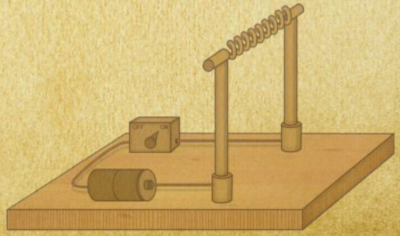
Welcome to

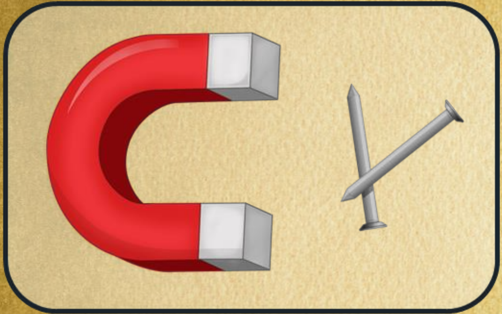
Aakash + BYJU'S NOTES

Magnetism and Matter



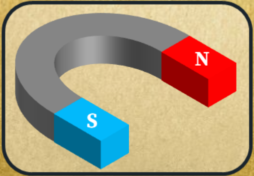
Introduction to Magnet

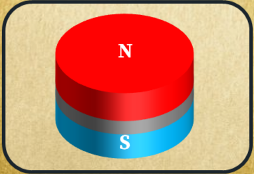
Magnet is a material that produces magnetic field and is able to attract materials like iron, nickel and cobalt.

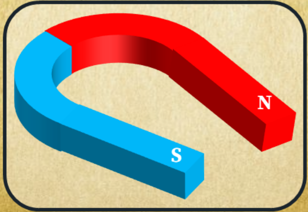


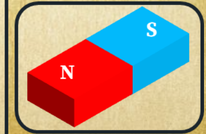
Types of Magnets

- Permanent Magnet
  - U-shaped Magnet
  - Circular Magnet
  - Horseshoe Magnet
  - Bar Magnet
- Temporary Magnet
- Electromagnet



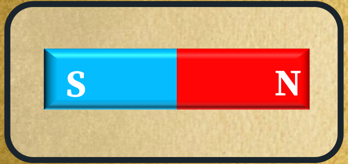


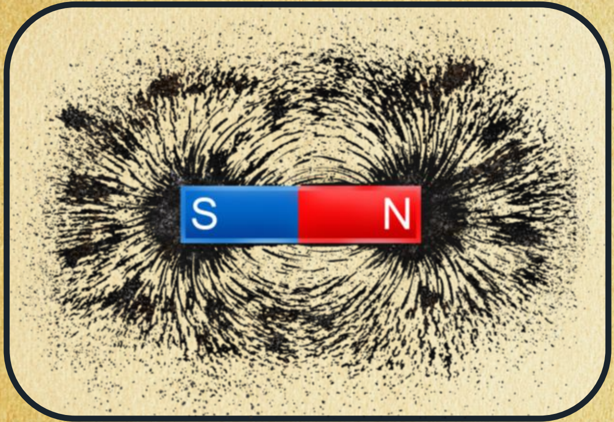




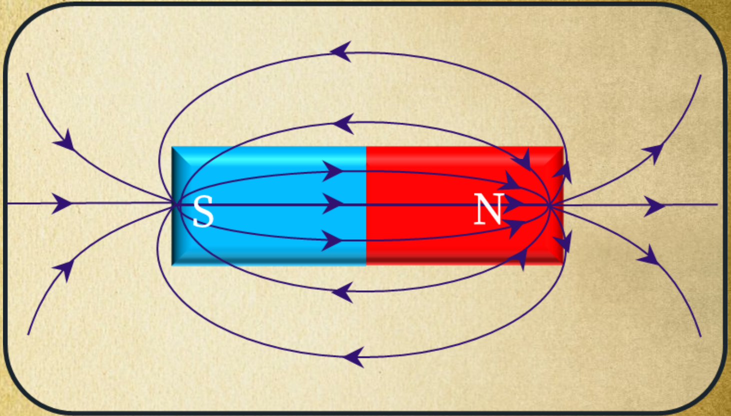
Bar Magnet

A bar magnet is a rectangular piece of object made up of iron, steel or any other substance that shows permanent magnetic properties.





Iron fillings around a bar magnet get aligned in a certain pattern.

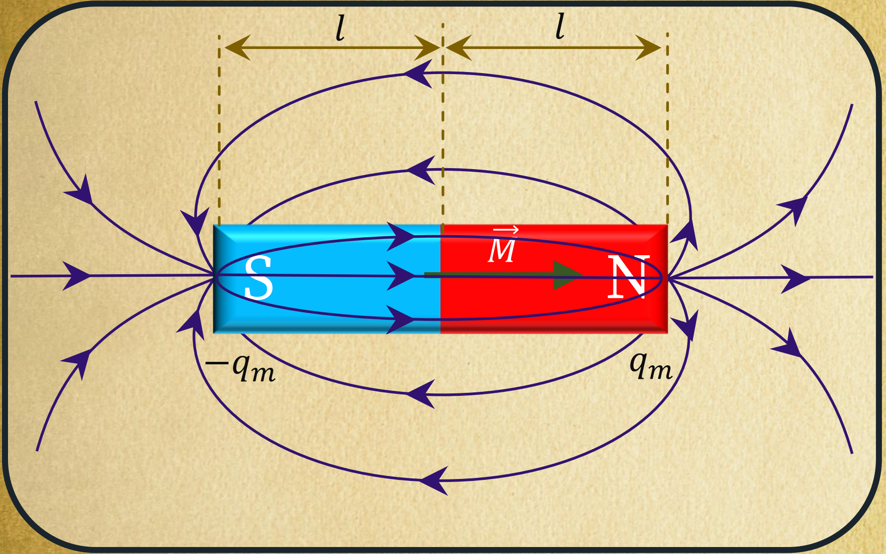


Field lines due to bar magnet

Properties of Magnetic Field Lines

- Magnetic field lines form closed loops.
- The tangent to the field line at a given point represents the direction of the net magnetic field at that point.
- Closer the field lines, stronger is the magnetic field.
- Magnetic field lines never intersect each other.

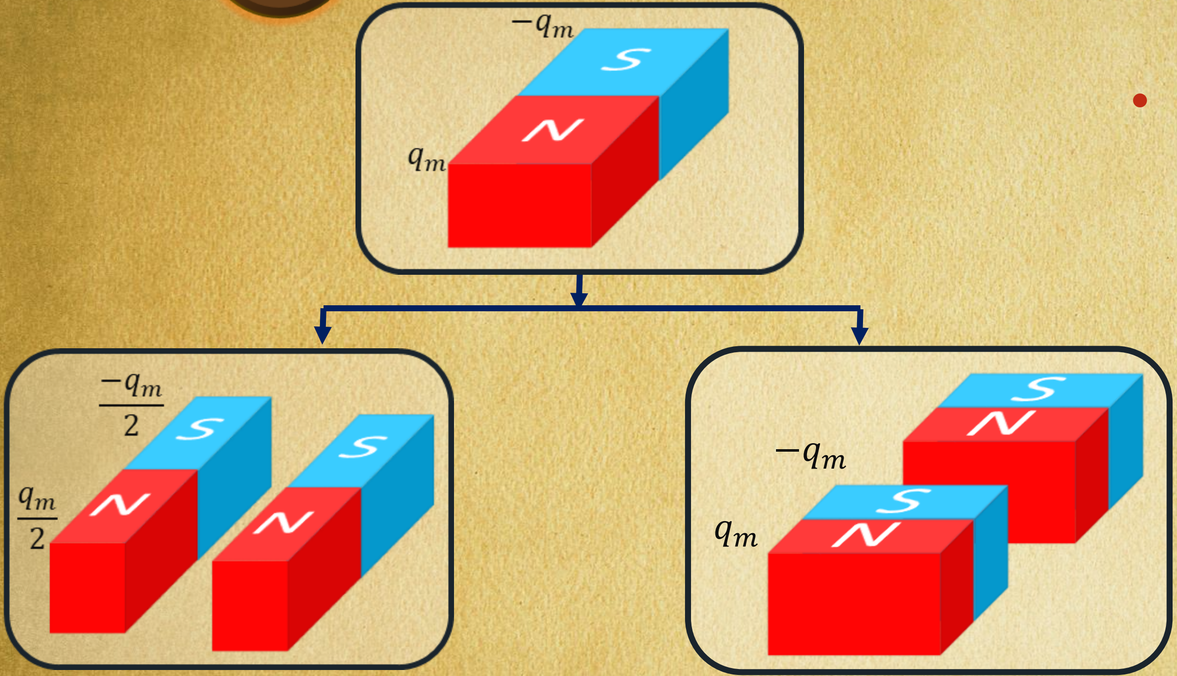
Magnetic Dipole Moment



$$\boxed{\vec{M} = q_m 2\vec{l}}$$

- Hypothetical $+q_m$ and $-q_m$ magnetic charge is assigned to north and south pole also called pole strength.
- The direction of length vector for a bar magnet is defined from the south pole to north pole.
- Direction of dipole moment is along the vector joining south pole to north pole.

Cutting of bar magnet



- Pole strength depends on:

1. Nature of material
2. Area of cross - section

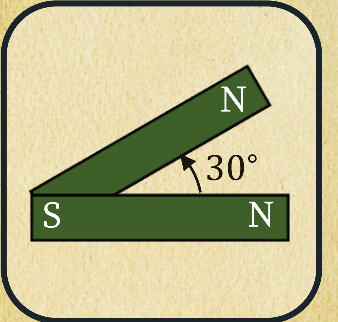
$$\boxed{q_m \propto \text{Area}}$$

- When a Bar magnet is cut in half perpendicular to the direction of dipole moment (along the area), the pole strength remains same. $\{q' = q_m\}$
- Dipole moment becomes half since length becomes half. $\{\vec{M} = q_m 2\vec{l}\}$
- Magnetic monopoles cannot exist.

Following figures show the arrangement of bar magnets in different configurations. Each magnet has magnetic dipole moment $\vec{M}$. Which configuration has highest net magnetic dipole moment?

$$|\vec{M}_{net}| = \sqrt{M^2 + M^2 + 2M^2 \cos 90^\circ}$$

$$= \sqrt{2}\,M$$



$$|\vec{M}_{net}| = \sqrt{M^2 + M^2 + 2M^2 \cos 30^\circ}$$

$$= \sqrt{2 + \sqrt{3}}\,M$$

$$|\vec{M}_{net}| = \sqrt{M^2 + M^2 + 2M^2 \cos 180^\circ}$$

$$= 0$$

$$|\vec{M}_{net}| = \sqrt{M^2 + M^2 + 2M^2 \cos 60^\circ}$$

$$= \sqrt{3}\,M$$

A bar magnet of magnetic moment M is placed at right angles to a magnetic induction B. If a force F is experienced by each pole of the magnet, the length of the magnet will be:

NEET 2003

Given: Magnetic Moment $= M$

Magnetic Field $= B$

Force $= F$

To find: L

Solution:

Torque experienced by a bar magnet when kept in a magnetic field is,

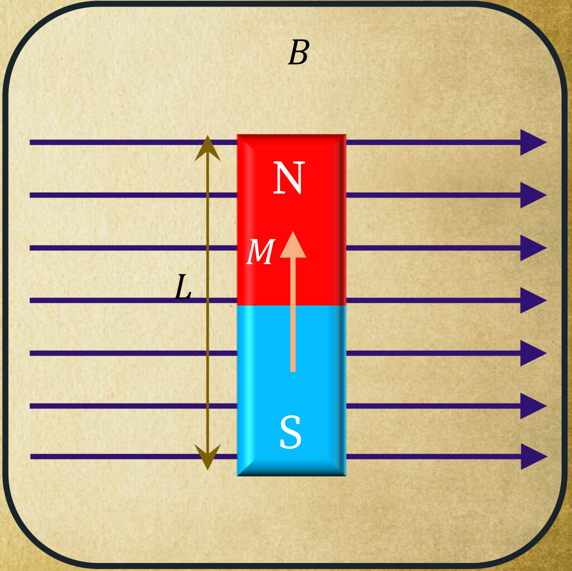
$$|\vec{\tau}| = |\vec{M} \times \vec{B}| = MB$$

(For $\theta = 90°$)

Mechanical torque is given by:

$$|\vec{\tau}| = |\vec{L} \times \vec{F}| = LF$$

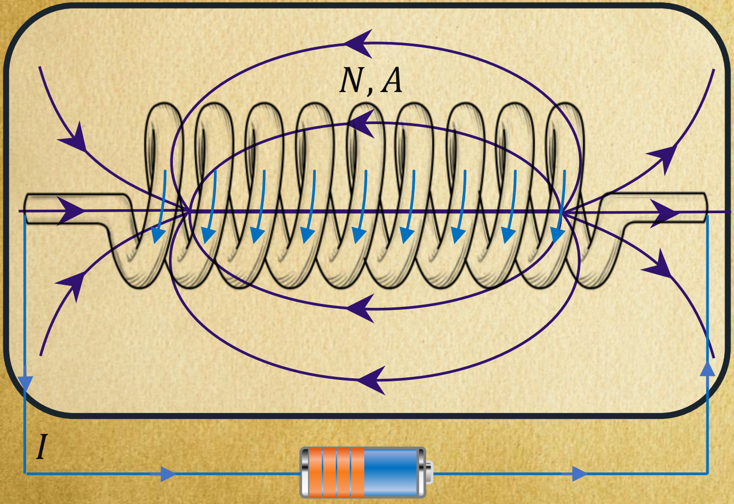
$$L = \frac{MB}{F}$$

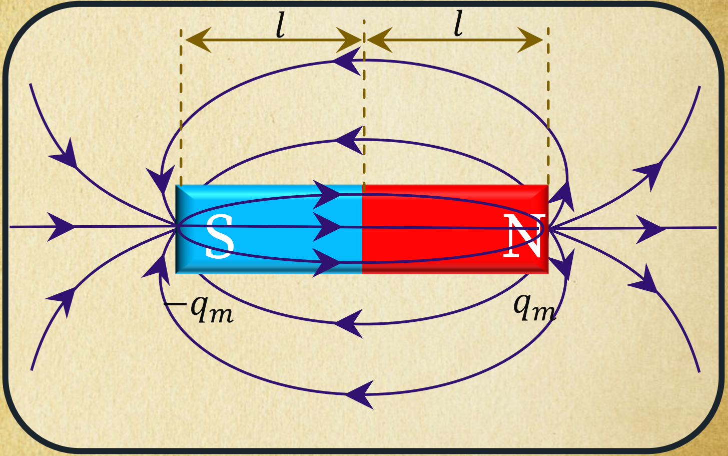


Bar Magnet as a Solenoid

The magnetic moment of a bar magnet is equal to the magnetic moment of an equivalent solenoid that produces the same magnetic field.

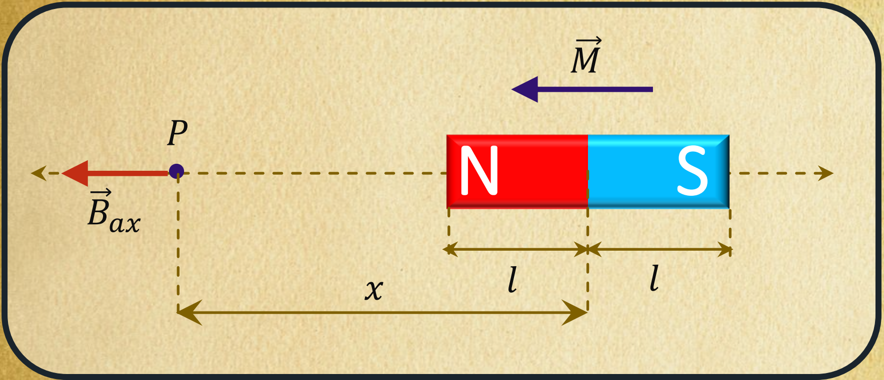
Magnetic moment $(M) = NIA$





$$M_{solenoid} = M_{bar}$$

Magnetic Field at an Axial Point



$$\vec{E}_{ax} = \left(\frac{1}{4\pi\epsilon_0}\right)\frac{2\vec{p}x}{(x^2 - l^2)^2}$$ (Electric field due to electric dipole)

$q \rightarrow q_m$ $\quad$ $\vec{p} \rightarrow \vec{M}$

$\vec{E} \rightarrow \vec{B}$ $\quad$ $\frac{1}{4\pi\epsilon_0} \rightarrow \frac{\mu_0}{4\pi}$

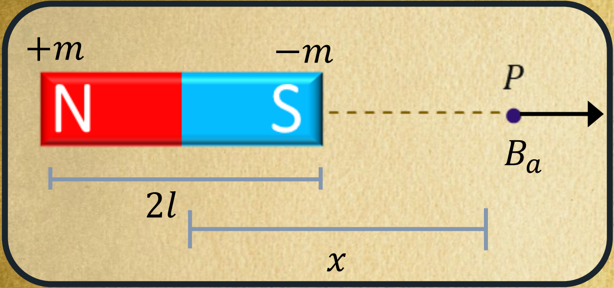
$$\vec{B}_{ax} = \left(\frac{\mu_0}{4\pi}\right)\frac{2\vec{M}x}{(x^2 - l^2)^2}$$ (Magnetic field due to magnetic dipole)

$x \gg l$

$$\vec{B}_{ax} = \left(\frac{\mu_0}{4\pi}\right)\frac{2\vec{M}}{x^3}$$

Magnetic field due to a bar magnet

Axial point

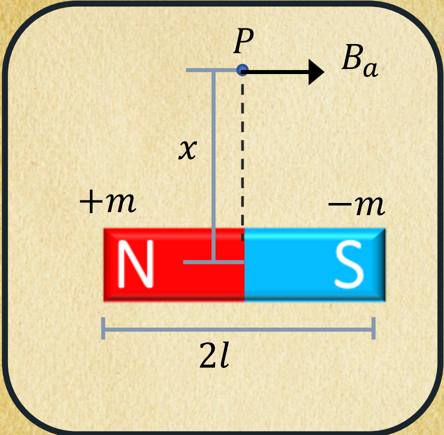


$$B_{ax} = \left(\frac{\mu_0}{4\pi}\right)\frac{2Mx}{(x^2 - a^2)^2}$$

For $x \gg l,$ at any axial point

$$\boxed{\vec{B}_{ax} = \left(\frac{\mu_0}{4\pi}\right)\frac{2\vec{M}}{x}}$$

Equatorial point

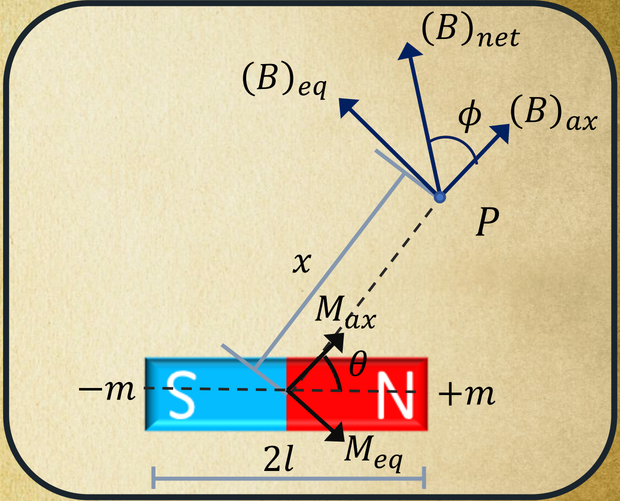


$$B_{eq} = \left(\frac{\mu_0}{4\pi}\right)\frac{-M}{(x^2 + a^2)^{\frac{3}{2}}}$$

For far off points, $x \gg l$

$$\boxed{\vec{B}_{eq} = \left(\frac{\mu_0}{4\pi}\right)\frac{-\vec{M}}{x^3}}$$

General point

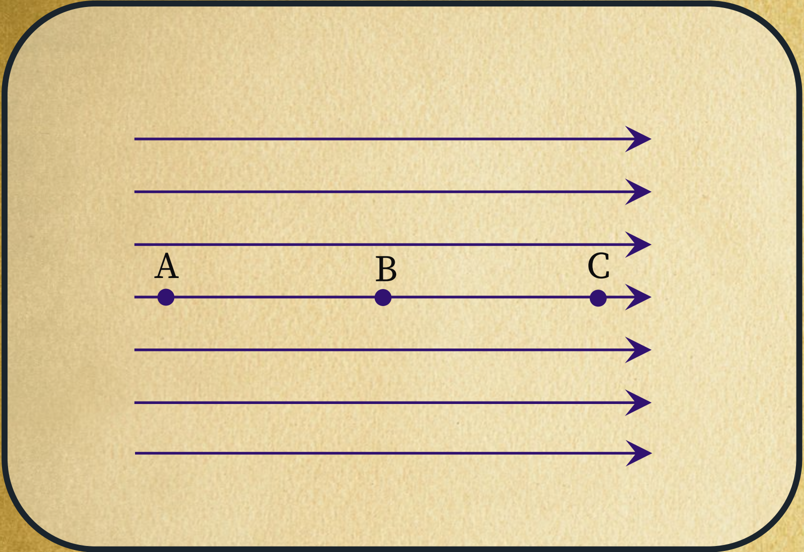


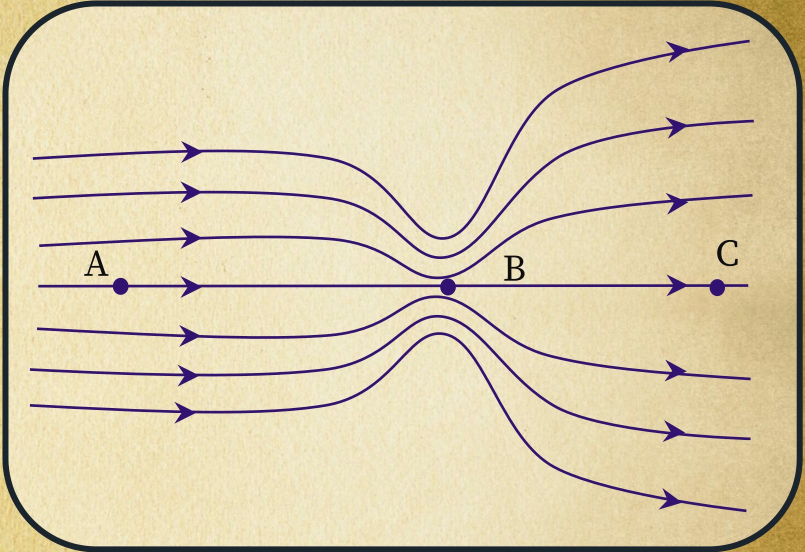
$$\boxed{|\vec{B}_{net}| = \frac{\mu_0\, M}{4\pi\, x^3}\sqrt{1 + 3\cos^2\theta}}$$

$$|\vec{B}_{net}| = \sqrt{B_{eq}^2 + B_{ax}^2}$$

$$\boxed{\tan\phi = \left|\frac{B_{eq}}{B_{ax}}\right| = \frac{\tan\theta}{2}}$$

Uniform and Non - Uniform Magnetic Field

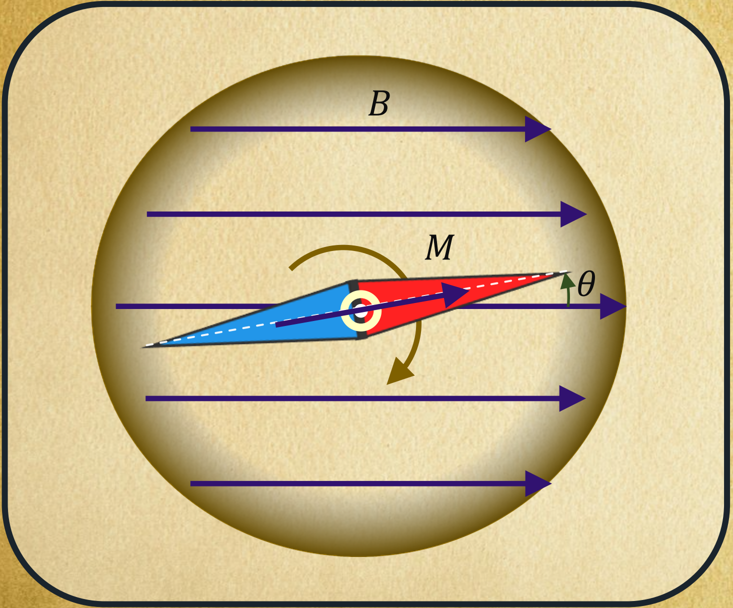




Uniform magnetic field has the same magnitude and direction throughout the region under consideration.

Non - Uniform magnetic field has different magnetic field at different points.

Torque experienced by a Magnet



Torque experienced by a bar magnet when kept in a magnetic field is:

$$\boxed{\tau = -MB\sin\theta}$$

Mechanical torque is given by:

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

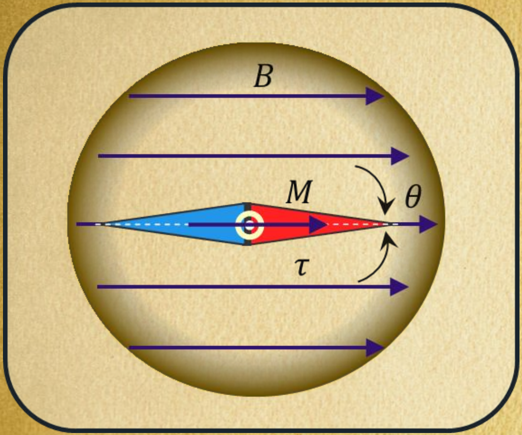
$$\boxed{-MB\sin\theta = I\frac{d^2\theta}{dt^2}}$$

(For small value of θ in radians)

$$\boxed{-MB\theta = I\frac{d^2\theta}{dt^2}}$$

$$\boxed{\omega^2 = \frac{MB}{I} \text{ and } T = 2\pi\sqrt{\frac{I}{MB}}}$$

Torque experienced by a Magnet



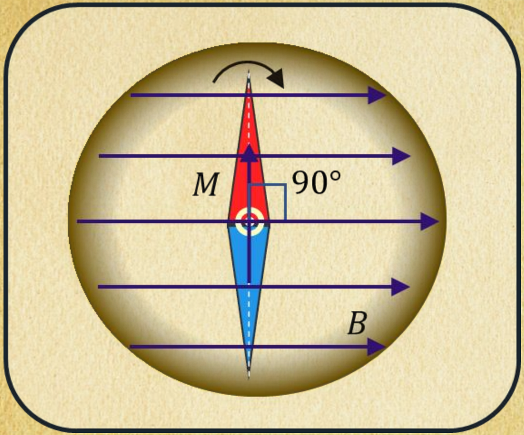
Case 1: $\theta = 0°$

$\tau = MB \sin\theta$

$\tau = MB \sin 0° = MB(0)$

$\boxed{\therefore \tau = 0}$

Needle is in equilibrium.



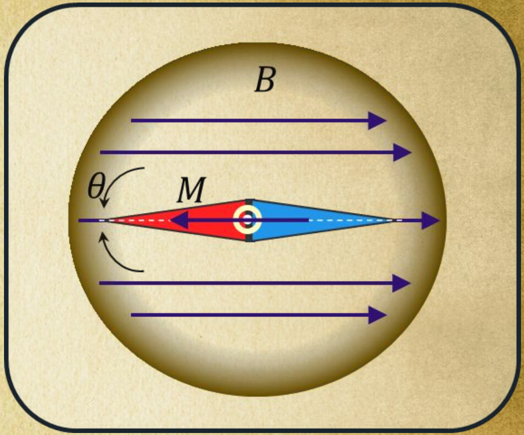
Case 2: $\theta = 90°$

$\tau = MB \sin\theta$

$\tau = MB \sin 90°$

$\boxed{\therefore \tau = MB}$

The net torque experienced will be maximum.



Case 3: $\theta = 180°$

$\tau = MB \sin\theta$

$\tau = MB \sin 180° = MB(0)$

$\boxed{\therefore \tau = 0}$

The needle is in equilibrium.

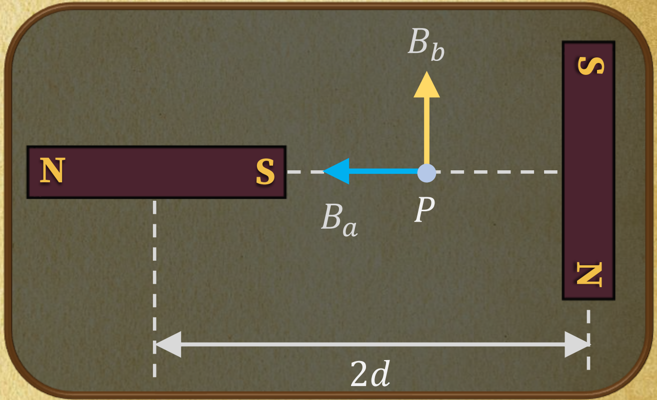
Figure shows two small identical magnetic dipoles a and b of magnetic moments M each, placed at a separation $2d$, with their axes perpendicular to each other. The magnetic field at the point P mid way between the dipoles is:

Given: Separation distance: $2d$

Magnetic moment of each magnet: M

To find: B_P

Solution:



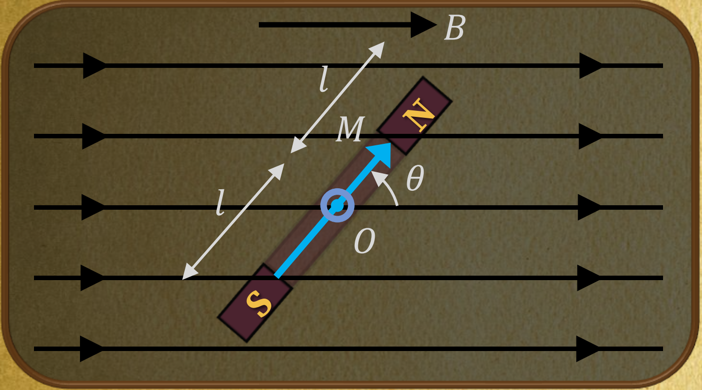
Magnetic field at P is given by:

$$B_a = \frac{\mu_0}{4\pi}\frac{2M}{d^3}$$

$$B_b = \frac{\mu_0}{4\pi}\frac{M}{d^3}$$

$$B_P = \sqrt{B_a^2 + B_b^2} = \frac{\sqrt{5}\mu_0 M}{4\pi d^3}$$

Dipole in Uniform Magnetic Field



Potential energy is given by: $U = -\vec{M} \cdot \vec{B} = -MB\cos\theta$

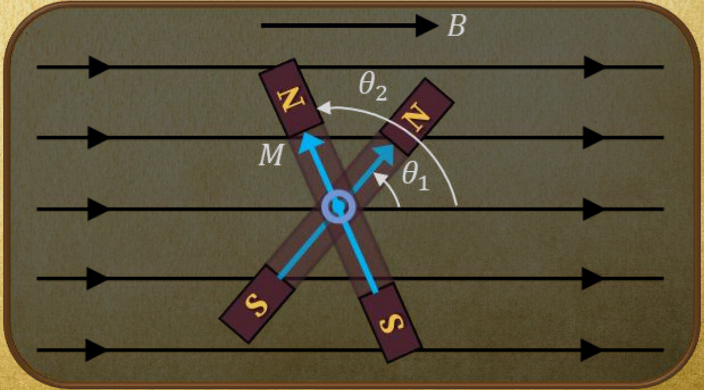
$\theta = 0°$	$\theta = 180°$	$\theta = 90°$
$U = -MB$	$U = MB$	$U = 0$
Stable Equilibrium	Unstable Equilibrium	

- External work done is given by:

$$W_{ext} = -MB(\cos\theta_2 - \cos\theta_1) = \Delta U$$

- Internal work done is given by:

$$W_{int} = MB(\cos\theta_2 - \cos\theta_1) = -\Delta U = -W_{ext}$$

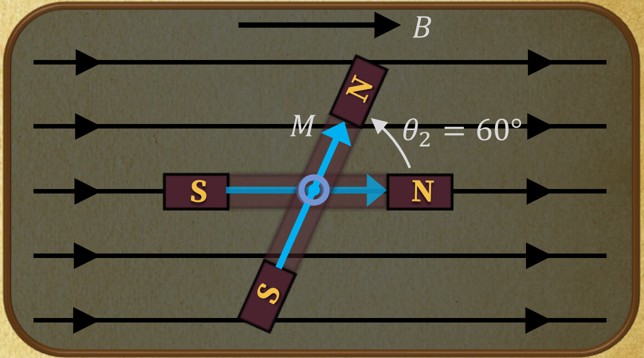


A bar magnet having a magnetic moment of $2 \times 10^4 JT^{-1}$ is free to rotate in a horizontal plane. A horizontal magnetic field, $B = 6 \times 10^{-4}\ T$, exists in the space. The work done in taking the magnet slowly from a direction parallel to the field to a direction 60° from the field is :

2009

Given: $M = 2 \times 10^4 JT^{-1}, B = 6 \times 10^{-4}\ T$

$\theta_1 = 0°, \theta_1 = 60°$



To find: W

Solution:

External work done is given by:

$$W = -MB(\cos\theta_2 - \cos\theta_1)$$

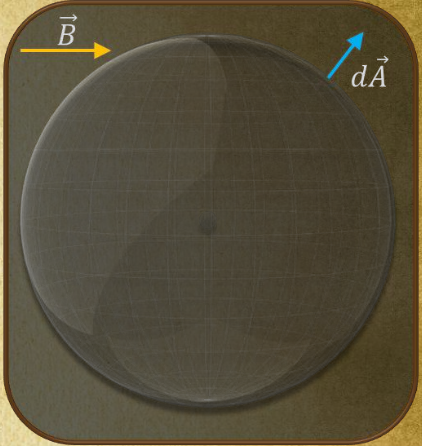
$$\Rightarrow W = -2 \times 10^4 \times 6 \times 10^{-4}(\cos 60° - \cos 0°)$$

$$\boxed{\therefore W = 6\ J}$$

Quantity	Electric Dipole	Magnetic Dipole
Charge	q	q_m
Dipole Moment	$\vec{p} = q(2\vec{l})$	$\vec{M} = q_m(2\vec{l})$
Field at an axial point	$\vec{E}_{ax} = \left(\frac{1}{4\pi\epsilon_0}\right)\frac{2\vec{p}x}{x^3}$	$\vec{B}_{ax} = \left(\frac{\mu_0}{4\pi}\right)\frac{2\vec{M}}{x^3}$
Field at equatorial point	$\vec{E}_{eq} = \left(\frac{1}{4\pi\epsilon_0}\right)\frac{-\vec{p}}{x^3}$	$\vec{B}_{eq} = \left(\frac{\mu_0}{4\pi}\right)\frac{-\vec{M}}{x^3}$
Field at general point	$\lvert\vec{E}_{net}\rvert = \left(\frac{1}{4\pi\epsilon_0}\right)\frac{\lvert\vec{p}\rvert}{x^3}\sqrt{1 + 3\cos^2\theta}$	$\lvert\vec{B}_{net}\rvert = \left(\frac{\mu_0}{4\pi}\right)\frac{\lvert\vec{M}\rvert}{x^3}\sqrt{1 + 3\cos^2\theta}$
Torque	$\vec{\tau}_{net} = \vec{p} \times \vec{E}$	$\vec{\tau}_{net} = \vec{M} \times \vec{B}$
Potential Energy	$U = -\vec{p} \cdot \vec{E}$	$U = -\vec{M} \cdot \vec{B}$
Work done in rotating in an external field	$W = -pE(\cos\theta_2 - \cos\theta_1)$	$W = -MB(\cos\theta_2 - \cos\theta_1)$

Gauss's Law for Magnetism

Gauss's Law: It states that the net magnetic flux through any closed surface is zero.



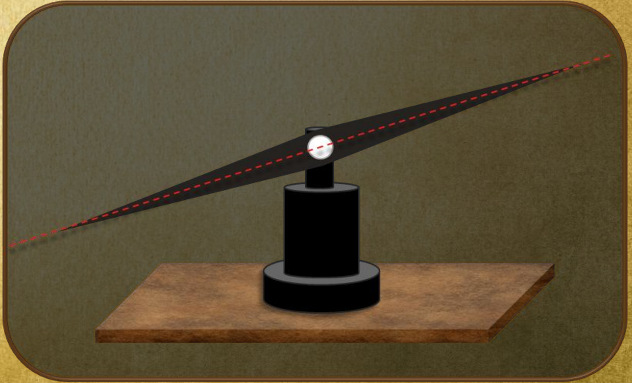
$$\boxed{\phi_B = \oint \vec{B} \cdot d\vec{A} = 0}$$

Reason: Magnetic monopoles do not exist

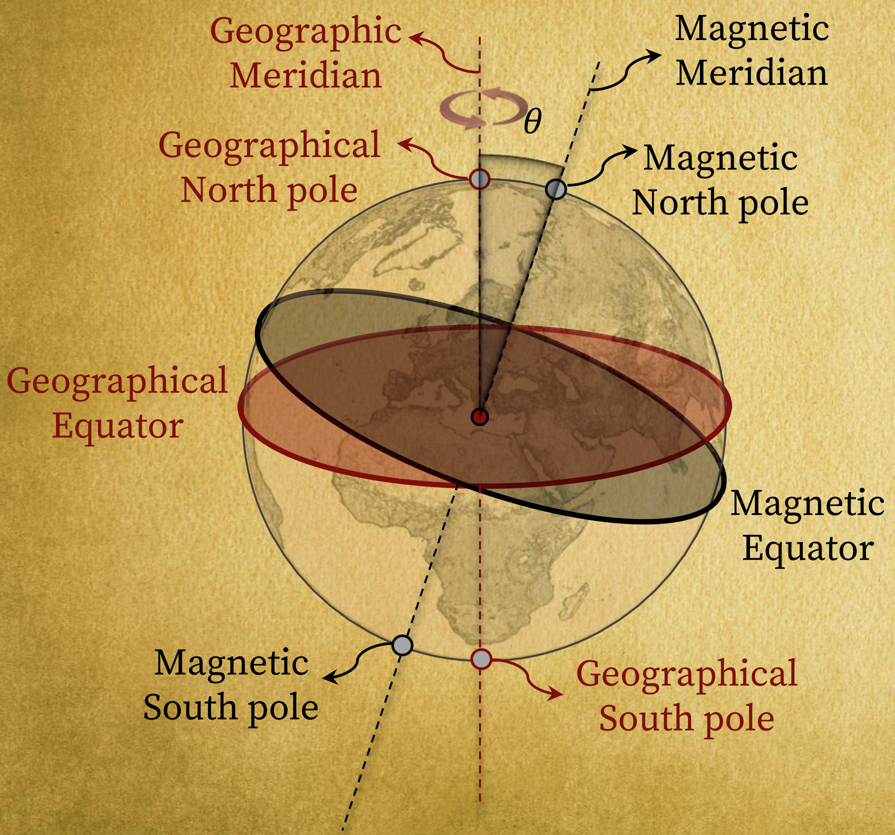
Earth's Magnetism

A free to rotate magnetic needle always orients itself along a particular direction

- Earth is a natural source of magnetic field.
- The most prominent cause of this magnetic field is the molten liquid deep inside the Earth.
- The motion of ionized particles, i.e., charged particles in the molten core of Earth constitutes convection currents.
- In case of the Earth, these currents behave like a coil and produce magnetic field in their surroundings.



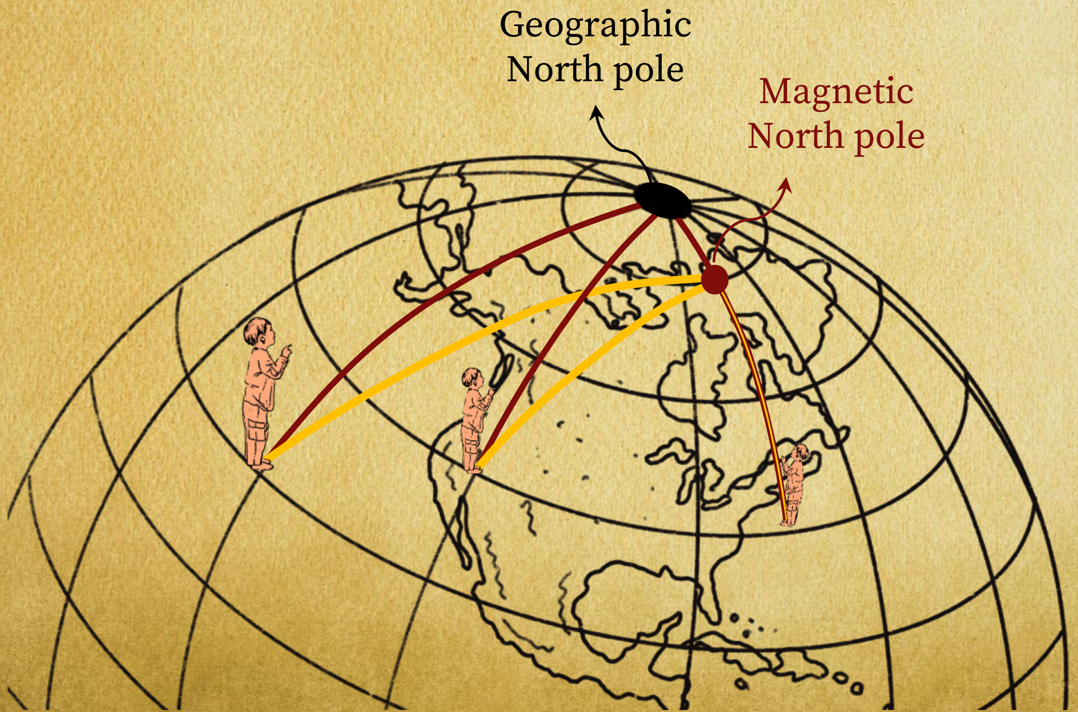
Geographical and Magnetic Meridian



- The Geographic meridian is an imaginary line joining the geographic north pole with the geographic south pole inside the Earth.
- Poles of Earth's magnet are opposite to the magnetic pole and geographical pole of the Earth.
- The magnetic meridian is an imaginary line joining the magnetic north pole with the magnetic south pole inside the Earth.

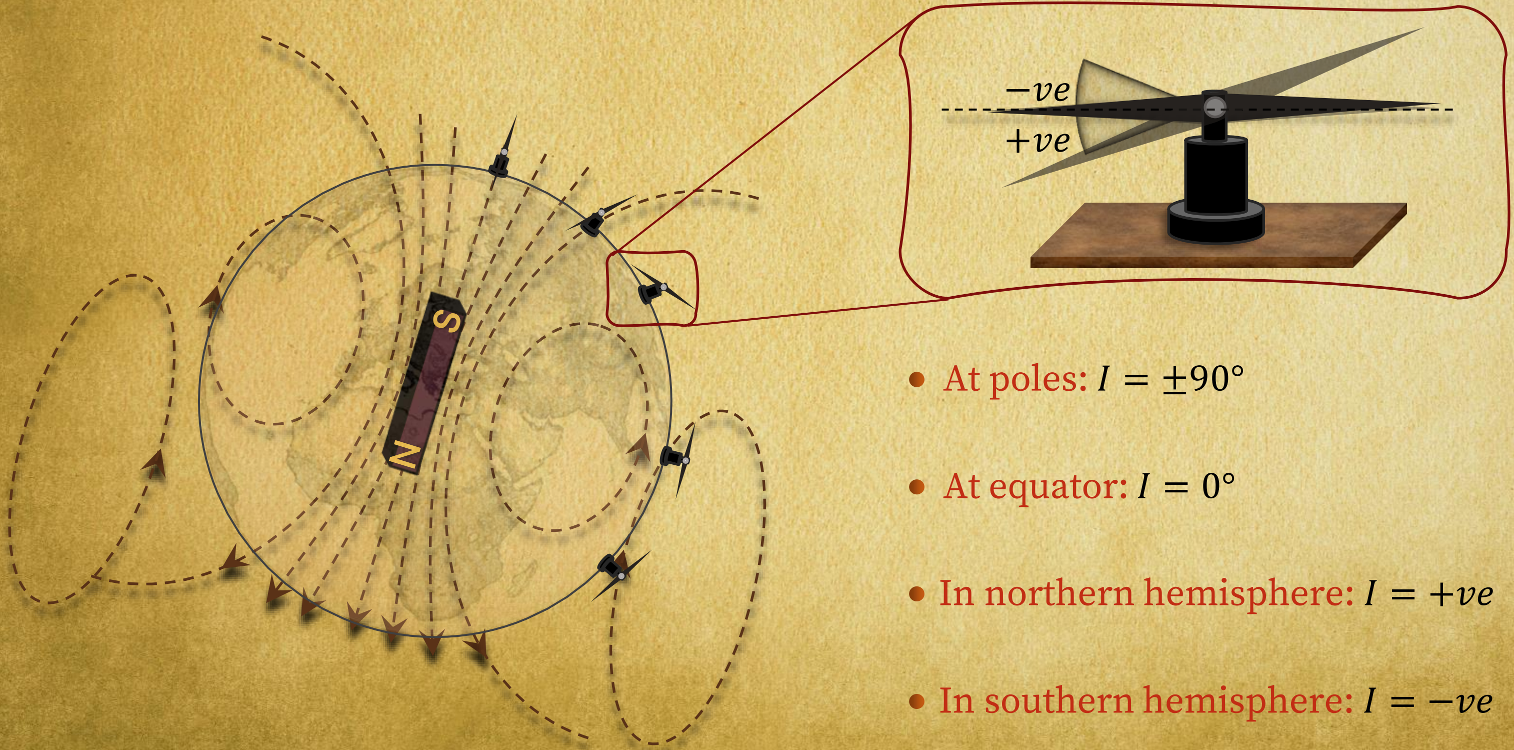
Magnetic Declination

The angle between true north (the line towards geographic north pole) and the direction towards which a compass points (horizontal component of the magnetic field) is called magnetic declination.



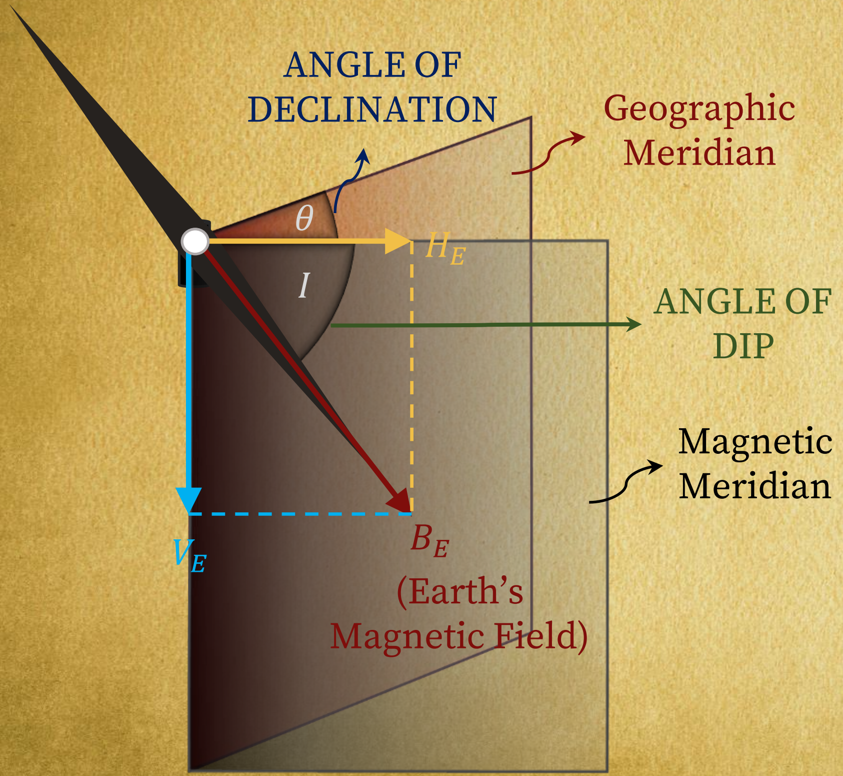
Magnetic Inclination (Angle of Dip)

Angle that is made by the Earth's magnetic field lines with the horizontal is called angle of dip.



- At poles: $I = \pm 90°$
- At equator: $I = 0°$
- In northern hemisphere: $I = +ve$
- In southern hemisphere: $I = -ve$

Components of Earth's Magnetic Field



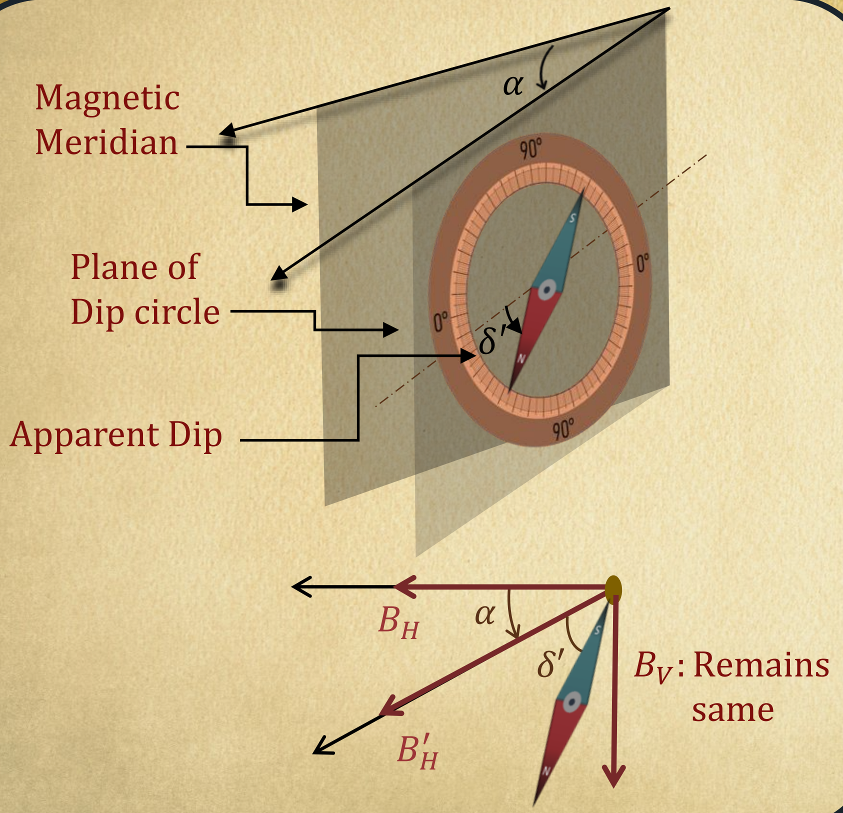
- Horizontal component of Earth's magnetic field is:

$$\boxed{H_E = B_E \cos I}$$

- Vertical component of Earth's magnetic field is:

$$\boxed{V_E = B_E \sin I}$$

Dip Circle



- True Dip: $\boxed{\delta = \tan^{-1}\frac{B_V}{B_H}}$

- Apparent Dip: $\boxed{\delta' = \tan^{-1}\frac{B_V}{B'_H}}$

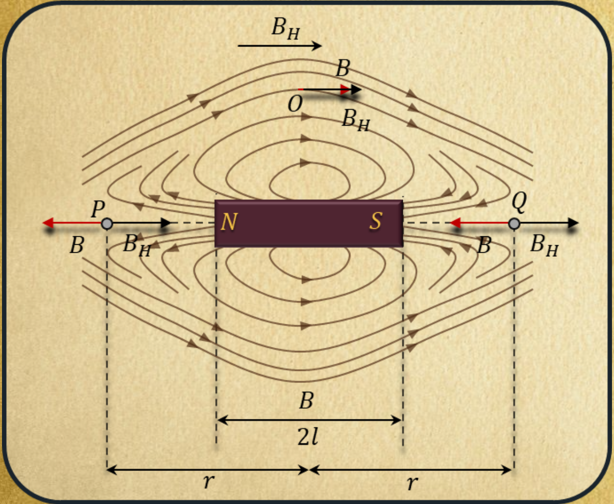
$$\because \tan\delta' = \frac{B_V}{B_H{'}} = \frac{B_V}{B_H\cos\alpha} = \frac{\tan\delta}{\cos\alpha}$$

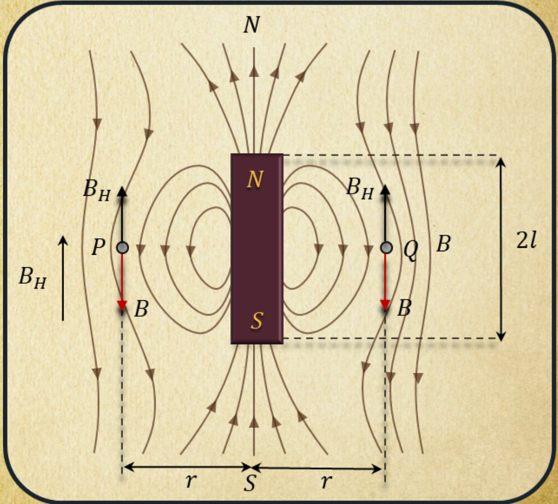
$$\boxed{\tan\delta = \tan\delta'\cos\alpha}$$

$$\boxed{\cot\delta' = \cot\delta.\cos\alpha}$$

Neutral Point

- At neutral points, net magnetic field due to the horizontal component of earth's magnetic field and the magnet is zero.
- Earth's magnetic field is equal and opposite to the magnetic field of the magnet.
- Two neutral points are equidistant from the magnet on its axis.





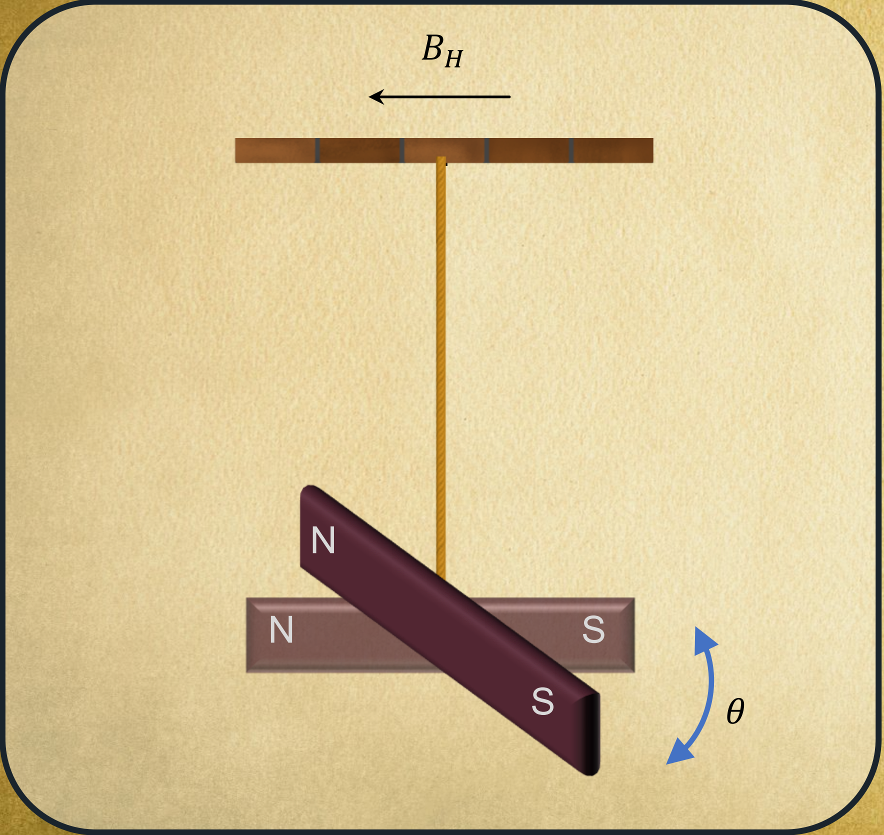
$$\frac{\mu_0}{4\pi}\frac{2M}{r^3} = B_H$$

- P and Q are neutral points.
- O is not a neutral point.

$$\frac{\mu_0}{4\pi}\frac{M}{r^3} = B_H$$

- Infinite neutral points exist.
- P and Q are neutral points.

Vibration (or) Oscillation Magnetometer



Torque is given by:

$$\tau = -MB_H \sin\theta$$

For small θ, $\sin\theta \approx \theta(in\ radian)$

$$\therefore \tau = -MB_H\theta \Rightarrow \alpha = -\frac{MB_H\theta}{I}$$

$$\boxed{\alpha = -\frac{MB_H}{I}\theta} \qquad \boxed{\alpha = -\omega^2\theta}$$

$$\boxed{\omega^2 = \frac{MB_H}{I} \Rightarrow T = 2\pi\sqrt{\frac{I}{MB_H}}} \quad \left\{T = \frac{2\pi}{\omega}\right\}$$

A vibration magnetometer placed in magnetic meridian has a small bar magnet. The magnet executes oscillations with a time period of $2\ s$ in earth's horizontal magnetic field of $24\ \mu T$. When a horizontal field of $18\ \mu T$ is produced opposite to the earth's field by placing a current carrying wire, the new time period of the magnet will be:

Given: Time period, $T = 2\ sec$
Earth's horizontal magnetic field, $B_{H1} = 24\ \mu T$ and $B_{H2} = 18\ \mu T$

Solution: $T = 2\pi\sqrt{\frac{I}{MB_H}} \Rightarrow T \propto \frac{1}{\sqrt{B_H}}$

$$\frac{T_2}{T_1} = \sqrt{\frac{B_{H1}}{B_{H2}}}$$

$$= \sqrt{\frac{24}{24-18}} = \sqrt{\frac{24}{6}} = 2$$

$$\boxed{T_2 = 4\ s}$$

Two bar magnets placed together in a vibration magnetometer take $3\ seconds$ for 1 vibration. If one magnet is reversed, the combination takes $4\ seconds$ for 1 vibration. Find the ratio of their magnetic moment.

Solution: Time period of oscillation of a bar magnet freely suspended is given by:

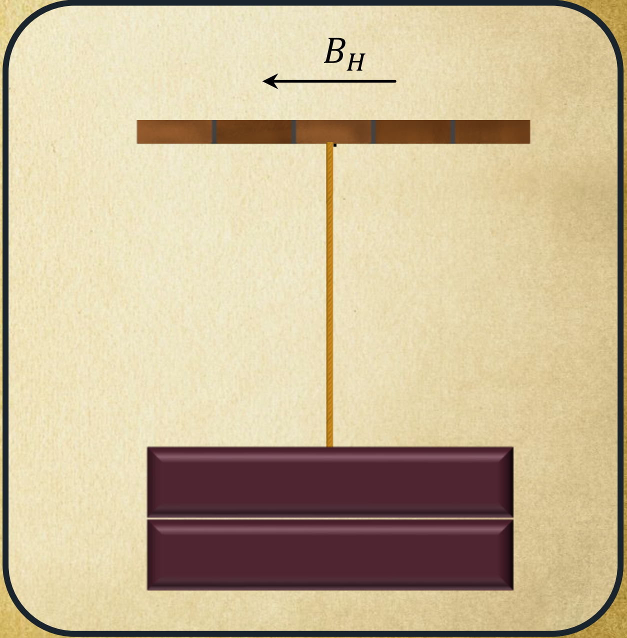
$$T = 2\pi\sqrt{\frac{I}{MB_H}}$$

Case 1: $T_1 = 2\pi\sqrt{\frac{I}{(M_1 + M_2)B_H}}$

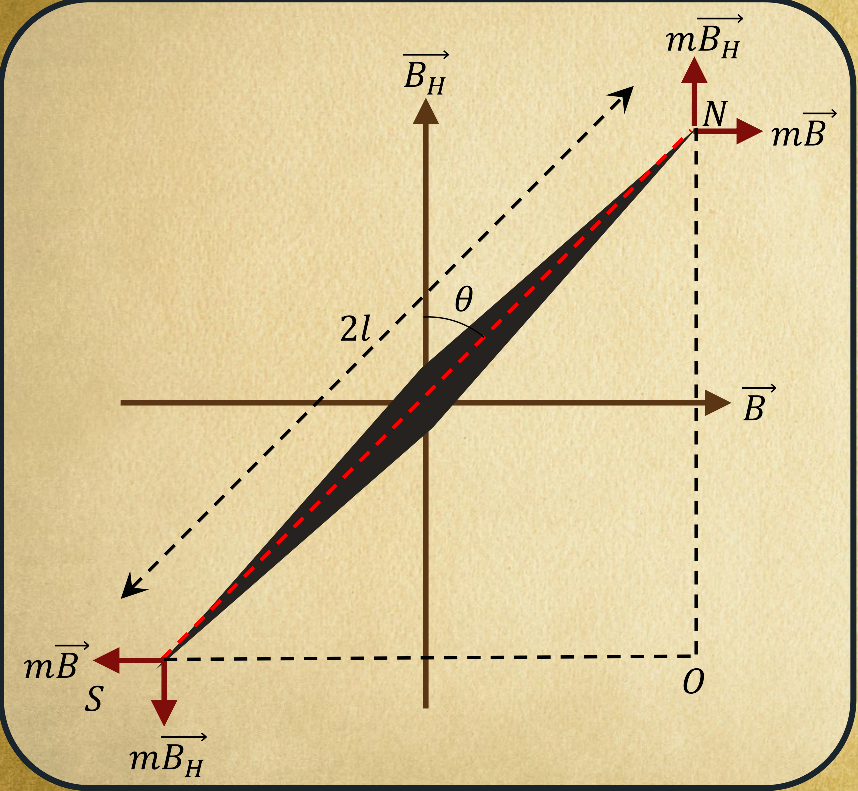
Case 2: $T_2 = 2\pi\sqrt{\frac{I}{(M_1 - M_2)B_H}}$

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

$$\boxed{\therefore \frac{M_1}{M_2} = \frac{T_2^2 + T_1^2}{T_2^2 - T_1^2} = \frac{25}{7}}$$



Deflection Magnetometer - Tangent Law



Deflecting couple due to forces $(mB, -mB)$

$$\tau_1 = mB \times NO = mB.\,2l\cos\theta$$
$$= (2ml)B\cos\theta$$
$$= MB\cos\theta$$

Deflecting couple due to forces $(mB_H, -mB_H)$

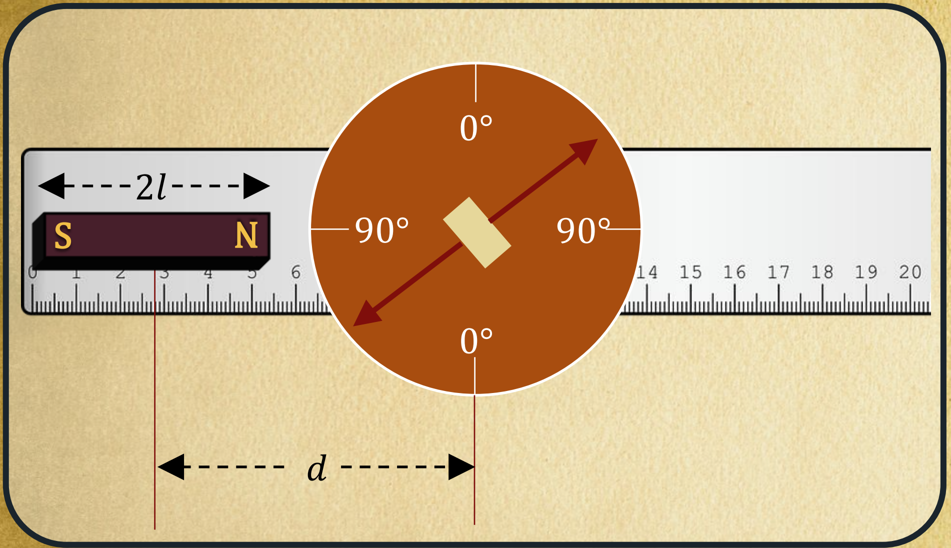
$$\tau_2 = mB_H \times SO = mB_H.\,2l\sin\theta$$
$$= (2ml)B_H\sin\theta$$
$$= MB_H\sin\theta$$

When the magnet is in equilibrium position$(\tau_1 = \tau_2)$,

$$B = B_H\frac{\sin\theta}{\cos\theta} = B_H\tan\theta$$

$$\boxed{\tan\theta = \frac{B}{B_H}}$$

Deflection Magnetometer – Tan A Position



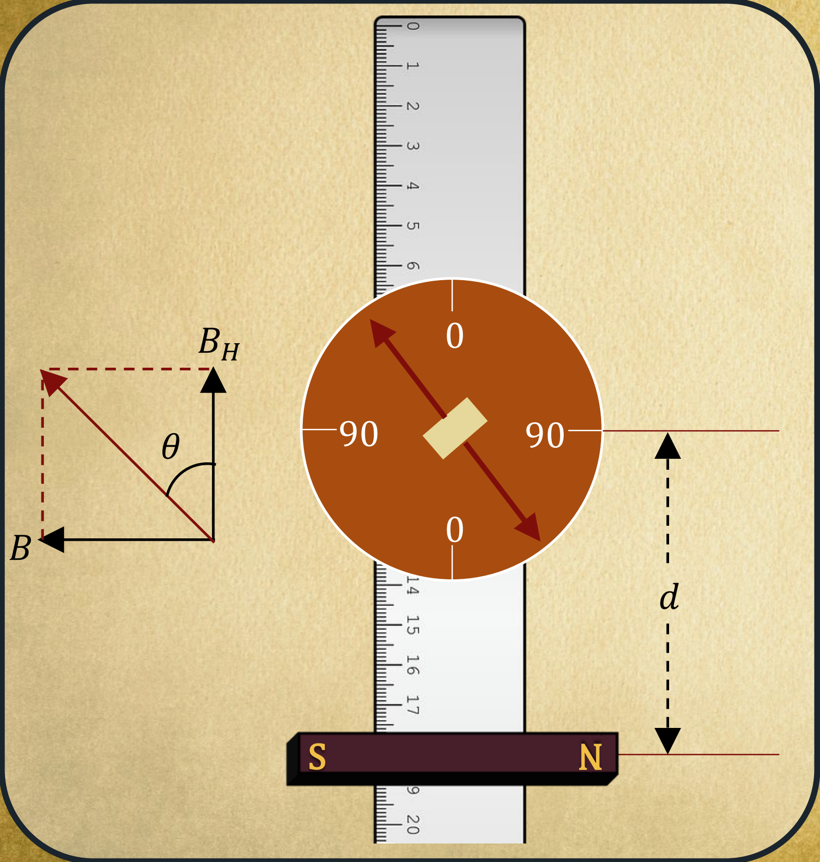
- The arms of magnetometer are kept along the magnetic East-West direction.
- The magnet NS is placed with its length parallel to the arm so that the compass needle is on end side-on position of the bar magnet NS.
- Magnetic Field due to the bar magnet at the site of the needle is: (When $B = B_H \tan\theta$)

$$\boxed{B = \frac{\mu_0}{4\pi}\frac{2Md}{(d^2 - l^2)^2} = B_H \tan\theta}$$

- For a short magnet:

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

Deflection Magnetometer - Tan B Position



Magnetic Field due to the bar magnet NS is:

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

For a short magnet:

$$B = \frac{\mu_0}{4\pi} \frac{M}{d^3}$$

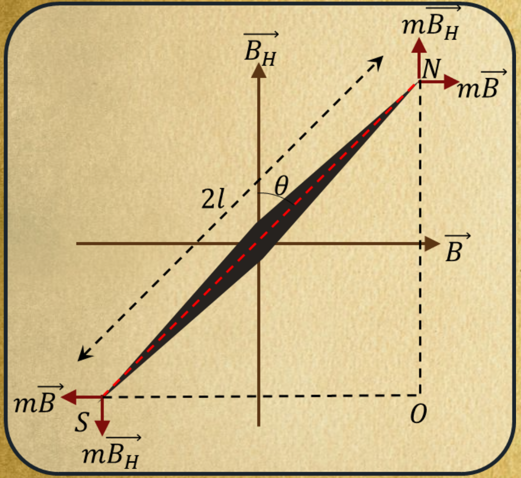
Using tangent law, $B = B_H \tan\theta$

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

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

Tangent Galvanometer

• To find the plane of magnetic meridian, the compass box is rotated in such a way that the plane of the coil is parallel to the compass needle.
• When the current is passed through the coil, the needle points towards net magnetic field.



Based on tangent law of two crossed magnetic field

The current in the circular coil is:

K = Reduction factor

$$I = \boxed{\frac{2rB_H}{\mu_0 n}} \tan\theta$$

$$I = K\tan\theta$$

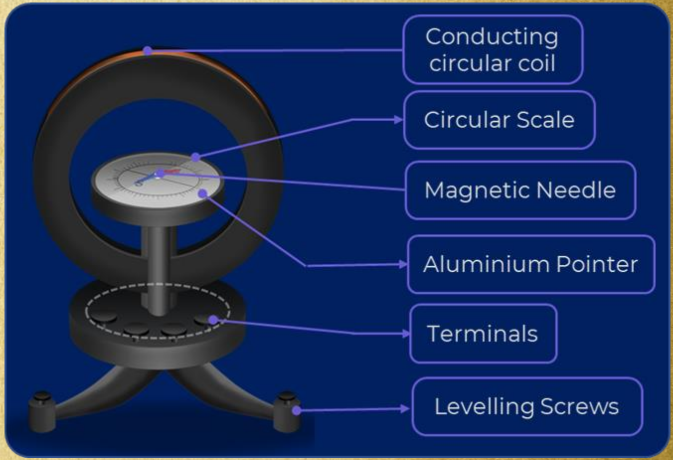
On differentiating both sides:

$$\frac{dI}{I} = \frac{(\sec\theta)^2}{\tan\theta}d\theta = \frac{d\theta}{\sin\theta\cos\theta} = \frac{2d\theta}{\sin 2\theta}$$

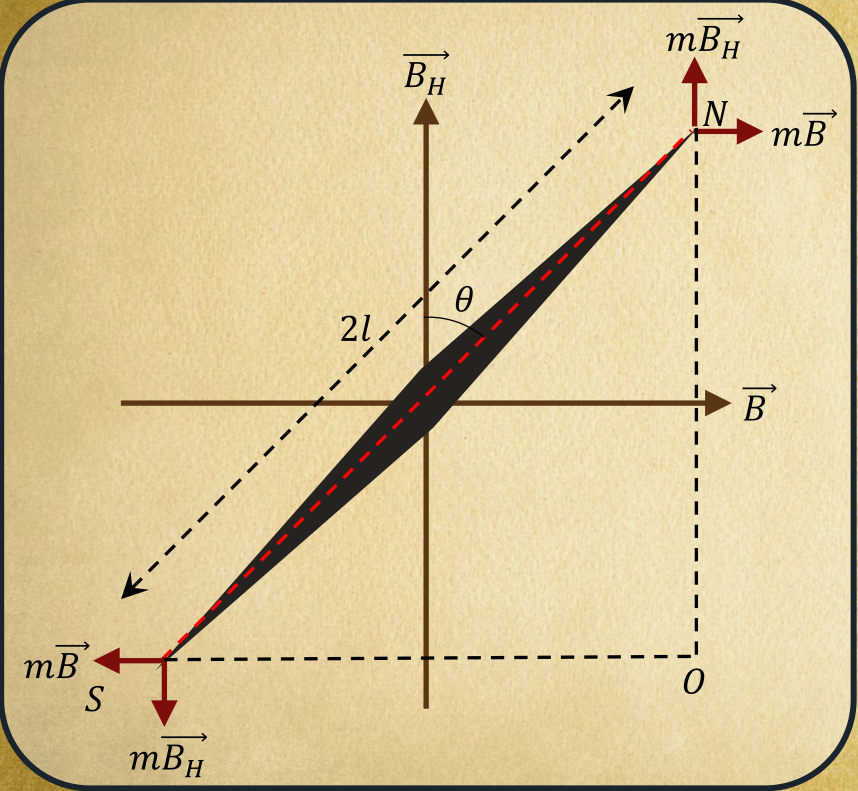
For higher accuracy:

$\frac{dI}{I}$ should be minimum $\Rightarrow \sin 2\theta$ should be maximum.

$$\boxed{\therefore \theta = 45^\circ}$$



Tangent Galvanometer



Sensitivity is measured by the deflection produced per unit current:

$$\frac{d\theta}{I} = \frac{1}{K(\sec\theta)^2}$$

$$= \frac{1}{K(1+(\tan\theta)^2)}$$

$$\boxed{\frac{d\theta}{I} = \frac{1}{K\left(1+\frac{I^2}{K^2}\right)}} \qquad \left[I = K\tan\theta \Rightarrow \frac{I}{K} = \tan\theta\right]$$

Sensitivity is large for small values of K and I.

Two tangent galvanometers differ only in the matter of number of turns in the coil. On passing current through the two joined in series, the first shows the deflection of $35°$ and the other shows $45°$ deflection. Compute the ratio of their number of turns. Take $\tan 35° = 0.7$.

Solution:

As the two tangent galvanometers are connected in series, they carry the same current.

i.e., $I_1 = I_2$

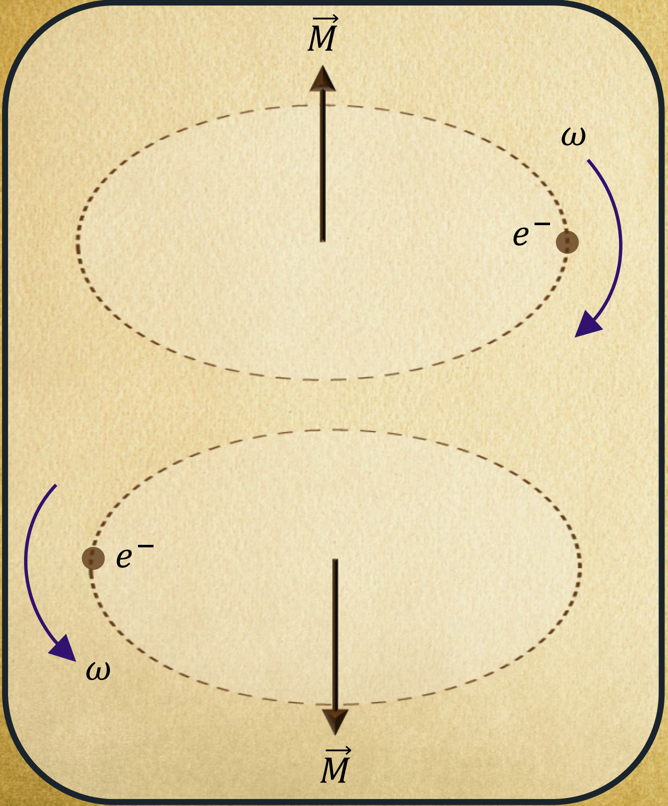
$$I_1 = \frac{2rB_H}{\mu_0 n_1} \tan\theta_1$$

$$I_2 = \frac{2rB_H}{\mu_0 n_2} \tan\theta_2$$

$$\frac{2rB_H}{\mu_0 n_1} \tan\theta_1 = \frac{2rB_H}{\mu_0 n_2} \tan\theta_2$$

$$\boxed{\therefore \frac{n_1}{n_2} = \frac{\tan\theta_1}{\tan\theta_2} = \frac{\tan 35°}{\tan 45°} = \frac{0.7}{1} = \frac{7}{10}}$$

Cause of Magnetism



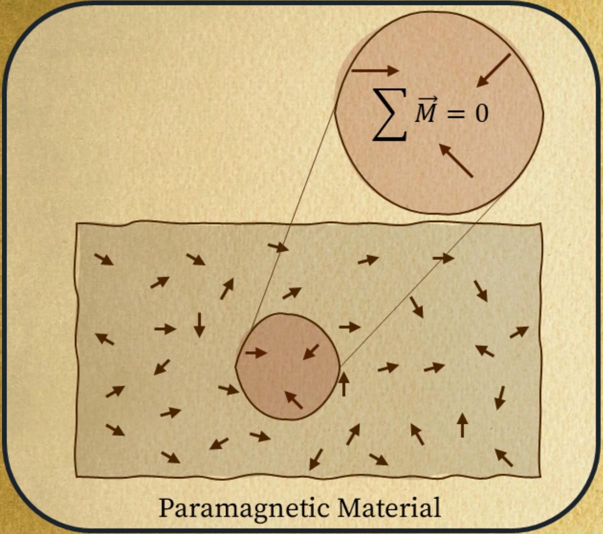
Magnetic moment of an atom is due to:

1. **Orbital motion of e^-**

2. Magnetic moment due to spin angular moment of e^-

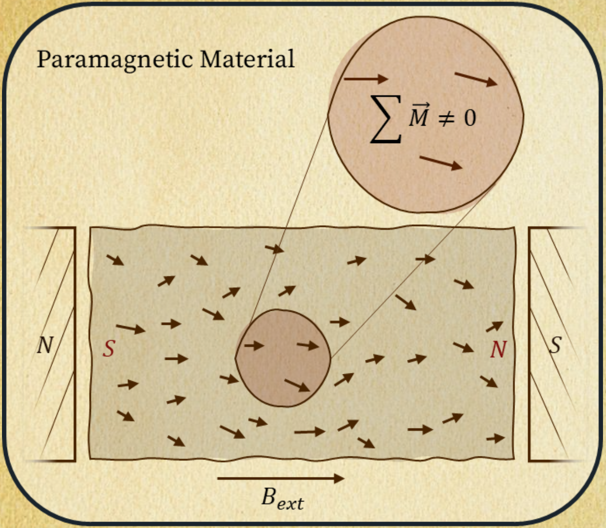
3. Magnetic moment of nucleus

Magnetic Material in External Uniform Magnetic Field



- Net magnetic moment $(\vec{M})$ is zero due to random alignment of dipoles.

$$\boxed{\sum \vec{M} = 0}$$



- Magnetic dipole are partially aligned in the direction of external magnetic field.
- Net magnetic field inside is greater than the external magnetic field.

$$\boxed{\sum \vec{M} \neq 0}$$

Magnetization vector:
It is defined as net magnetic moment per unit volume.
It is also called as intensity of magnetisation.

- Formula:

$$\boxed{\vec{I} = \frac{\sum \vec{M}_{net}}{V}}$$

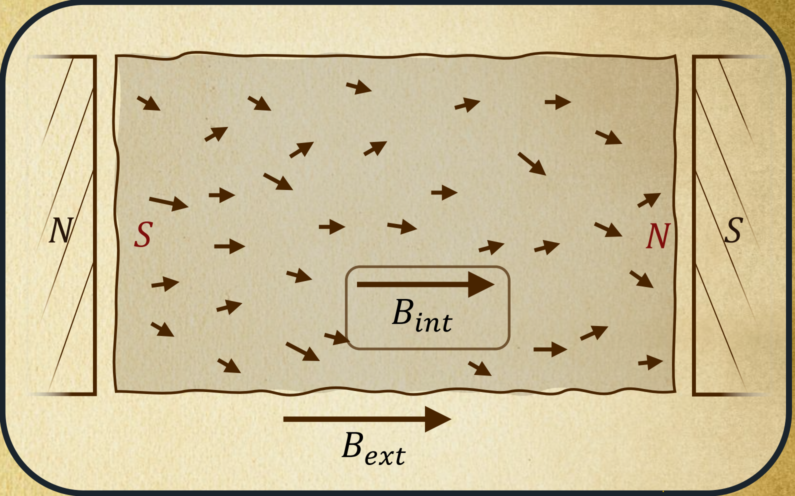
- SI unit: Am^{-1}
- Dimension: $[I] = [AL^{-1}]$

Magnetic Intensity and Susceptibility

Magnetic Intensity: It is defined as ability of magnetic field to magnetize a material medium.

- Magnetic intensity is:

$$\boxed{\vec{H} = \frac{\vec{B}}{\mu_0} - \vec{I}}$$



Magnetic susceptibility of a material indicates how easily a material gets magnetized in the presence of external magnetic field.

- The relation between $\vec{I}$ and $\vec{H}$ is:

$$\vec{I} \propto \vec{H}$$

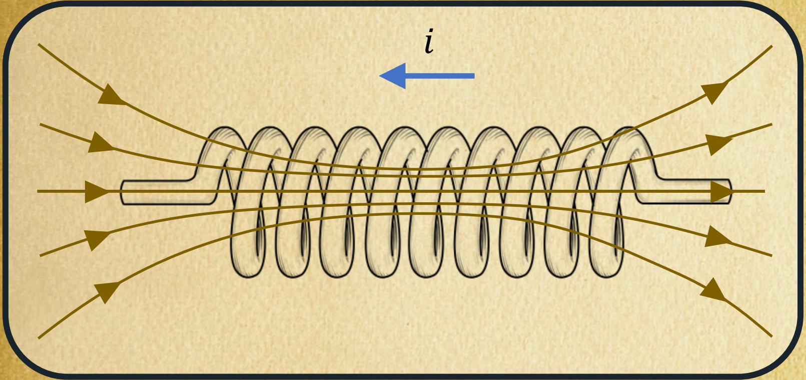
$$\boxed{\therefore \vec{I} = \chi\vec{H}}$$

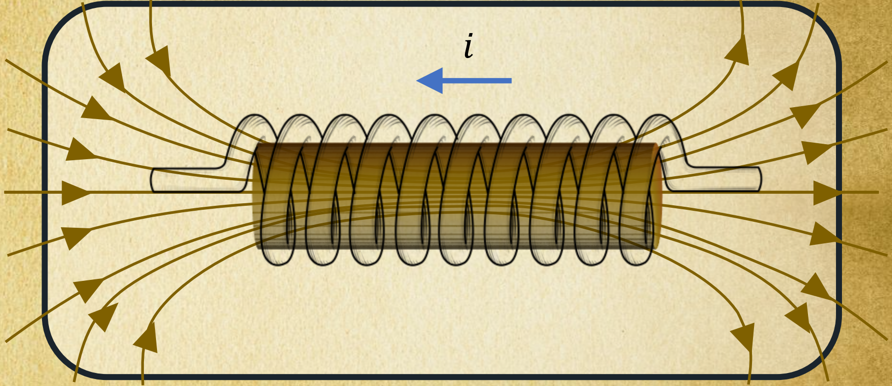
- The relation between μ and χ is:

$$\boxed{\mu = \mu_0(1 + \chi)}$$

Relative Permeability

Relative permeability is the factor by which magnetic field changes when a material is introduced.





$$\vec{B}_0 = \mu_0 \vec{H}$$

$$\vec{B}_m = \mu_m \vec{H}$$

$$\mu_r = \frac{|\vec{B}_m|}{|\vec{B}_0|} = \frac{\mu_m}{\mu_0}$$

An iron rod of susceptibility 599 is subjected to a magnetising field of 1200 Am^{-1}. The permeability of the material of the rod is : ($\mu_0 = 4\pi \times 10^{-7}\ TmA^{-1}$)

Given: $\chi_m = 599, B = 1200\ Am^{-1}, \mu_0 = 4\pi \times 10^{-7}\ TmA^{-1}$

Solution:

Relative permeability is given by:

$$\mu_r = 1 + \chi_m$$

$$\Rightarrow \mu_r = 1 + 599 = 600$$

Permeability of the rod is:

$$\mu = \mu_r \mu_0$$

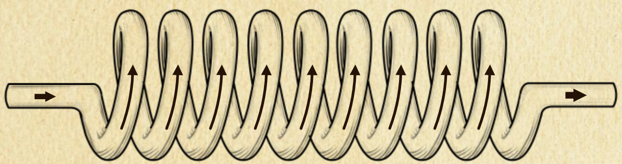
$$\boxed{\therefore \mu = 2.4\pi \times 10^{-4}\ TmA^{-1}}$$

A solenoid has a material of relative permeability 400. If solenoid has 1000 turns per meter and carries a current of $2A$, find:

1) H
2) B_{net} and
3) I

Given: $\mu_r = 400, n = 1000\ turns/m, I = 2A$

Diagram:



Solution:

$$B_0 = \mu_0 nI$$

$$B_0 = \mu_0 H$$

$$\Rightarrow H = nI$$

$$\Rightarrow H = 1000 \times 2$$

$$\boxed{\therefore H = 2 \times 10^3\ Am^{-1}}$$

$$B_m = \mu_m H$$

$$\Rightarrow B_m = \mu_r \mu_0 H$$

$$\boxed{\therefore B_{net} = 1.0048\ T}$$

$$I = \chi H$$

$$\mu_r = 1 + \chi$$

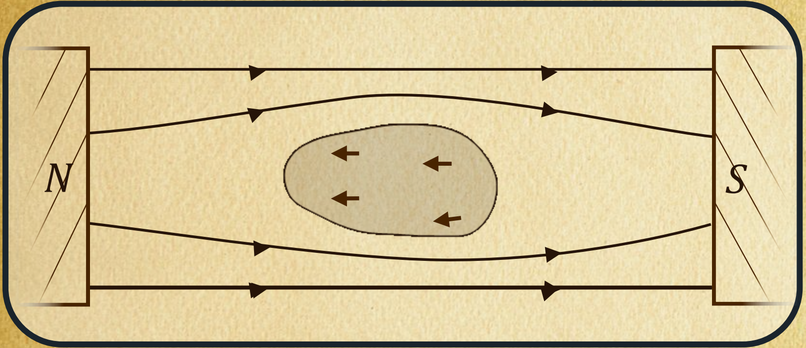
$$\chi = 400 - 1 = 399$$

$$I = 399 \times 2 \times 10^3$$

$$\boxed{\therefore I = 7.98 \times 10^5\ Am^{-1}}$$

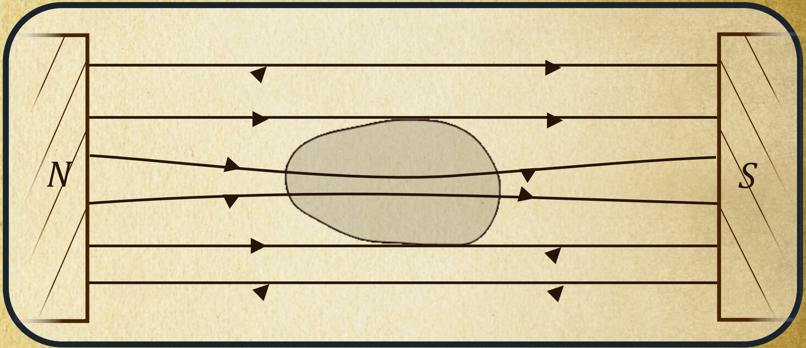
Diamagnetism and Paramagnetism

Diamagnetic Substance



- A small magnetization occurs opposite to the direction of the external magnetic field.
- Magnetic susceptibility is small and negative.
  χ is $-ve$ and $\mu_r < 1$
- Magnetic field lines are repelled from diamagnetic substances.

Paramagnetic Substance



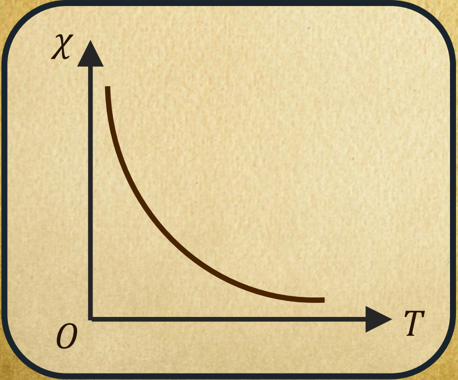
- Atomic dipoles get partially aligned in the presence of external magnetic field.
- Magnetic susceptibility is small and positive.
  χ is $+ve$ and $\mu_r > 1$
- Magnetic field lines get denser inside a paramagnetic substance.

Curie's Law

Curie's Law: Magnetization $(\vec{I})$ of a paramagnetic substance is inversely proportional to absolute temperature (T).

For a given magnetic intensity:

$T \uparrow$ → Randomization of individual atoms increase, so magnetic moments decreases → $I \downarrow$ → $\chi \downarrow$



$$\boxed{I \propto \frac{B_0}{T}} \longrightarrow \boxed{I = C\frac{B_0}{T}}$$

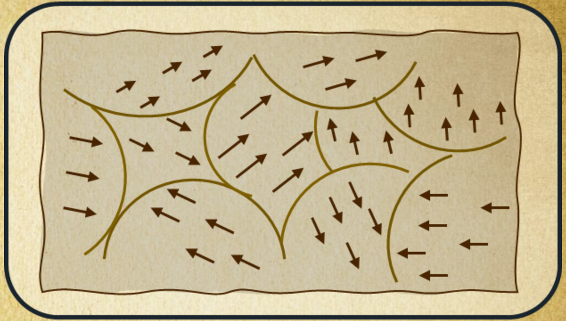
Where, C = Curie's constant

$I = \chi H$, $B_0 = \mu_0 H$

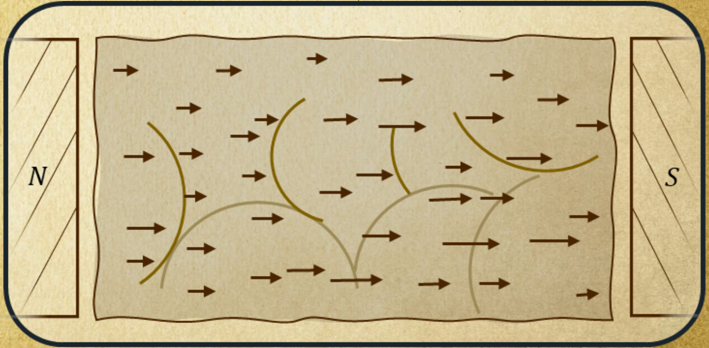
$$\boxed{\chi = C\frac{\mu_0}{T}}$$

Ferromagnetic Materials

- Atomic dipoles interact with each other to align in same direction in small volumes known as domains.
- On application of external magnetic field, domains align themselves in the direction of magnetic field.
- Domains aligned in the direction of magnetic field also grow in size. (Domain Growth)
- Magnetic susceptibility (χ) is positive and relative permeability is very large. $(\mu_r \gg 1)$



Without external magnetic field



After magnetic field is applied

On removal of external magnetic field:

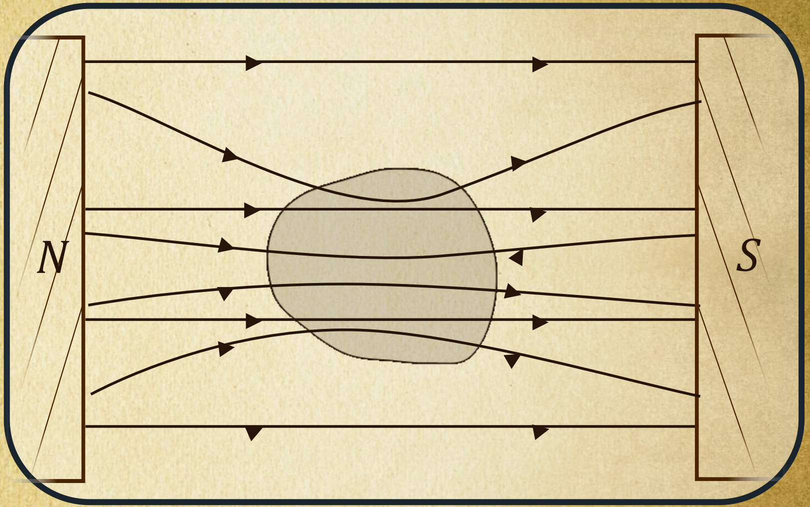
- If Magnetization persists:
  - The material is hard ferromagnetic material. (Ex. Alnico)
- If Magnetization disappears:
  - The material is soft ferromagnetic material. (Ex. Soft iron)

Ferromagnetic Materials

- On increasing temperature, ferromagnetic property decreases.
- At a certain temperature, materials lose their ferromagnetic properties and become paramagnetic.
- The transition temperature at which a ferromagnetic material changes to paramagnetic is called Curie's temperature.
- The susceptibility above Curie temperature in paramagnetic state is given by :

$$\boxed{\chi = C\frac{\mu_0}{T - T_C}}$$

Where,
T_c = Curie temperature
C = Curie's constant



Classification of Magnetic Materials

Diamagnetism

- Magnetic moment for individual atom is zero.
- Hence the net magnetic moment for the material becomes zero.
- Ex- He_2^4 $\boxed{\uparrow\downarrow}$
- Magnetic field lines are repelled.
- Susceptibility is negative.
- Relative permeability (μ_r) is between 0 and 1.

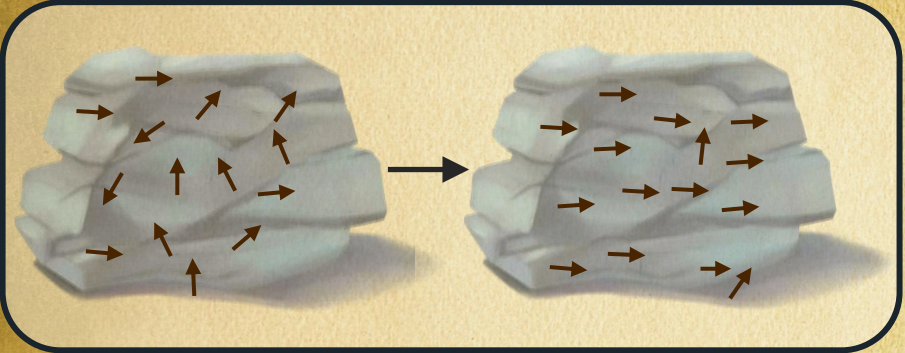
Paramagnetism

- The magnetic dipole moment for individual atom is non-zero.
- The tiny atomic dipole moments are distributed in random directions.
- Hence net magnetic moment is zero.
- Ex- C_6^{12} $\boxed{\uparrow\downarrow}$ $\boxed{\uparrow\downarrow}\boxed{\uparrow}\boxed{\uparrow}$
- Magnetic field lines are attracted.
- Susceptibility is small and positive.
- Relative permeability is slightly greater than 1.

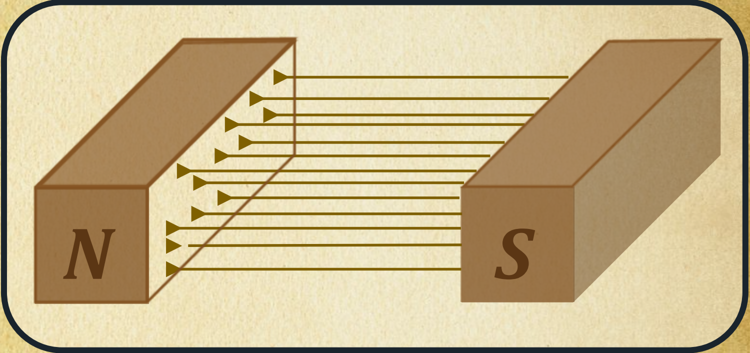
Ferromagnetism

- Various regions called domains are created where individual dipole moments are aligned in same direction.
- Different domains have their magnetic dipole moments in different directions.
- Hence the net dipole moment is zero.
- Magnetic field lines are strongly attracted.
- Susceptibility is large and positive.
- Relative permeability is greater than 1.

Magnetization and Magnetic Intensity



- Magnetization is the measure of the internal magnetic field produced and is defined as the net dipole moment per unit volume.
- The response of a substance in aligning the domains to an external magnetic field is known as magnetization (I).



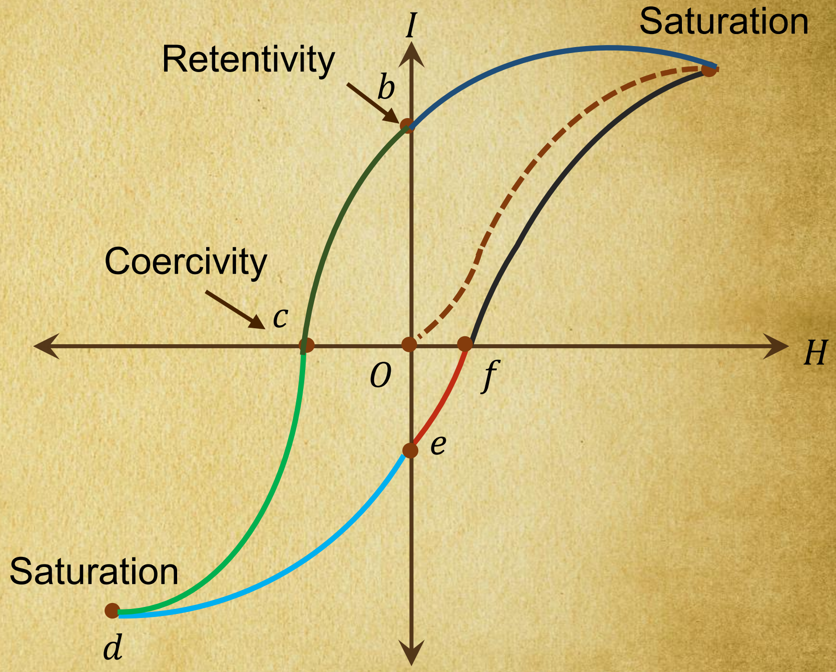
- The external magnetic effect/intensity which is independent of the material inside the field is known as magnetic intensity (H).

Hysteresis Curve

- Saturation point : At this point, domains of ferro-magnetic material are aligned due to application of external magnetic field, and the material becomes magnetically saturated.

- Retentivity : The value (OB) of B at $H = 0$ is called "Retentivity" or "Remanence". This is due to the fact that domains are not completely randomized even though $H = 0$.

- Coercivity : The value (OC) of magnetizing field H needed to reduce net magnetic field B to zero is called "Coercivity".



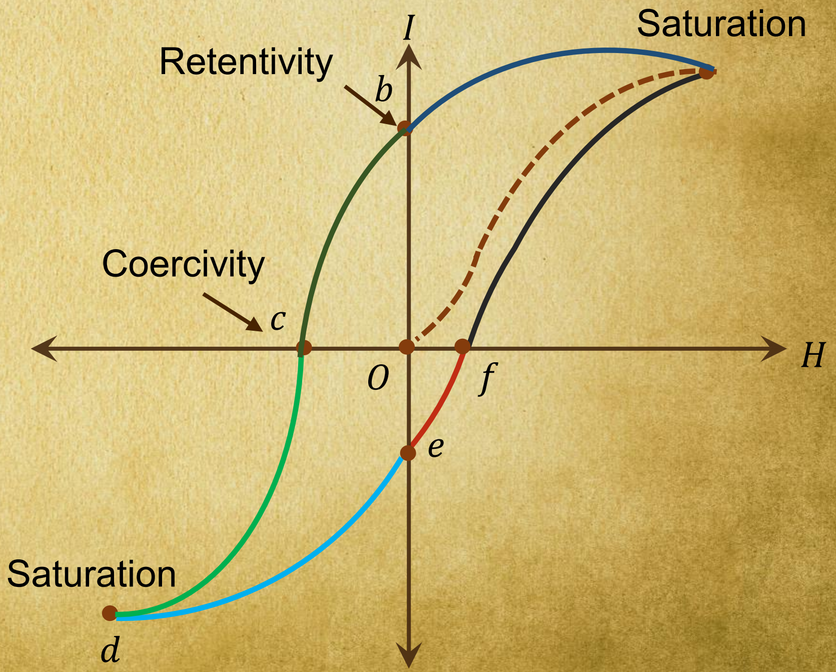
Hysteresis Curve

- When the net magnetic field B of ferro-magnetic substances is plotted against magnetic intensity H for a complete cycle of magnetization and demagnetization, the resulting loop is called "Hysteresis loop".

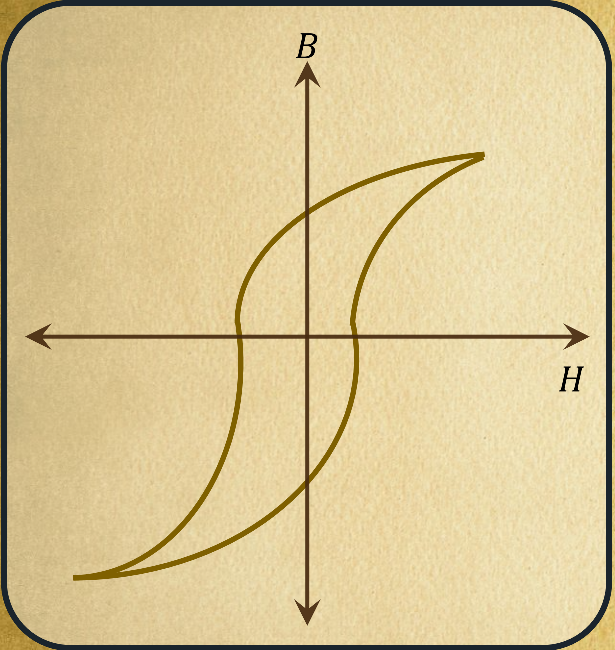
- Hysteresis loss : Energy lost in form of heat during a complete cycle of magnetization and demagnetization.

- Area of hysteresis loop ∝ Thermal energy developed per unit volume of the material in a hysteresis cycle.

- For a complete cycle of magnetization and demagnetization, the net magnetic field B lags behind the magnetic intensity or magnetizing field H.



$B - H$ and $I - H$ Curves



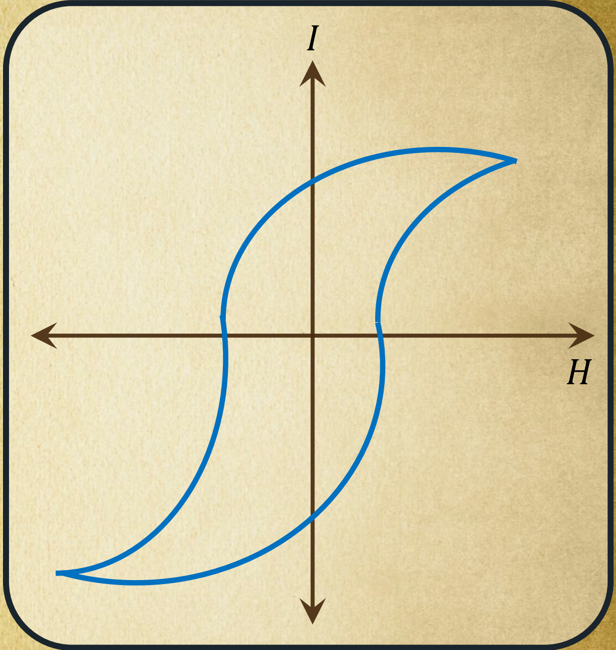
$$\boxed{\vec{B} = \mu_o(\vec{H} + \vec{I})}$$

$\vec{B}$ = Net magnetic field

μ_o = Permeability of free space

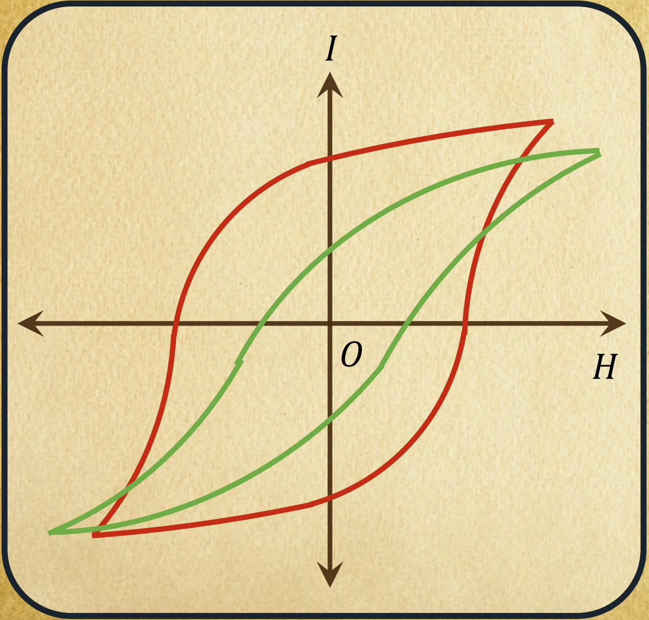
$\vec{H}$ = Magnetic intensity

$\vec{I}$ = Magnetization vector



Hysteresis Loss

The area enclosed by the hysteresis loop is proportional to the energy supplied per unit volume of material in each cycle which is lost as heat.



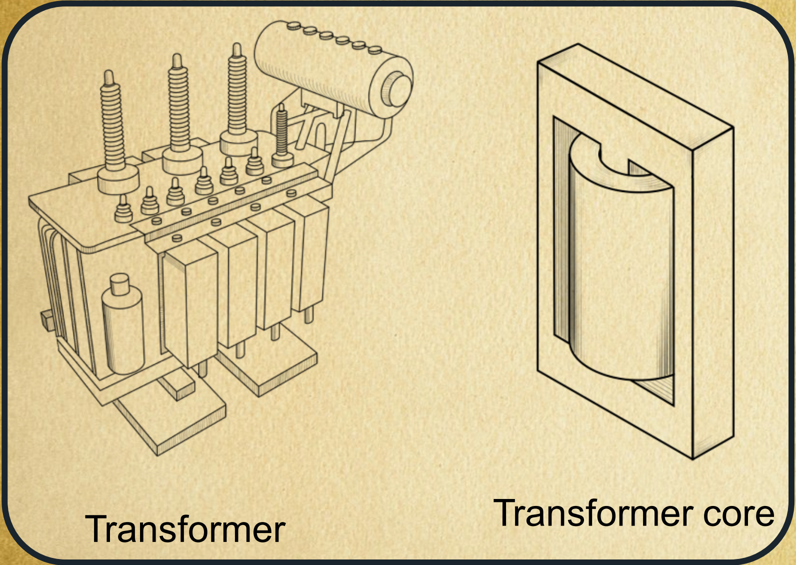
For permanent magnet:

- High saturation of magnetisation
- High Retentivity
- High Coercivity
- More area is enclosed which means more heat is lost in each cycle.

For temporary magnet (or electromagnet):

- High saturation of magnetisation
- Low Retentivity
- Low Coercivity
- Less area is enclosed which means less heat is lost in each cycle.

Which material is better to use in the coil of a generator or the core of a transformer?



Material to be used should have:

- Low Retentivity
- Low Coercivity
- Small area of hysteresis loop

A Soft Iron

C Stainless steel

B Mild steel

D Hard iron