Two bodies even after being neutral (showing no electric interaction) may attract / repel strongly if they have a special property. This property is known as magnetism. This force is called magnetic force. Those bodies are called magnets.

When a bar magnet is suspended at its middle, as shown, and it is free to rotate in the horizontal plane it always comes to equilibrium in a fixed direction.

One end of the magnet (say A) is directed approximately towards north and the other end (say B) approximately towards south. This observation is made everywhere on the earth. Due to this reason the end A, which points towards north direction is called NORTH POLE and the other end which points towards south direction is called SOUTH POLE. They can be marked as 'N' and 'S' on the magnet.



Pole Strength, Magnetic Dipole and Dipole Moment

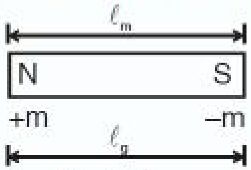
A magnet always has two poles 'N' and 'S' and like poles of two magnets repel each other and the unlike poles of two magnets attract each other they form action reaction pair.

North pole is treated as positive pole (or positive magnetic charge) and the south pole is treated as –ve pole (or –ve magnetic charge). They are quantitatively represented by their "POLE STRENGTH" +m and –m respectively (just like we have charges +q and –q in electrostatics).

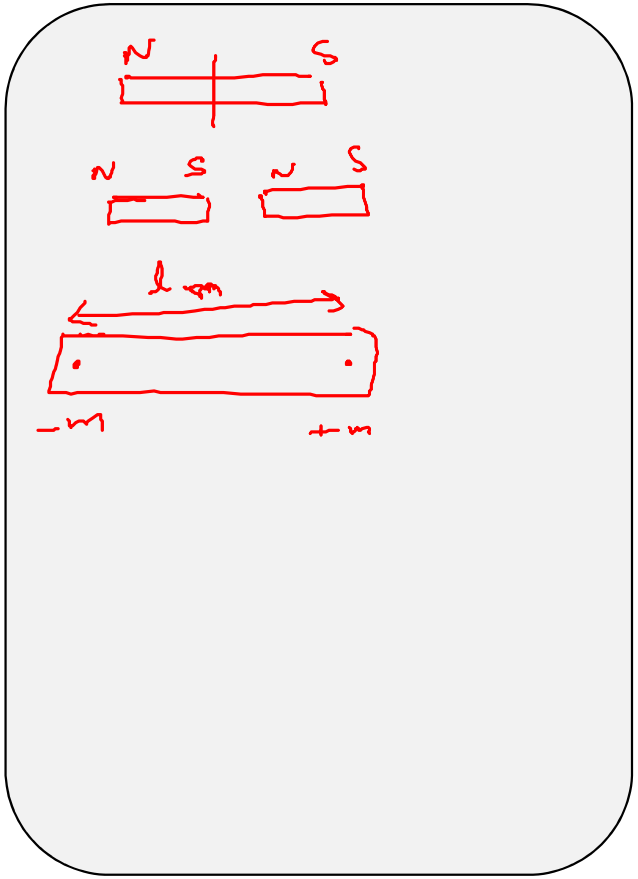
Pole strength is a scalar quantity and represents the strength of the pole hence, of the magnet also).

A magnet can be treated as a dipole since it always has two opposite poles (just like in electric dipole we have two opposite charges –q and +q). It is called MAGNETIC DIPOLE and it has a MAGNETIC DIPOLE MOMENT. It is represented by $\vec{M}$. It is a vector quantity.

It's direction is from –m to +m that means from 'S' to 'N')



$M = m.\ell_m$ here ℓ_m = magnetic length of the magnet. ℓ_m is slightly less than ℓ_g (it is geometrical length of the magnet = end to end distance). The 'N' and 'S' are not located exactly at the ends of the magnet. For calculation purposes we can assume $\ell_m = \ell_g$ [Actually $\ell_m/\ell_g \simeq 0.84$].



Magnetic Field and Strength of Magnetic Field

The physical space around a magnetic pole has special influence due to which other pole experience a force. That special influence is called MAGNETIC FIELD and that force is called 'MAGNETIC FORCE'. This field is qualitatively represented by 'STRENGTH OF MAGNETIC FIELD' or "MAGNETIC INDUCTION" or "MAGNETIC FLUX DENSITY". It is represented by $\vec{B}$. It is a vector quantity.

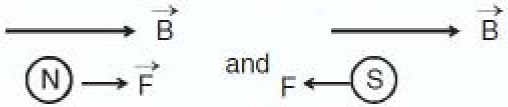
Definition of $\vec{B}$: The magnetic force experienced by a north pole of unit pole strength at a point due to some other poles (called source) is called the strength of magnetic field at that point due to the source.

Mathematically,

$$\boxed{\vec{B} = \frac{\vec{F}}{m}}$$

S.I. unit of $\vec{B}$ is **Tesla** or **Weber/m²** (abbreviated as T and Wb/m²).

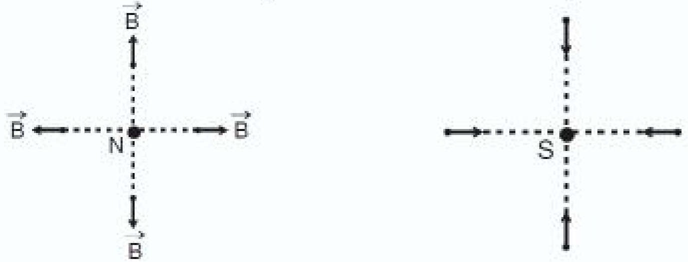
We can also write $\vec{F} = m\vec{B}$. According to this direction of on +ve pole (North pole) will be in the direction of field and on –ve pole (south pole) it will be opposite to the direction of $\vec{B}$.



Magnetic Field due to a Single Pole

$$B = \left(\frac{\mu_0}{4\pi}\right)\frac{m}{r^2}$$ (Similar to the case of a point charge in electrostatics)

Direction of B due to north pole and due to south poles are as shown



in vector form $\vec{\mathbf{B}} = \left(\frac{\mu_0}{4\pi}\right)\frac{m}{r^3}\vec{r}$

here m is with sign and $\vec{r}$ = position vector of the test point with respect to the pole.

$E = K\frac{q}{r^2}$

$K = \frac{1}{4\pi\varepsilon_0}$

In mag. field

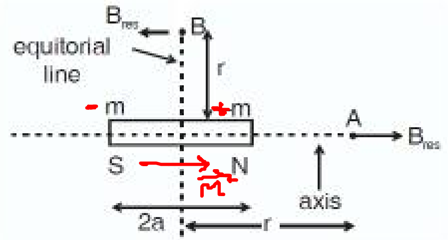
$\frac{1}{\varepsilon_0} \rightarrow \mu_0$

$K = \frac{\mu_0}{4\pi}$

Magnetic Field due to a Bar Magnet

at A (on the axis) $= 2\left(\frac{\mu_0}{4\pi}\right)\frac{\vec{M}}{r^3}$ for a << r

at B (on the equatorial) $= -\left(\frac{\mu_0}{4\pi}\right)\frac{\vec{M}}{r^3}$ for a << r



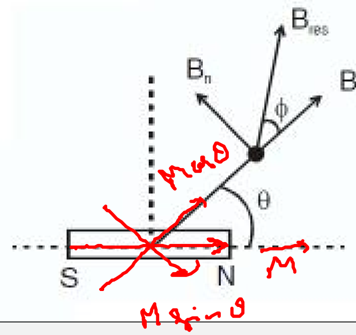
At General point :

$B_r = 2\left(\frac{\mu_0}{4\pi}\right)\frac{M\cos\theta}{r^3}$

$B_n = \left(\frac{\mu_0}{4\pi}\right)\frac{M\sin\theta}{r^3}$

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

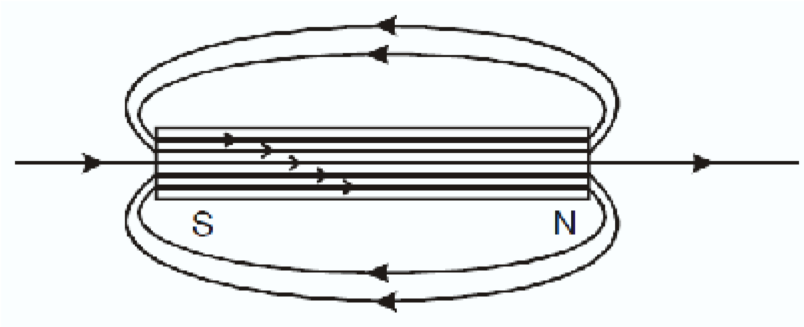
$\tan\phi = \frac{B_n}{B_r} = \frac{\tan\theta}{2}$

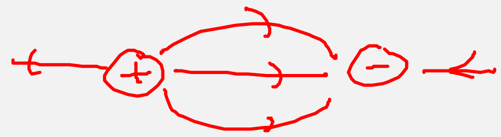


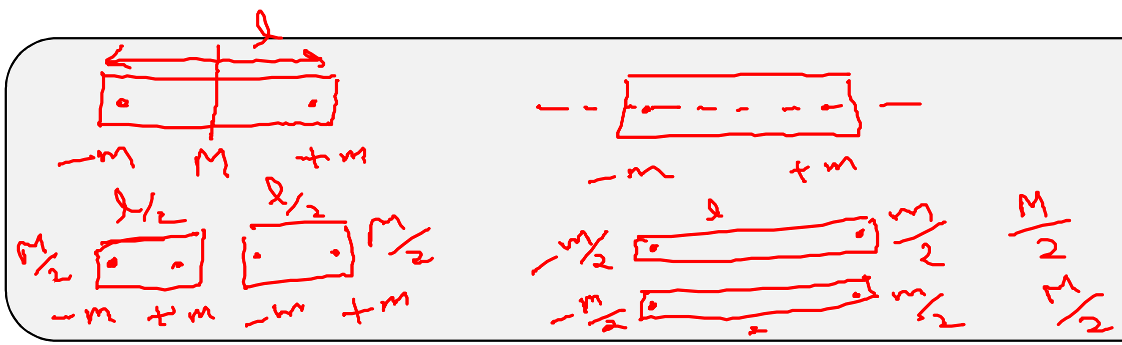
$E_{axis} = \frac{2k\vec{p}}{r^3}$

$B_{axis} = 2 \cdot \frac{\mu_0}{4\pi} \cdot \frac{\vec{M}}{r^3}$

Magnetic Lines of Force of a Bar Magnet





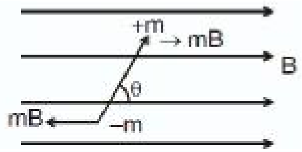


Magnet in an External Uniform Magnetic Field

$F_{res} = 0$ (for any angle)

$\tau = MB \sin\theta$

*here θ is angle between $\vec{B}$ and $\vec{M}$



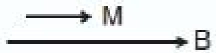
Note :

- $\vec{\tau}$ acts such that it tries to make $\vec{M}$ parallel to $\vec{B}$.
- $\vec{\tau}$ is same about every point of the dipole
- it's potential energy is

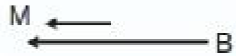
$U = -MB\cos\theta$

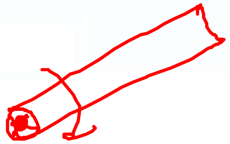
$= -\vec{M}\cdot\vec{B}$

$\theta = 0^\circ$ is stable equilibrium



$\theta = \pi$ is unstable equilibrium





for small 'θ' the dipole performs SHM about $\theta = 0^\circ$ position

Angular frequency of SHM

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

here $I = I_{cm}$ if the dipole is free to rotate

$= I_{hinge}$ if the dipole is hinged

$T = 2\pi\sqrt{\frac{I}{PE}}$

$W_{int.\ force\ (mag.)} = U_i - U_f$

$W_{ext\ force} = U_f - U_i$

Magnetism and Gauss's Law

The net magnetic flux through any closed surface is zero.

$$\oint \vec{B}.d\vec{S} = 0$$

It is a reflection of the fact that isolated magnetic poles (also called monopoles) are not known to exist.

Sources of Magnetism

- We have seen charges in motion (as in a current) produce magnetic fields. This is one source of magnetism.
- Another source is the electron itself. Electrons behave as if they were tiny magnets.
- Every electron in an atom behaves as a magnet in two ways, each having two magnetic dipole moments:
- Spin magnetic dipole moment - due to the “rotation” of an electron.
- Orbital magnetic dipole moment - due to the “revolution” of an electron about the nucleus.

Magnetization or Intensity of Magnetization (M)

- Magnetization: It is a measure of how a material respond when magnetic field is applied to it.
- Intensity of Magnetization (M): When a material is magnetized, it develops a net magnetic moment. The magnetic moment per unit volume is called intensity of magnetization.

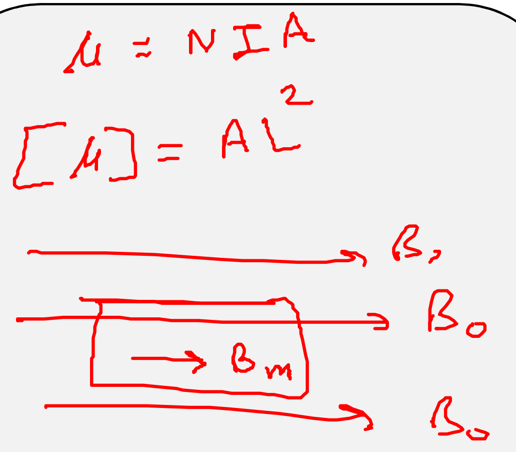
$$\vec{M} = \frac{\vec{\mu}_{total}}{V}$$

- M is a vector with dimensions $[L^{-1}A]$ and is measured in a units of Am^{-1}.
- Consider a magnetic material producing a field B_m in an external field B_0. The total field is the vector sum of the external field and the field generated by the material.

$$\vec{B} = \vec{B}_0 + \vec{B}_m$$

We define $\vec{B}_m = \mu_0 \vec{M}$

So, Total field will be, $\vec{B} = \vec{B}_0 + \mu_0 \vec{M}$



Magnetic Intensity (H)

Magnetic Intensity is defined as $\vec{H} = \frac{\vec{B}_0}{\mu_0} = \frac{\vec{B}}{\mu_0} - \vec{M}$

H has the same dimensions as M and is measured in units of A m^{-1}

Thus, the total magnetic field B is written as

$$\boxed{\vec{B} = \mu_0(\vec{H} + \vec{M})}$$

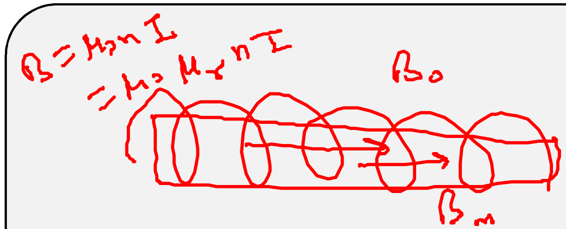
$\vec{B_0} = \vec{B} - \mu_0 \vec{M}$

Magnetic Susceptibility (χ)

- The total magnetic field inside any sample has two parts:
- One, due to external factors such as the current in the solenoid. This is represented by H.
- The other is due to the specific nature of the magnetic material, namely M.
- M can be influenced by external factors. This influence is mathematically expressed as

$$\vec{M} = \chi \vec{H}$$

- where χ is a dimensionless constant known as magnetic susceptibility.
- It is a measure of how a magnetic material responds to an external field.
- It is small and positive for materials, which are called paramagnetic.
- It is small and negative for materials, which are termed diamagnetic.
- In diamagnetic substance M and H are opposite in directions.



$$\vec{B} = \vec{B}_0 + \vec{B}_m = \mu_0 \vec{H} + \mu_0 \vec{M} = \mu_0(\vec{H} + \vec{M})$$

$$\vec{B} = \mu_0(\vec{H} + \chi \vec{H}) = \mu_0(1+\chi)\vec{H}$$

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Permeability (μ) and relative Permeability (μ_r)

We have seen that, net magnetic field is given by

$$\vec{B} = \mu_0(\vec{H} + \vec{M})$$

$$\vec{B} = \mu_0(1+\chi)\vec{H}$$

$$\vec{B} = \mu_0\mu_r\vec{H}$$

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

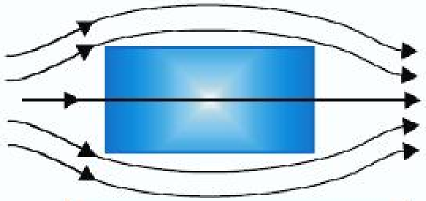
Where, $\mu_r = (1+\chi)$ is a dimensionless quantity called the relative magnetic permeability of the substance.

Magnetic permeability of the substance is μ and it has the same dimensions and units as μ_0

$$\mu = \mu_0\mu_r = \mu_0(1+\chi)$$

Diamagnetism

- These substance have tendency to move from stronger to the weaker part of the external magnetic field. In other words, magnetic field would repel a diamagnetic substance.
- Examples : bismuth, copper, lead, silicon, nitrogen (at STP), water and sodium chloride.
- The most exotic diamagnetic materials are *superconductors*. *These* are metals, cooled to very low temperatures which exhibits both *perfect conductivity and perfect diamagnetism. Here the field lines are completely* expelled! $\chi = -1$ and $\mu_r = 0$.
- A superconductor repels a magnet and (by Newton's third law) is repelled by the magnet. The phenomenon of perfect diamagnetism in superconductors is called the *Meissner effect*

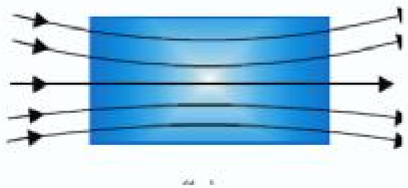


Diamagnetic
$-1 \le \chi < 0$
$0 \le \mu_r < 1$
$\mu < \mu_0$

$\mu_r = 1 + \chi$

Paramagnetism

- These substance get weakly magnetized when placed in an external magnetic field. They have tendency to move from a region of weak magnetic field to strong magnetic field, i.e., they get weakly attracted to a magnet.
- Examples : aluminium, sodium, calcium, oxygen (at STP) and copper chloride.



- Experimentally, one finds that the magnetization of a paramagnetic material is inversely proportional to the

$$M = C\frac{B_0}{T} \quad \text{or} \quad \chi = C\frac{\mu_0}{T}$$

- This is known as *Curie's law*. The constant *C is called Curie's constant*. χ and μ_r *depend not only on the material, but also* on the temperature.
- As field is increased or temp. is lowered, the magnetization increases until it reaches the saturation value, *at which point all the dipoles are* perfectly aligned with the field. Beyond this, Curie's law is no longer valid.

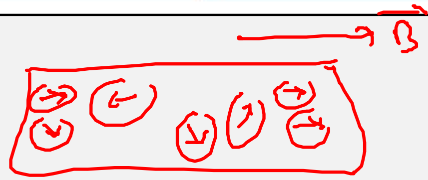
Paramagnetic

$0 < \chi < \varepsilon$

$1 < \mu_r < 1 + \varepsilon$

$\mu > \mu_0$

$M = \chi H$



Ferromagnetism

- These substance gets strongly magnetized when placed in an external magnetic field. They have strong tendency to move from a region of weak magnetic field to strong magnetic field, i.e., they get strongly attracted to a magnet.
- Examples : iron, cobalt, nickel, gadolinium, etc.
- The relative magnetic permeability is high.
- The ferromagnetic property depends on temperature. At high enough temperature, a ferromagnet becomes a paramagnet.
- The temperature of transition from ferromagnetic to paramagnetism is called the *Curie temperature* T_c.
- The susceptibility above the Curie temperature, i.e., in the paramagnetic phase is described by,

$$\chi = \frac{C}{T - T_c} \quad (T > T_c)$$

For $T > T_C$ paramagnetic behavior
For $T < T_C$ ferromagnetic behavior

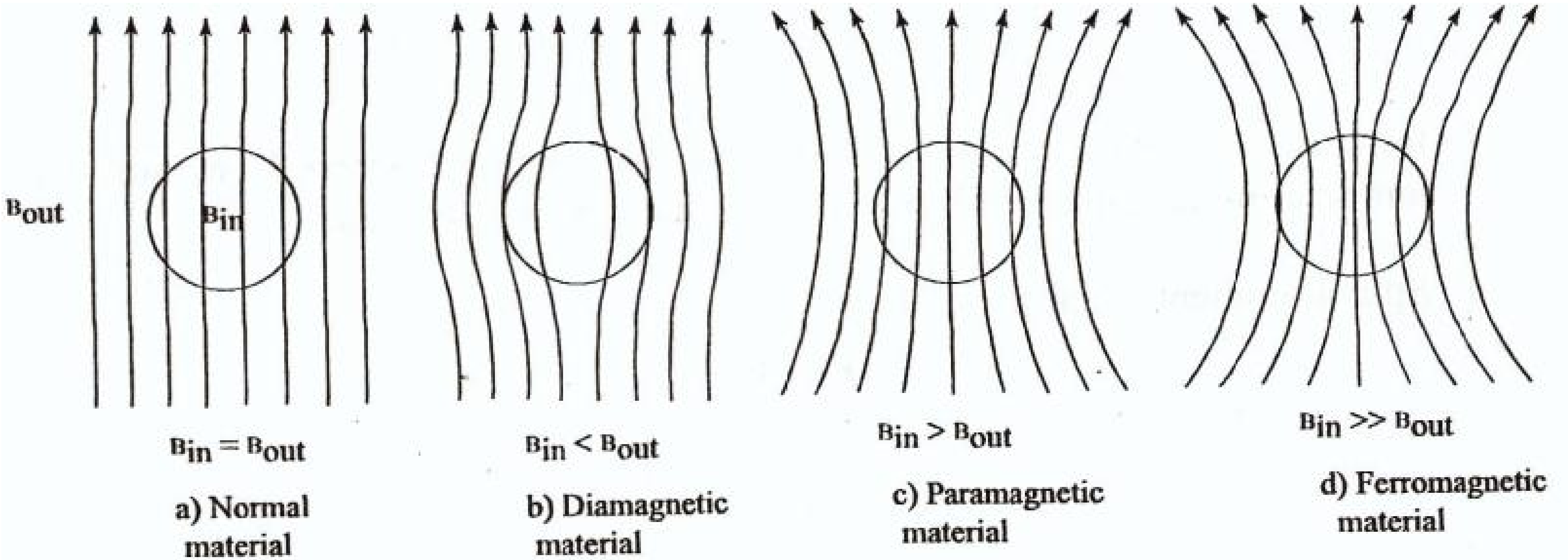
$\chi >> 1$

$\mu_r >> 1$

Hard and Soft Ferromagnets

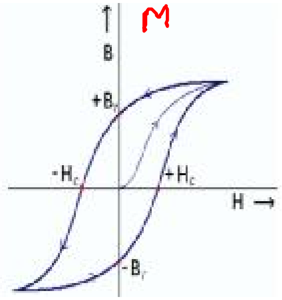
- **Hard Ferromagnets** : In some ferromagnetic material the magnetization persists even after removal of external magnetic field. Such materials are called *hard magnetic materials* or *hard ferromagnets*.
- Example : Alnico (an alloy of iron, aluminium, nickel, cobalt and copper), naturally occurring lodestone
- Used to form permanent magnets
- **Soft Ferromagnets** : In some ferromagnetic material the magnetization disappears on removal of external magnetic field. Such materials are called *soft feromagnetic materials*.
- Example : Soft Iron
- Used to form temporary magnets like electromagnets

Behavior of Field Line in Material



Hystetresis

- ***Hysteresis of ferromagnetic materials refers to the lag of magnetization behind the magnetizing field.***
- A hysteresis loop is a curve showing the change in magnetic induction of a ferromagnetic material with an external field.



- When the external magnetic field is increased the magnetic induction increases.
- Once magnetic saturation has been achieved, a decrease in the applied field back to zero results in a macroscopically permanent or residual magnetization, known as ***remanance***, M_r. The corresponding induction, B_r, is called ***retentivity*** or ***remanent induction*** of the magnetic material. This effect of retardation by material is called hysteresis.
- The magnetic field strength needed to bring the induced magnetization to zero is termed as **coercivity**, H_c. This must be applied anti-parallel to the original field.
- A further increase in the field in the opposite direction results in a maximum induction in the opposite direction. The field can once again be reversed, and the field-magnetization loop can be closed, this loop is known as hysteresis loop or B H plot or M H plot.

Area under hysteresis loop = energy loss.

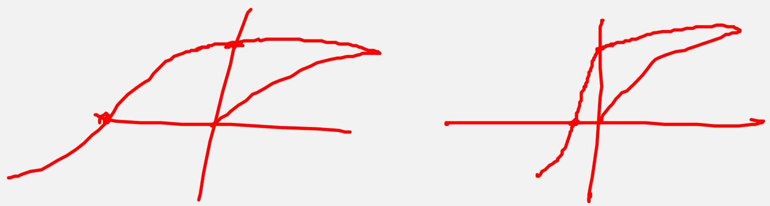
Permanent Magnets

- Substances which at room temperature retain their ferromagnetic property for a long period of time are called permanent magnets.

- An efficient way to make a permanent magnet is to place a ferromagnetic rod in a solenoid and pass a current. The magnetic field of the solenoid magnetizes the rod.

- Suitable material for permanent magnet should have high retentivity so that the magnet is strong and high coercivity so that the magnetization is not erased by stray magnetic fields, temperature fluctuations or minor mechanical damage.

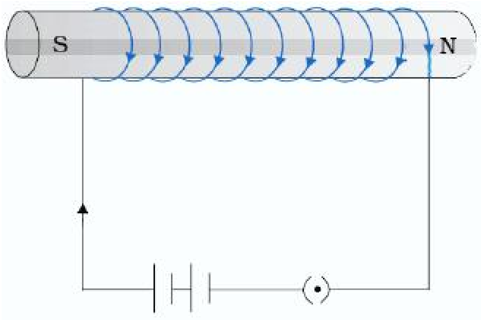
- Further, the material should have a high permeability.



Electromagnets

- An electromagnet is a type of magnet in which the magnetic field is produced by an electric current. The magnetic field disappears when the current is turned off.

- Electromagnets usually consist of wire wound into a coil. Core of electromagnets are made of ferromagnetic materials which have high permeability and low retentivity. Soft iron is a suitable material for electromagnets.



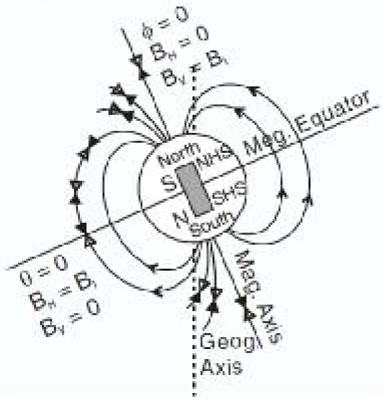
- Electromagnets are used in electric bells, loudspeakers and telephone diaphragms.

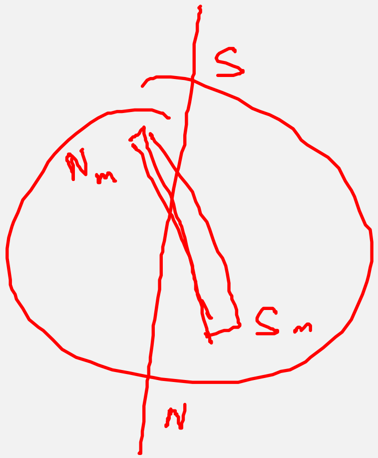
- Giant electromagnets are used in cranes to lift machinery, and bulk quantities of iron and steel.

Terrestrial Magnetism (Earth's Magnetism)

The idea that earth is magnetised was first suggested towards the end of the six-teenth century by Dr William Gilbert.

The earth behaves as a magnetic dipole inclined at a small angle (11.5°) to the earth's axis of rotation with its south pole pointing north. The lines of force of earth's magnetic field are shown in figure which are parallel to the earth's surface near the equator and perpendicular to it near the poles.





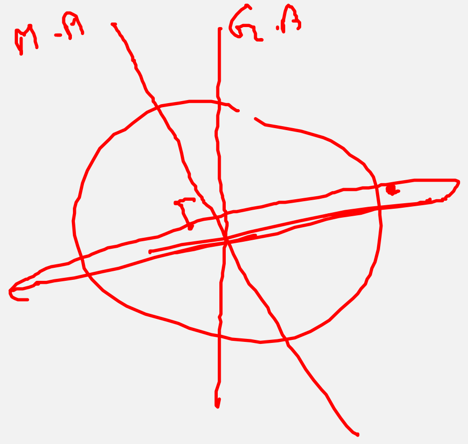
Some Important Terms

(a) The **magnetic meridian** at a place is not a line but a vertical plane passing through the axis of a freely suspended magnet, i.e., it is a plane which contains the place and the magnetic axis.

(b) The **geographical meridian** at a place is a vertical plane which passes through the line joining the geographical north and south, i.e., it is a plane which contains the place and earth's axis of rotation, i.e., geographical axis.

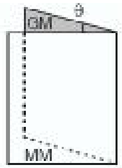
(c) The **magnetic Equator** is a great circle (a circle with the centre at earth's centre) on earth's surface which is perpendicular to the magnetic axis. The magnetic equator passing through Trivandrum in South India divides the earth into two hemispheres. The hemisphere containing south polarity of earth's magnetism is called the northern hemisphere (NHS) while the other, the southern hemisphere (SHS).

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

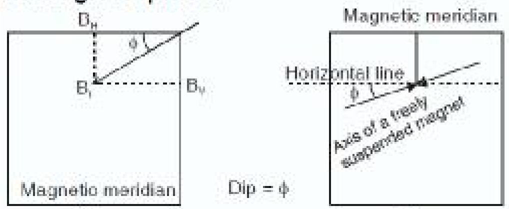


Elements of the Earth's Magnetism

(a) Variation or Declination θ : At a given place the angle between the geographical meridian and the magnetic meridian is called declination.



(b) Inclination or Angle of Dip ϕ : It is the angle which the direction of resultant intensity of earth's magnetic field subtends with horizontal line in magnetic meridian at the given place. Actually it is the angle which the axis of a freely suspended magnet (up or down) subtends with the horizontal in magnetic meridian at a given place.



(A) (B)

(c) Horizontal Component of Earth's Magnetic Field B_H : At a given place it is defined as the component of earth's magnetic field along the horizontal in the magnetic meridian. It is represented by B_H and is measured with the help of a **vibration** or **deflection magnetometer**.

If at a place magnetic field of earth is B_I and angle of dip ϕ, then

$$B_H = B_I \cos\phi \quad \text{and} \quad B_V = B_I \sin\phi$$

so that,

$$\boxed{\tan\phi = \frac{B_V}{B_H}} \quad \text{and} \quad I = \sqrt{B_H^2 + B_V^2}$$