Unit IV: Magnetism.

Magnetism is a physical phenomena which is produced by the motion of electric charges across a body, resulting in attractive and repulsive force between objects.

Magnetic pole: The preferred regions of attraction ~~between~~ near the ends of a magnet where the magnetic force due to the bar magnet is maximum are known as magnetic poles.

Properties of a magnet:

1) **Attractive property:** A magnet can attract small pieces of magnetic substances like iron, nickel, cobalt etc.

2) **Directive property:** A magnet suspended freely, aligns itself with the geographic N-S line.

3) Unlike poles attract and like poles repel.

4) Magnetic poles exist in pairs.

5) **Inductive property:** When a piece of soft iron, cobalt is placed near a magnet, it gets magnetised.

* **Magnetic field:** The space around a bar-magnet upto which its influence can be felt is known as magnetic field.

Unit: Tesla.

* Magnetic lines of force:

The imaginary lines which represent the magnetic field around a magnet are known as magnetic lines of force.

* Properties of magnetic lines of force:

1) Magnetic lines of force originate at the N-pole and terminate at the south pole.

2) Magnetic lines of force form closed loops.

3) They are not straight in nature but curved.

4) Magnetic lines or magnetic field are formed due to a bar-magnet or current carrying wire.

* Theory of magnetism:

Magnetism is a fundamental force of nature that arises due to the motion of electric charges. The theory of magnetism explains the origin, behaviour and effects of magnetic fields and magnetic materials.

At the atomic level, magnetism originates from two sources:

- Electron spin.
- Orbital motion of electrons around the nucleus.

In most atoms, magnetic effects cancel out, but in some (like iron, cobalt, nickel) unpaired electrons align to produce a net magnetic moment.

* **Induced magnetism:**

Induced magnetism is the process by which a material becomes magnetized when placed in a magnetic field.

When a magnetic material like iron, cobalt or nickel, is placed near or inside of magnetic field, it temporarily becomes a magnet.

* **Inverse Square Law of Magnetism:**

Suppose two magnetic poles of pole strength m_1 & m_2 are placed at a distance 'r' apart. The force of attraction or repulsion between them is:

(a) directly proportional to the product of magnetic pole strength.

$$F \propto m_1 m_2 \rightarrow (1)$$

(b) inversely proportional to the square of distance between them.

$$F \propto \frac{1}{r^2} \rightarrow (2)$$

from (1) & (2): $F \propto \frac{m_1 m_2}{r^2}$

$\Rightarrow F = k \frac{m_1 m_2}{r^2}$, where k is the const of proportionality

In S.I units, $k = \frac{\mu_0}{4\pi} = 10^{-7}\ Wb\ A^{-1} m^{-1}$

$\therefore \boxed{F = \frac{\mu_0}{4\pi} \frac{m_1 m_2}{r^2}}$ μ_0 is called permeability of free space.

Permeability:

Magnetic permeability (μ) is the ability of a material to support the formation of a magnetic field within itself.

Types of magnetic materials:

(1) Dia-magnetic substances:

1) A diamagnetic substance is feebly repelled by a magnet.
2) When a rod of diamagnetic substance is suspended inside a magnetic field, it slowly aligns itself at right angles to the field.
3) When a diamagnetic substance is placed inside a magnetic field, the magnetic field lines become less dense inside it.
4) The magnetic susceptibility (χ_m) has a small -ve value.

$$\chi_m < 0.$$

5) They don't obey Curie's law. Ex: Bismuth, copper, silver etc.

(2) Para-magnetic substance:

1) A para-magnetic substance is feebly attracted by a magnet.
2) When a rod of para-magnetic substance is suspended inside a magnetic field, it slowly aligns itself parallel to the field.
3) When a para-magnetic substance is placed inside a magnetic field the magnetic field lines become more dense inside it.

4) The magnetic susceptibility (χ_m) has a small +ve value.

$$\chi_m > 1$$

5) They obey Curie's law.

Ex: Aluminium, Magnesium, Sodium, Calcium etc.

(3) Ferro-magnetic substances:

1) A ferro-magnetic substance is strongly attracted by a magnet.
2) When a rod of ferro-magnetic substance is suspended inside a magnetic field, it quickly aligns itself with the field.
3) When a ferro-magnetic substance is placed inside a magnetic field, then field lines rush through it.
4) The magnetic susceptibility (χ_m) has a large +ve value.

$$\chi_m >> 1.$$

5) They obey Curie's law.

Ex: Iron, copper, Nickel. etc.

* Magnetic potential:

Magnetic potential is a concept used to describe magnetic fields using potential functions. They are mainly of two types:

(a) Magnetic Scalar Potential.

(b) Magnetic Vector potential.

* Magnetic Intensity:

Magnetic intensity (H) is the amount of magnetizing force applied to a magnetic material.

Unit: A/m. $[H] = \frac{[A]}{[L]} = [AL^{-1}]$

* Tangent law:

The tangent law is used in magnetism to determine the resultant magnetic field when two magnetic fields act perpendicularly to each other.

When a magnetic needle, is under the influence of two perpendicular magnetic fields the needle comes to rest at an angle θ such that:

$$\boxed{\tan\theta = \frac{B_2}{B_1}}$$

* Deflection Magnetometer:

A deflection magnetometer is an instrument used to measure the magnetic field strength by observing the deflection angle of a magnetic needle in the presence of magnetic fields.

* Terrestrial magnetism:

Terrestrial magnetism refers to the magnetic field of the Earth. The Earth behaves like a giant magnet with its own magnetic field, which influences many natural processes.

- Earth's magnetic field: The Earth's magnetic field is mainly generated by the movement of the molten iron in the Earth's outer core (geo-dynamo effect). Due to this, the Earth consists of two poles: N-pole and S-pole.

* Components of Earth's magnetic field:

(1) Magnetic declination: It is the angle between the geographic meridian and magnetic meridian.

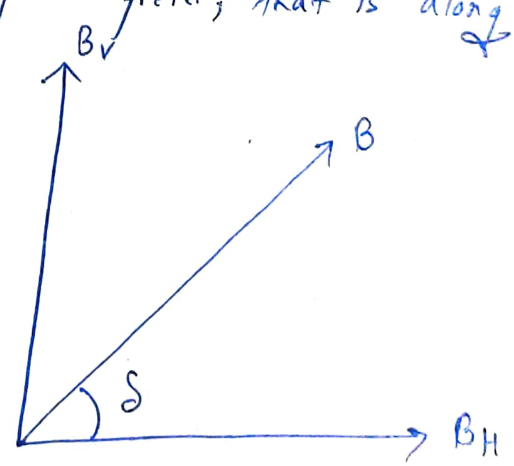
(2) Magnetic inclination or dip: It is the angle between the Earth's total magnetic field and its horizontal component. It is denoted by δ.

(3) Horizontal component of Earth's magnetic field (B_H):
It is the component of Earth's magnetic field, that is along the horizontal direction.

From the fig alongside:

$$B_H = B\sin\delta$$

$$B_V = B\cos\delta.$$



Magnetic dipole and dipole moment

- **Magnetic dipole:** An arrangement of two magnetic poles of equal and opposite strength separated by a certain distance is called magnetic dipole.

- **Magnetic length:** The distance between the two ~~and~~ poles of a bar magnet is called magnetic length. It is denoted by $\overrightarrow{2l}$ and its direction is from south to North.

- **Magnetic dipole moment** ($\vec{M}$)

The product of the strength of either pole and the distance between them is called magnetic dipole moment

$$\boxed{\vec{M} = m(\overrightarrow{2l})}$$

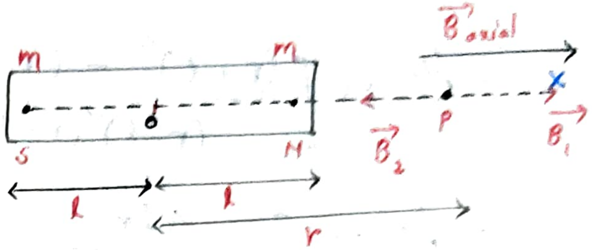
It is a vector quantity and its direction is from south to north.

Unit: Am^2

Dimension: $[AL^2]$.

Magnetic field at the axial point of a bar-magnet

Let us consider a bar-magnet NS having pole strength m. Let $2l$ be the length of the magnet and O be its centre. Let P be a point at a distance r from the centre of the bar-magnet.



Now, Magnetic field due to the N pole at the point P is

$$\vec{B_1} = \frac{\mu_0}{4\pi} \frac{m}{NP^2} \quad (\text{Along } PX)$$

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

Magnetic field due to the S pole at the point P is :

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

$$= \frac{\mu_0}{4\pi} \frac{m}{(r+l)^2}$$

Now : $|\vec{B_1}| > |\vec{B_2}|$

So, total magnetic field at the point P is given by :

$$\vec{B} = \sqrt{B_1^2 + B_2^2 + 2B_1B_2\cos 180^\circ}$$

$$= \sqrt{B_1^2 + B_2^2 - 2B_1B_2}$$

$$= \sqrt{(B_1 - B_2)^2}$$

$$= B_1 - B_2$$

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

$$= \frac{\mu_0}{4\pi} m \left[\frac{1}{(r-l)^2} - \frac{1}{(r+l)^2} \right]$$

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

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

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

$$= \frac{\mu_0}{4\pi} \frac{2Mr}{(r^2-l^2)^2} \quad \text{(Along PX)}$$

$$\therefore \boxed{|\vec{B}_{axial}| = \frac{\mu_0}{4\pi} \frac{2Mr}{(r^2-l^2)^2}}$$

Special case! If the point P very far away from the dipole (or length of dipole is very small)

then $r >> l$ or $r^2 - l^2 \simeq r^2$

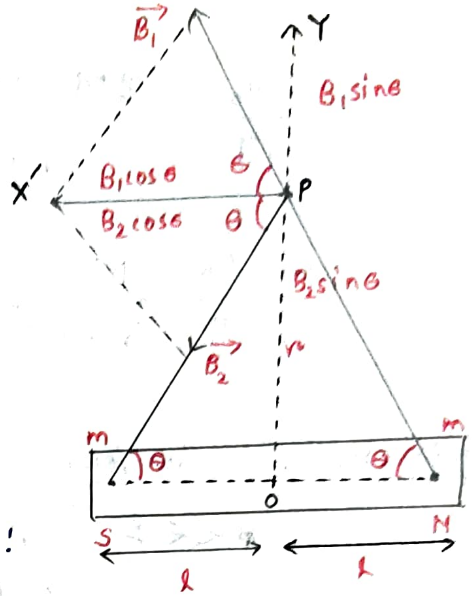
$$\therefore \vec{B}_{axial} = \frac{\mu_0}{4\pi} \frac{2Mr}{(r^2)^2}$$

$$= \frac{\mu_0}{4\pi} \frac{2M}{r^3} \quad \text{(Along PX)}$$

Magnetic field at the equatorial point of a magnetic dipole

Let us consider a bar-magnet NS having pole strength m and length 2l, and centre O. We have to determine magnetic field at a point P which lies on the equatorial plane of the dipole.

Magnetic field due to the North -pole :



$$\vec{B_1} = \frac{\mu_0}{4\pi} \frac{m}{NP^2} \quad (\text{Along } NP)$$

$$= \frac{\mu_0}{4\pi} \frac{m}{(r^2+l^2)} \quad (\text{along } NP)$$

Magnetic field due to the S-pole :

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

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

$$\therefore \quad |\vec{B_1}| = |\vec{B_2}|$$

Now we resolve the magnetic field $\vec{B_1}$ and $\vec{B_2}$ into components :

- $B_1 \sin\theta$ along Y
- $B_2 \sin\theta$ along Y'
- $B_1 \cos\theta$ and $B_2 \cos\theta$ along X'

Now the components $B_1 \sin\theta$ & $B_2 \sin\theta$ are equal and opposite and hence will cancel out each other.

So the resultant ~~of~~ magnetic field is only due to the $\cos\theta$ components.

$$B = B_1 \cos\theta + B_2 \cos\theta$$

$$= 2 B_1 \cos\theta$$

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

$$= 2 \frac{\mu_0}{4\pi} \frac{m}{(r^2+l^2)} \cdot \frac{l}{(r^2+l^2)^{1/2}}$$

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

$$= \frac{\mu_0}{4\pi} \frac{M}{(r^2+l^2)^{3/2}} \quad (\text{along } PX')$$

Special case: If the length of the dipole is very small

$$r >> l$$

$$r^2 + l^2 \simeq r^2$$

$$B_{equi} = \frac{\mu_0}{4\pi} \frac{M}{(r^2)^{3/2}}$$

$$\boxed{B_{equi} = \frac{\mu_0}{4\pi} \frac{M}{r^3}}$$