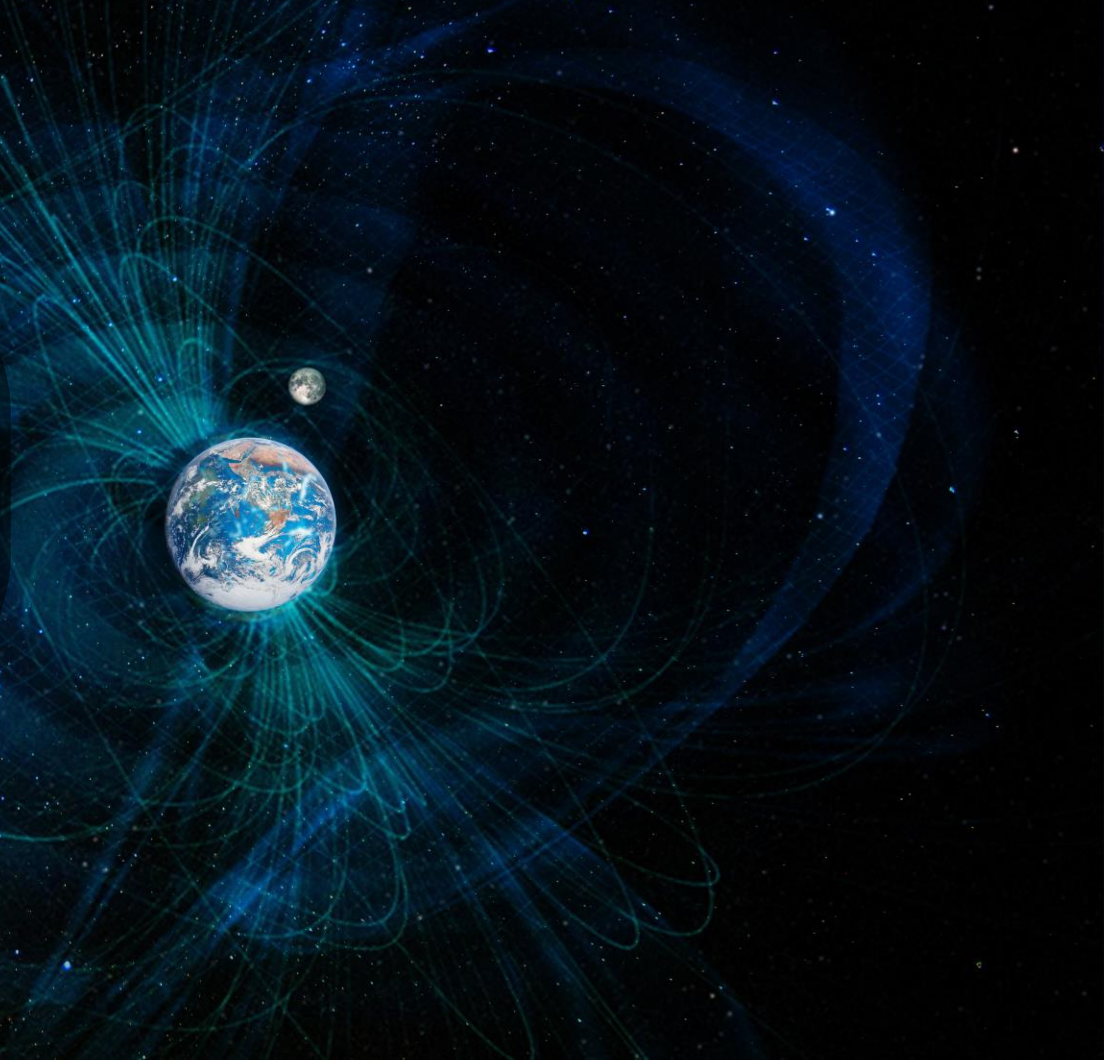
Welcome to

Aakash + BYJU'S NOTES

Magnetism and Matter

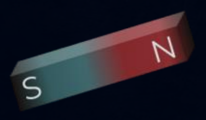


Introduction to Magnet

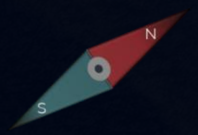
Magnet is a material that produces magnetic field and is able to attract materials like iron, nickel and cobalt.

Types of Magnets

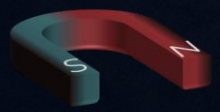
- Permanent Magnets
- Temporary Magnets
- Electromagnets



Bar Magnet

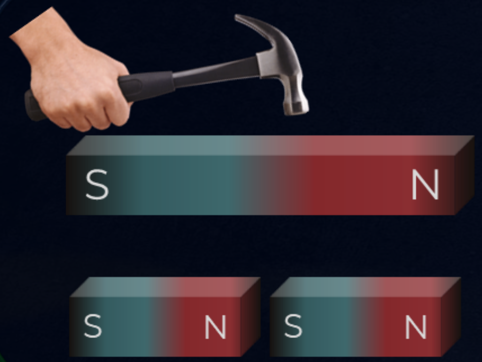


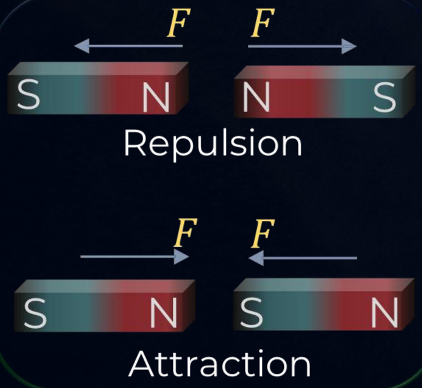
Magnetic Needle



U-shaped Magnet

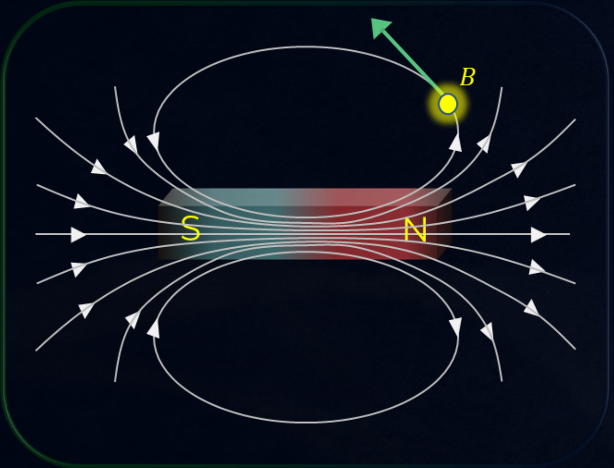
Bar Magnet





- A bar magnet is a rectangular piece of object made up of iron, steel or any other substance that shows permanent magnetic properties.
- It produces its own persistent magnetic field.
- The poles of a bar magnet are situated near the ends.
- The bar magnet has two poles: North pole (N) and South pole (S).
- Magnetic monopoles do not exist.
- Like poles repel each other and unlike poles attract each other.
- Forces form action-reaction pair and act along the line joining the magnets.

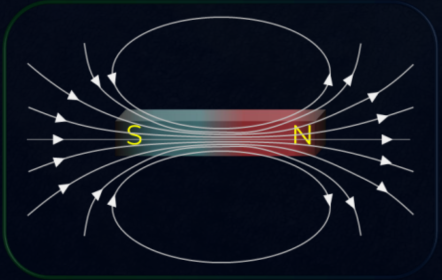
Properties of Magnetic Field Lines

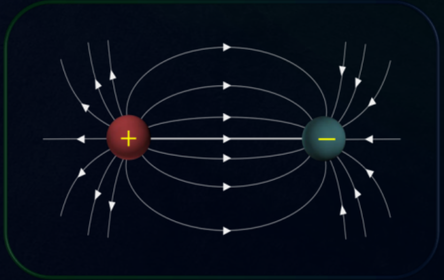


- Magnetic field lines never intersect with each other.
- Magnetic field lines appear to originate from the North pole and terminate at the South pole.
- Inside the magnet, the direction of the field lines is from the South pole to the North pole.
- The tangent at any point on the field line gives the direction of the field.
- The density of the field lines is directly proportional to the strength of field.

Analogy between Bar Magnet and Electric Dipole

Magnetic Dipole





Electric Dipole

North pole $\equiv +ve$ Charge $= +m$

South pole $\equiv -ve$ Charge $= -m$

Magnetic Dipole Moment

Pole Strength (m):
The pole strength is equivalent to electric charge.

Geometric Length (l_g):
It is the actual length of the magnet.

Magnetic Length (l_m):
It is the distance between the two poles of the magnet.

$$l_m \approx 0.84 l_g$$

- A bar magnet is identical to a magnetic dipole.
- Magnetic moment is a vector quantity, and its direction is from South pole to North pole.

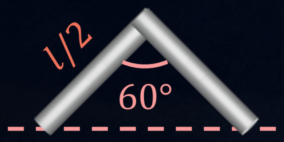
$$\vec{M} = m\,\vec{l}$$

m = Pole Strength

$\vec{l}$ = Magnetic length

A straight steel wire of length 'l' has a magnetic moment 'M'. It is bent into two different shapes as shown. Find the ratio of net magnetic moments of system A and system B.

system A



system B

Let us assume the pole strength of steel wire to be m

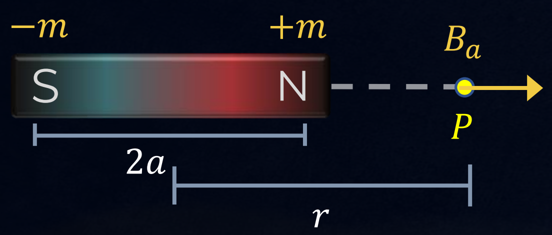
$$M_A = ml' = m\left(2\frac{l}{2}\sin 30^\circ\right) = \frac{1}{2}ml = \frac{M}{2}$$

$$M_B = ml'' = m(2R) = m\left(\frac{2l}{\pi}\right) = \frac{2}{\pi}ml = \frac{2M}{\pi}$$

$$\frac{M_A}{M_B} = \frac{M/2}{2M/\pi} = \frac{\pi}{4}$$

Magnetic field due to Magnetic dipole

Axial Point

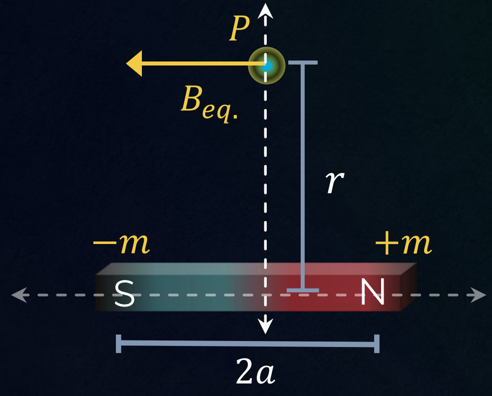


$$B_{ax} = \left(\frac{\mu_0}{4\pi}\right)\frac{2Mr}{(r^2 - a^2)^2}$$

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

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

Equatorial Point

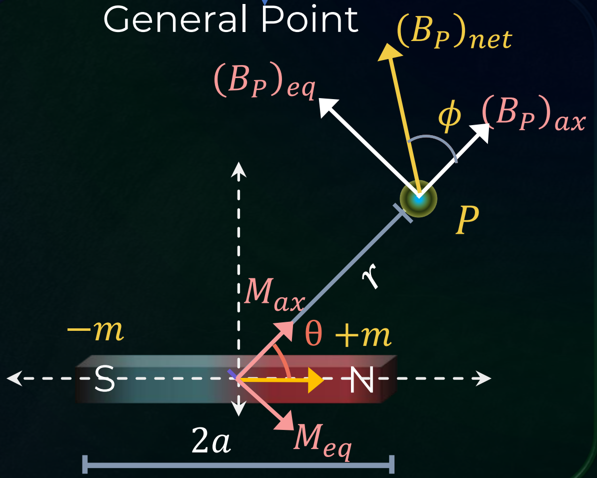


$$B_{eq} = \left(\frac{\mu_0}{4\pi}\right)\frac{M}{(r^2 + a^2)^{\frac{3}{2}}}$$

For far off points, $r \gg l$

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

General Point



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

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

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

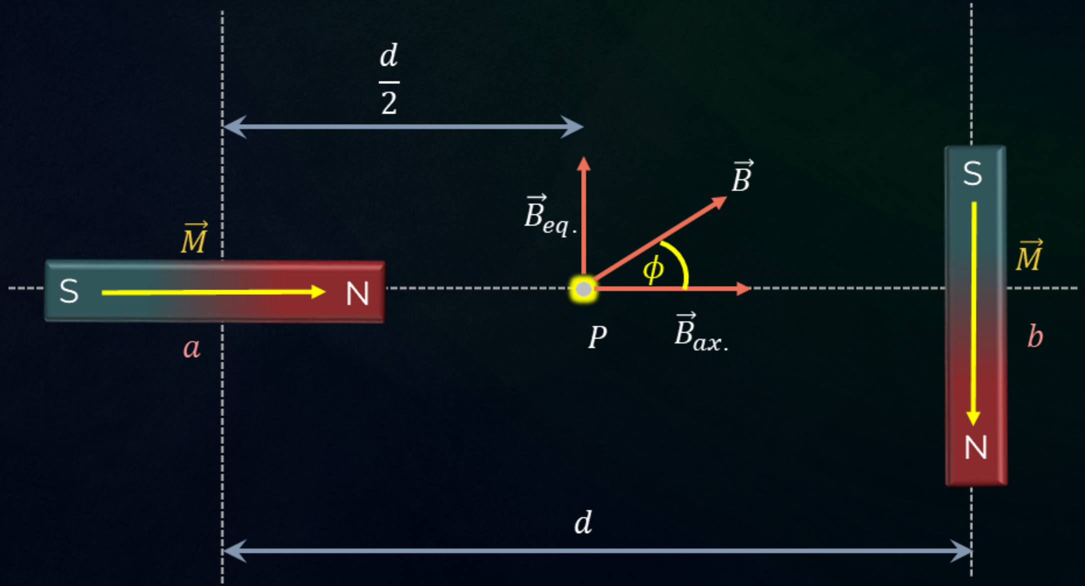
Two identical magnetic dipoles a and b of magnetic moments M each, are placed at a separation d, with their axes perpendicular to each other as shown. Find the magnetic field at the point P midway between the dipoles, in magnitude and direction.

$$\vec{B}_{ax.} = \left(\frac{\mu_0}{4\pi}\right)\frac{2\vec{M}}{r^3} = \frac{4\mu_0 M}{\pi d^3} = 2B_0$$

$$\vec{B}_{eq.} = -\left(\frac{\mu_0}{4\pi}\right)\frac{\vec{M}}{r^3} = \frac{2\mu_0 M}{\pi d^3} = B_0$$

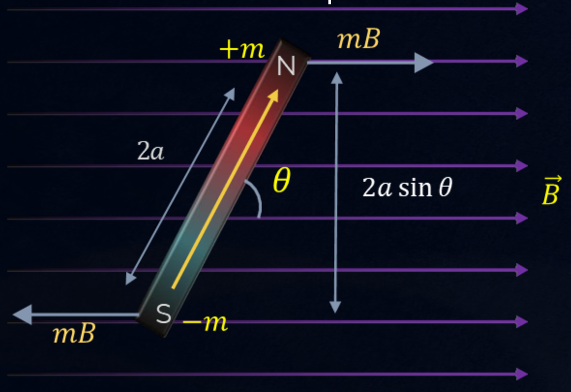
$$\boxed{|\vec{B}_{net}| = \sqrt{B_{eq}^2 + B_{ax}^2} = \sqrt{5}B_o = \frac{2\sqrt{5}\mu_o M}{\pi d^3}}$$

$$\boxed{\tan\phi = \left|\frac{B_{eq}}{B_{ax}}\right| = \frac{B_o}{2B_o} = \frac{1}{2}}$$



Bar Magnet in Uniform External field

Torque



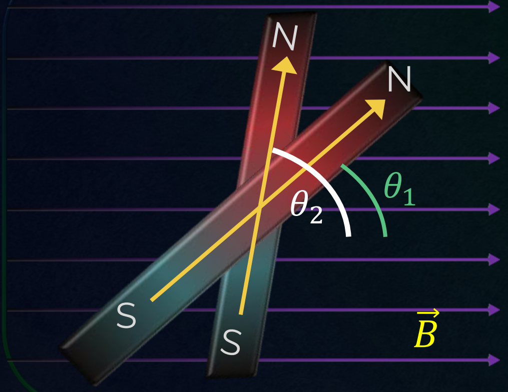
$$\tau = mB \times 2a\sin\theta$$

$$\tau = MB\sin\theta$$

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

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

Work done



$$dW = \tau d\theta$$

$$dW = MB\sin\theta\, d\theta$$

On integration,

$$\boxed{W = -MB(\cos\theta_2 - \cos\theta_1)}$$

$$W_{mag} = MB(\cos\theta_2 - \cos\theta_1)$$

Potential Energy

$$\Delta U = -W_{mag}$$

$$U_f - U_i = -MB(\cos\theta_2 - \cos\theta_1)$$

$$\theta_2 = \theta, \theta_1 = 90° \; and \; U_i = 0$$

$$U_f - 0 = -MB(\cos\theta_2 - \cos 90°)$$

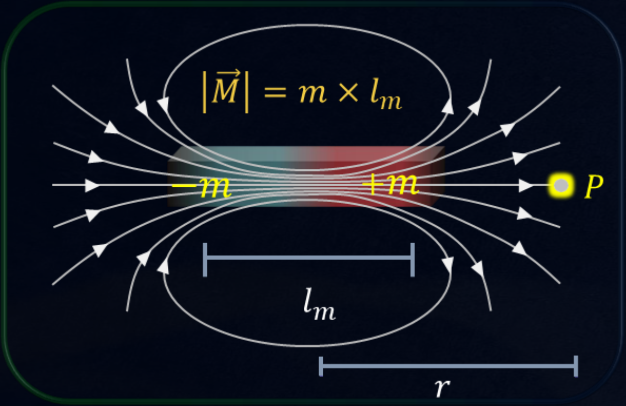
(Taking $P.E. = 0$ at $\theta = 90°$ as reference point)

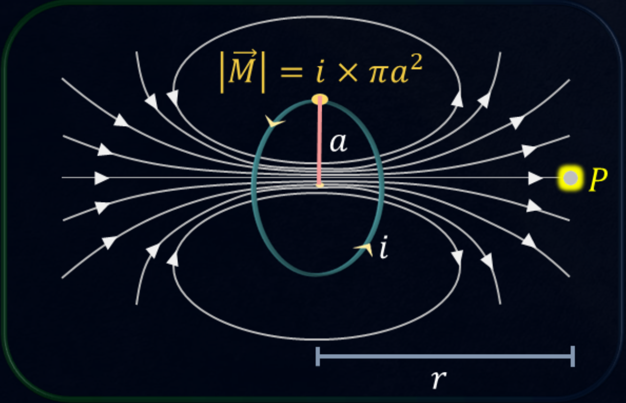
$$\boxed{U(\theta) = -MB(\cos\theta) = -\vec{M}.\vec{B}}$$

Analogy between Electricity and Magnetism

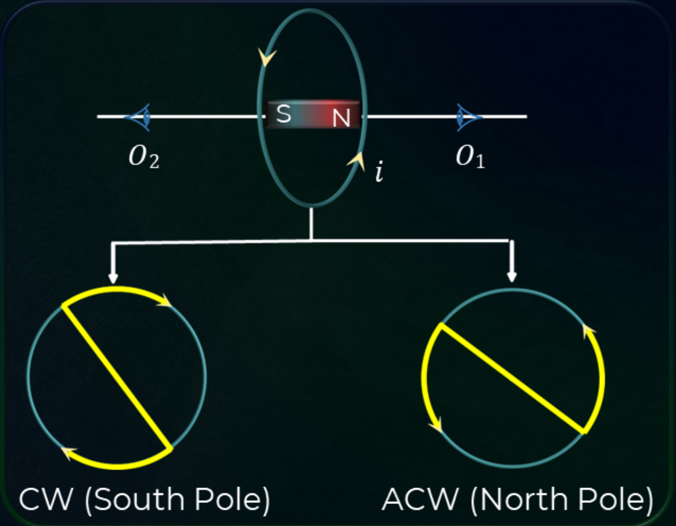
Physical Quantity	Electrostatics	Magnetism
	$1/\varepsilon_0$	μ_0
Dipole moment	$\vec{p}$	$\vec{M}$
Axial field for a dipole	$\vec{E}_{ax} = \frac{1}{4\pi\varepsilon_0}\frac{2\vec{p}}{r^3}$	$\vec{B}_{ax} = \frac{\mu_0}{4\pi}\frac{2\vec{M}}{r^3}$
Equatorial field for a dipole	$\vec{E}_{eq} = -\frac{1}{4\pi\varepsilon_0}\frac{\vec{p}}{r^3}$	$\vec{B}_{eq} = -\frac{\mu_0}{4\pi}\frac{\vec{M}}{r^3}$
In external field: Torque	$\vec{p} \times \vec{E}$	$\vec{M} \times \vec{B}$
In external field: Potential Energy	$-\vec{p}.\vec{E}$	$-\vec{M}.\vec{B}$

Current carrying loop as Equivalent Dipole





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



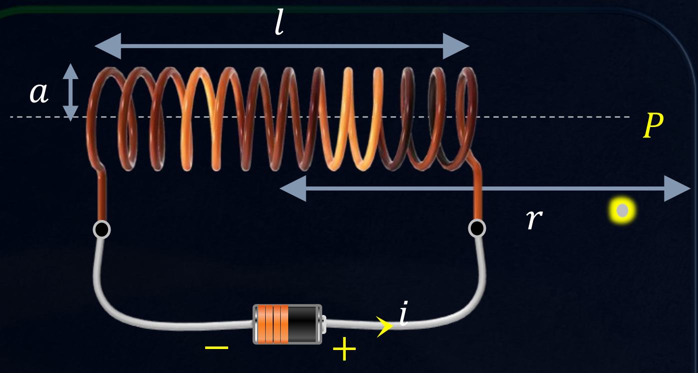
For observer 1, Current in loop is

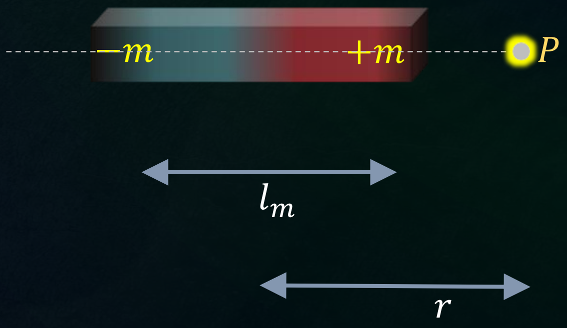
Anti-clockwise → North Pole

For observer 2, Current in loop is

Clockwise → South Pole

Solenoid as Equivalent Bar Magnet





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

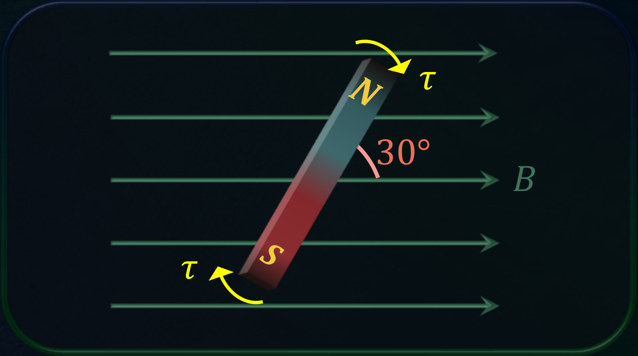
A small bar magnet placed with its axis at 30° with an external field of 0.06 T experiences a torque of 0.018 Nm. The minimum work required to rotate it from its stable to unstable equilibrium position is:

Given: $B = 0.06\,T, \quad \tau = 0.018\,Nm, \quad \theta = 30°$

Solution:

$$\tau = 0.018 = MB\sin 30° \quad \Rightarrow \quad M = 0.6\,Am^2$$

- Position of stable equilibrium ($\theta = 0°$)
- Position of unstable equilibrium ($\theta = 180°$)



$$W = MB(\cos\theta_1 - \cos\theta_2) = MB(\cos 0° - \cos 180°)$$

$$W = 2MB = 2 \times 0.6 \times 0.06$$

$$\boxed{W = 7.2 \times 10^{-2}\,J}$$

Angular SHM of Dipole

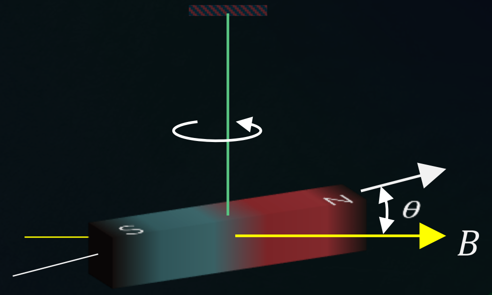
$\tau = -MB\sin\theta = -MB\theta$ [for very small θ , $\sin\theta \approx \theta$]

$$I\frac{d^2\theta}{dt^2} = -MB\theta \Rightarrow \frac{d^2\theta}{dt^2} = -\frac{MB}{I}\theta \qquad \therefore\ \omega^2 = \frac{MB}{I}$$

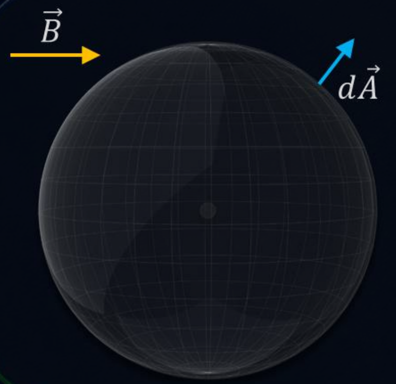
So, dipole will execute angular SHM with time period :

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

Rotate by a small angular displacement θ



Gauss's Law for Magnetism



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
- There are no sources or sinks of magnetic field ($\vec{B}$)

The length of a magnet is large compared to its width and breadth. The time period of its oscillation in a vibration magnetometer is $2\ s$. The magnet is cut along its length into three equal parts and these parts are then placed on each other with their like poles together. The time period of this combination will be.

Given: $T = 2\ s$ $\quad T = 2\pi\sqrt{\dfrac{I}{MB}}$ $\quad$ Where $I = \dfrac{1}{12} m_b l^2$

Solution: When the magnet is cut into three pieces the pole strength (m) will remain the same and

Moment of inertia of new magnet, $\quad I' = \dfrac{1}{12}\left(\dfrac{m_b}{3}\right)\left(\dfrac{l}{3}\right)^2 \times 3 = \dfrac{I}{9}$

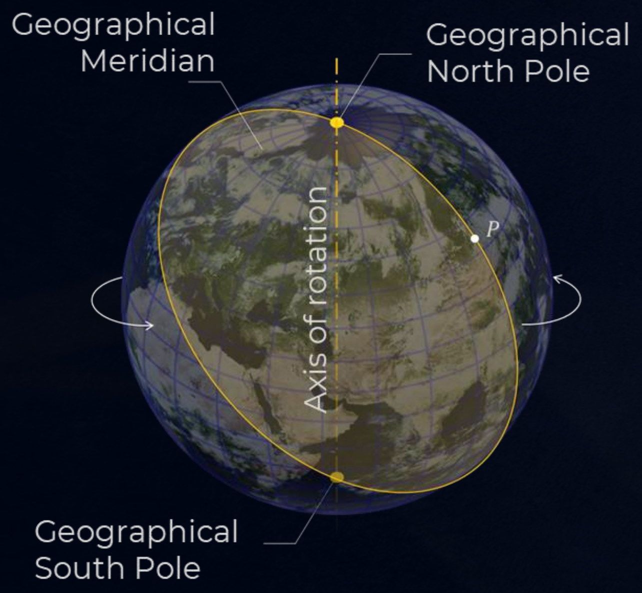
Magnetic moment $(M) = ml$

$\therefore$ New magnetic moment, $\quad M' = m\left(\dfrac{l}{3}\right) \times 3 = ml = M$

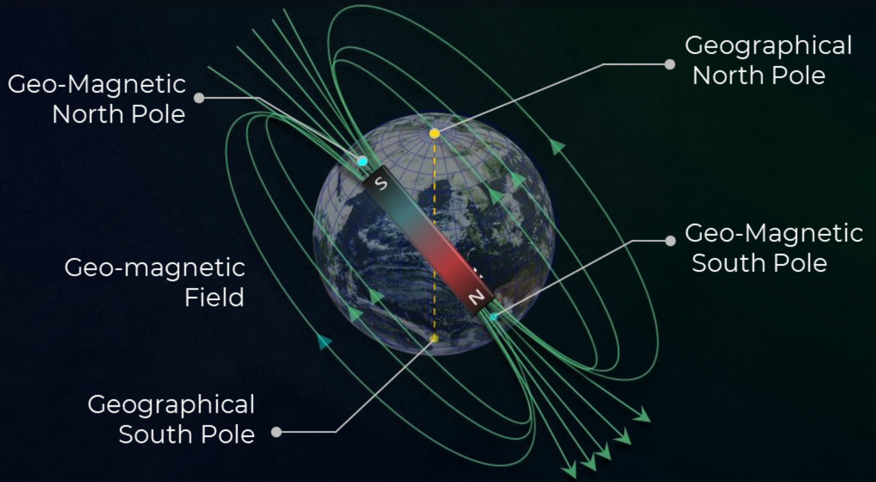
$\therefore$ New time period, $\quad T' = 2\pi\sqrt{\dfrac{I'}{M'B}} = 2\pi\sqrt{\dfrac{I}{9MB}} = T/3$

$$\boxed{T' = \frac{T}{3} = \frac{2}{3}\ s}$$

Earth's Magnetism



A plane passing through the geographical poles and a given point P on the earth's surface is called the Geographical Meridian at the point P



Magnetic Elements of Earth

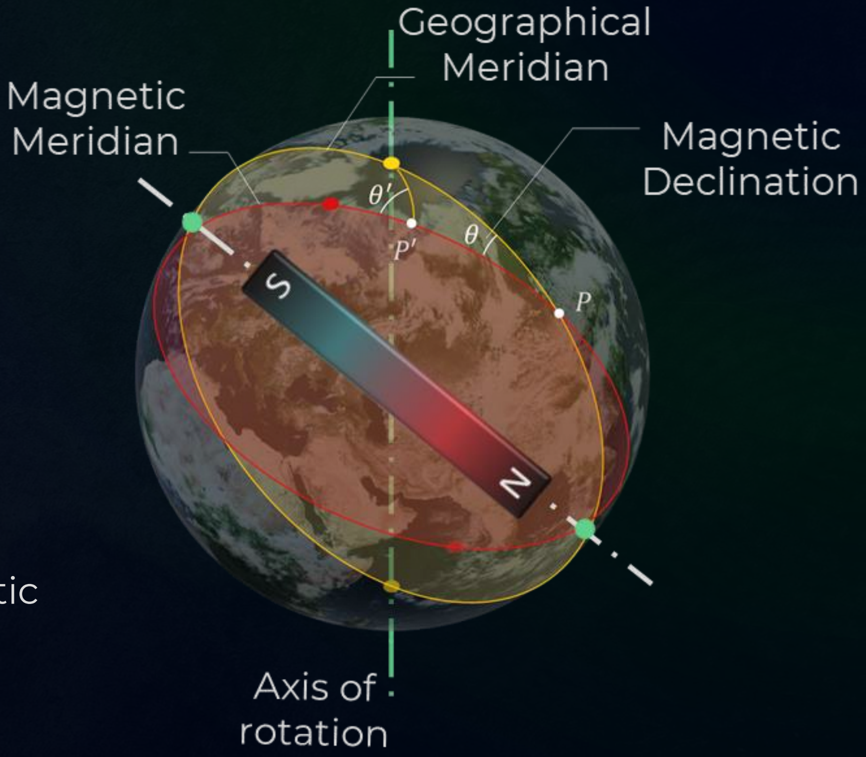
- Magnetic declination
- Magnetic inclination(Dip)
- Horizontal component of earth's magnetic field

Magnetic Declination

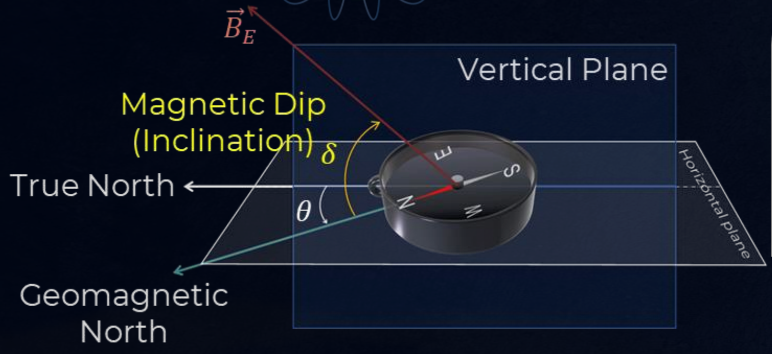
The angle made by the magnetic meridian at a point with the geographical meridian is called Declination at that point.

θ : Angle of declination

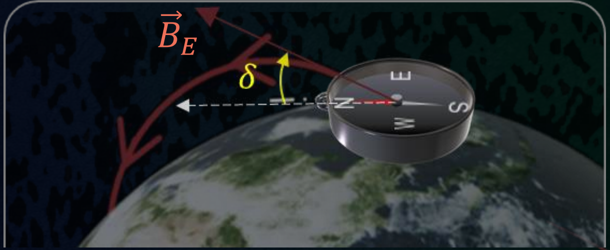
$\theta' > \theta$ (As we move closer to the Pole, Magnetic Declination increases)



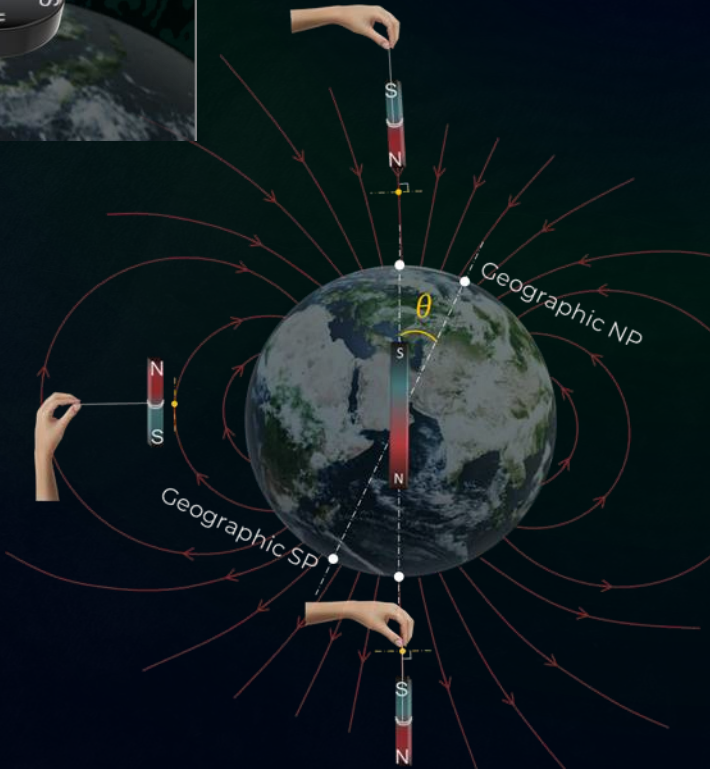
Magnetic Inclination (Dip)



δ : Angle of dip



The angle made by the Earth's magnetic field with the horizontal direction in the magnetic meridian is called Inclination or Dip at that point.



- Near magnetic north pole angle of dip is 90°.
- Near magnetic south pole angle of dip is 90°.
- Near magnetic equator, dip is zero.

The earth's magnetic field at geomagnetic poles has a magnitude $6.2 \times 10^{-5}\ T$. Find the magnitude and the direction of the field at a point on the earth's surface where the radius makes an angle of 135° with the axis of the earth's assumed magnetic dipole. What is the inclination (dip) at this point?

$$|B_P| = \frac{\mu_0}{4\pi}\frac{M}{r^3}\sqrt{1 + 3(\cos\theta)^2}$$

At $\theta = 0°$ $\rightarrow$ $B_P = 6.2 \times 10^{-5}\ T$

$$\frac{\mu_0}{4\pi}\frac{M}{r^3} = 3.1 \times 10^{-5}\ T$$

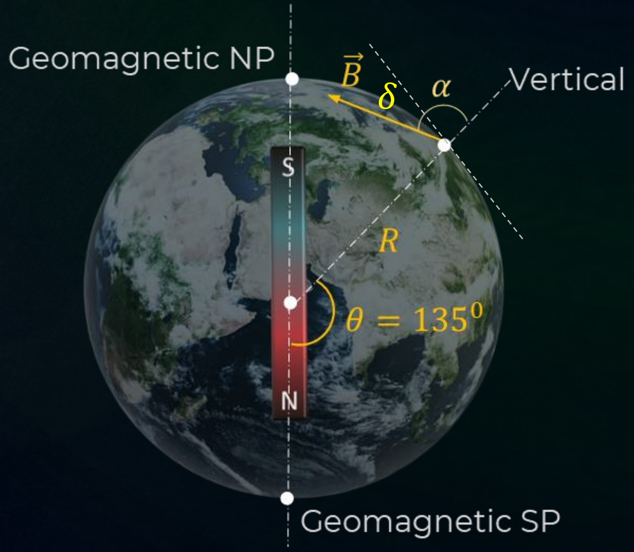
At $\theta = 135°$ $\rightarrow$ $B = \frac{\mu_0}{4\pi}\frac{M}{r^3}\sqrt{1 + 3/2}$

$$\boxed{B = 4.9 \times 10^{-5}\ T}$$

$$\tan\alpha = \frac{\tan\theta}{2} = \frac{\tan 135°}{2} = -0.5$$

$$\boxed{\alpha = 153°}$$

$$\boxed{\delta = 153° - 90° = 63°}$$



Horizontal component of earth's magnetic field

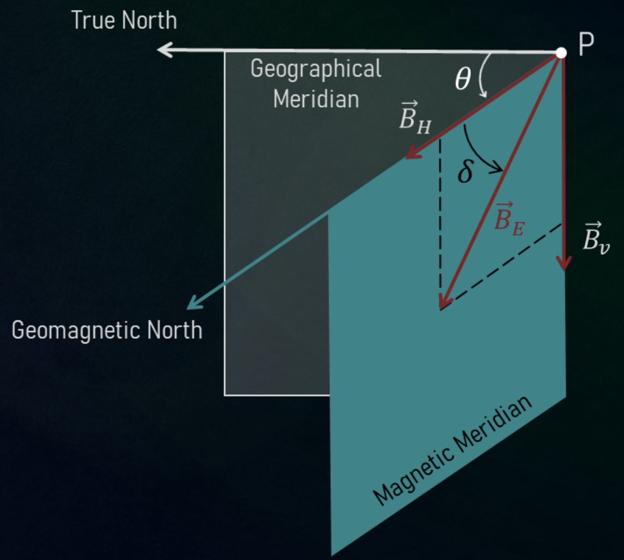
- Magnetic needle gives the direction of Horizontal Component of earth's magnetic field.

$$B_E = B_H / cos\delta$$

$$\delta = \tan^{-1}\frac{B_V}{B_H}$$

- Tangent Law

$$B_V = B_H \tan\delta$$



A magnet makes 10 oscillations per minute at a place where the angle of dip is 45° and the total intensity is $0.4\ gauss$. Calculate the frequency of oscillations at another place where the angle of dip is 60° and the intensity of the field is equal to $0.5\ gauss$.

In case of angular SHM of a magnet in magnetic field :

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

For a given magnet at two different places, we would have :

$$\frac{T_2}{T_1} = \sqrt{\frac{B_1\cos\theta_1}{B_2\cos\theta_2}}$$

Given :

$B_1 = 0.4\ gauss$ $\quad \theta_1 = 45°$

$B_2 = 0.5\ gauss$ $\quad \theta_2 = 60°$

$$T_1 = \frac{60}{10} = 6\ sec$$

$$\frac{T_2}{6} = \sqrt{\frac{0.4\times\cos 45°}{0.5\times\cos 60°}}$$

$$T_2 = 6.38\ sec$$

$$\frac{1}{f_2} = 6.38\ sec$$

$$\boxed{f_2 = 0.157\ Hz}$$

A magnetic needle having magnetic moment $10\ Am^2$ and length $2.0\ cm$ is clamped at its center in such a way that it can rotate in vertical east-west plane. A horizontal force towards east is applied at the north pole to keep the needle fixed at an angle of $30°$ with the vertical. Find the magnitude of the applied force. The vertical component of the earth's magnetic field is $40\ \mu T$.

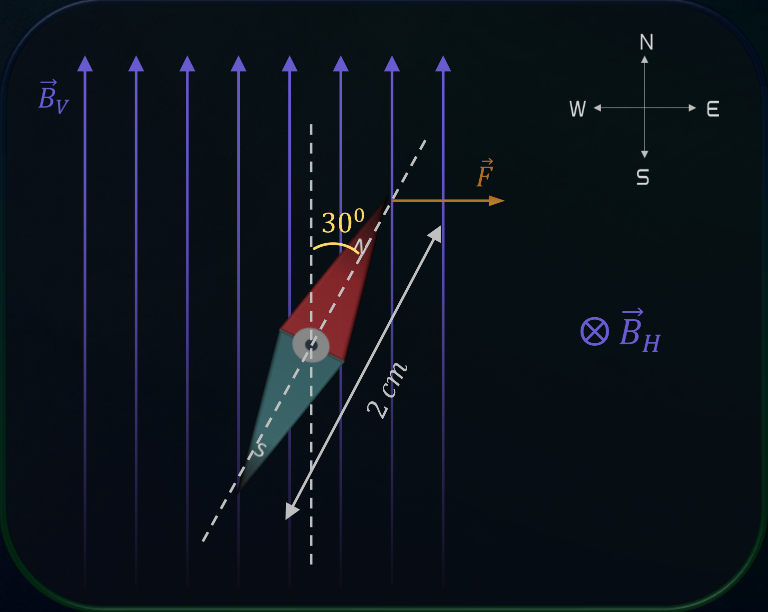
- $\vec{B}_H$ doesn't produce any torque on the needle.
- For rotational equilibrium :

$$\left|\vec{M} \times \vec{B}_V\right| = \left|\vec{r} \times \vec{F}\right|$$

$$MB_V \sin 30° = rF \sin 60°$$

$$10 \times (40 \times 10^{-6}) \times \frac{1}{2} = \frac{2 \times 10^{-2}}{2} \times F \times \frac{\sqrt{3}}{2}$$

$$\boxed{F = 2.3 \times 10^{-2}\ N}$$



?

A bar magnet of magnetic moment $2.0\ Am^2$ is free to rotate about a vertical axis through its center. The magnet is released from the east-west position. Find the kinetic energy of the magnet as it takes the north-south position. The horizontal component of the earth's magnetic field is $B_H = 25\ \mu T$.

- Change in potential energy due to change in orientation of bar magnet :

$$\Delta U = -MB\left[\cos\theta_f - \cos\theta_i\right]$$

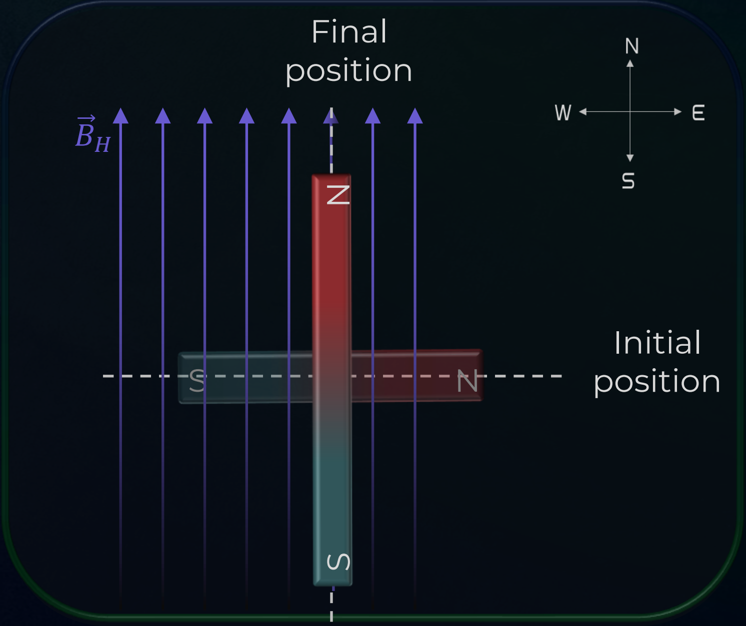
$$\Delta U = -2 \times 25 \times 10^{-6}[\cos 0° - \cos 90°]$$

$$\Delta U = -50\ \ \mu J$$

- Loss in potential energy = Gain in kinetic energy

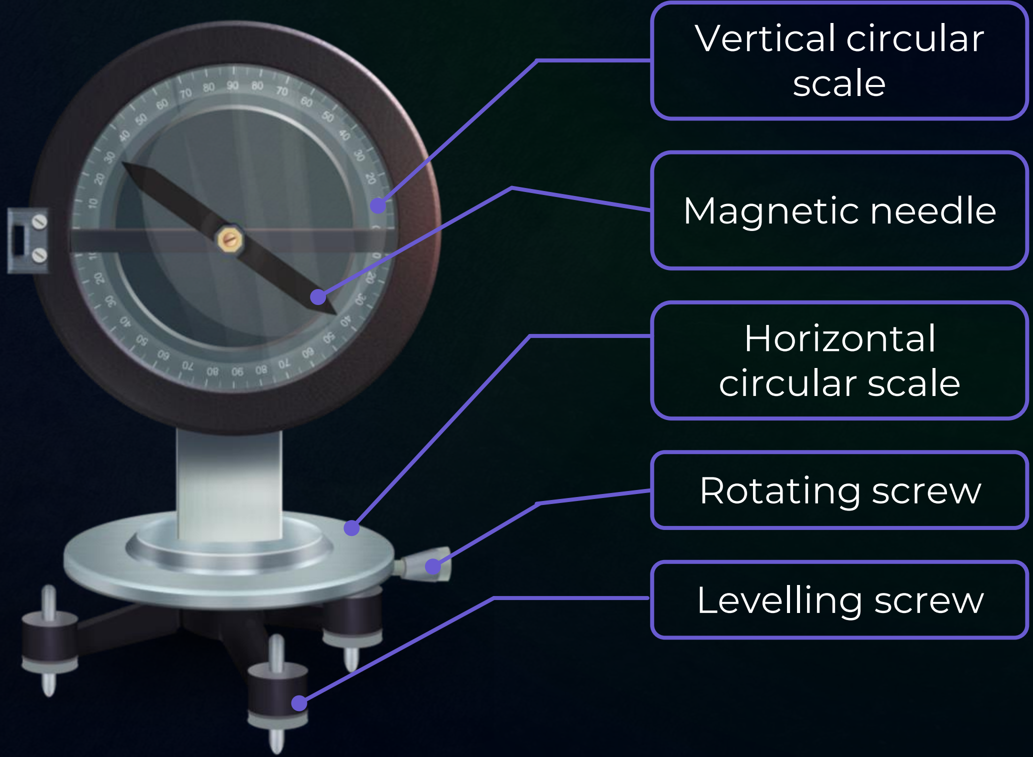
- So, kinetic energy of the magnet as it takes to north-south position is,

$$\boxed{K = 50\ \ \mu J}$$



Dip Circle : Experimental Setup

- Vertical circular scale can be rotated using the rotating screw and the angle of rotation is measured with the help of horizontal circular scale.
- Vertical circular scale is divided into four quadrants.
- Each quadrants graduates from $0°$ to $90°$ with $0° - 0°$ in horizontal and $90° - 90°$ in vertical.
- The horizontal circular scale is graduated from $0°$ to $360°$.



Steps To Measure True Dip

Step -1

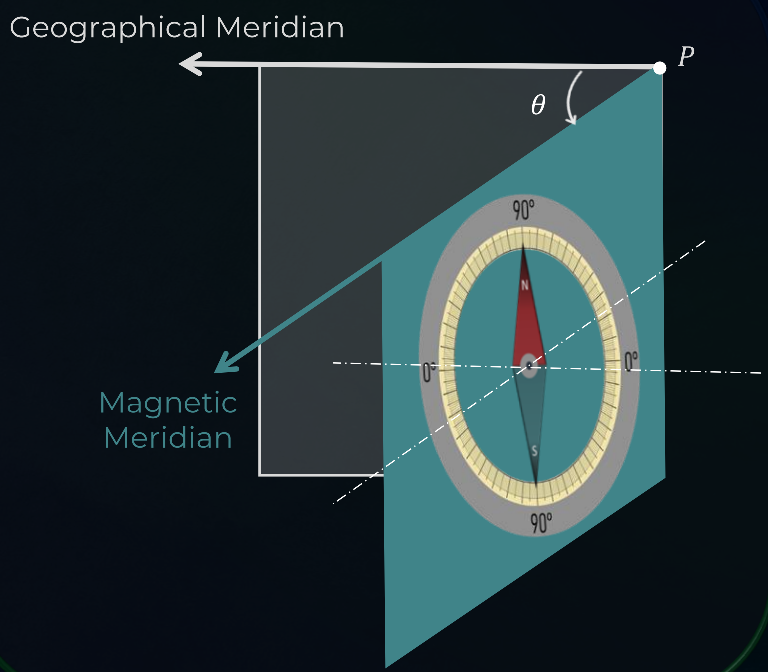
The angular position of the vertical circular scale should be such that the needle remains in $90° - 90°$ position.
For this position of the needle, $\vec{B}_H$ doesn't produce any force on it because $\vec{B}_H$ is perpendicular to the needle.

Step -2

The vertical circular scale needs to rotate by $90°$ so that it becomes parallel to magnetic meridian.

- Consequently, the needle will deflect from $90° - 90°$ position and it will get aligned along the direction of Earth's magnetic field.

The angle δ with horizontal is "Angle of dip" and this is "true dip".



Apparent Dip

α : Angle between the plane of Dip circle and Magnetic Meridian

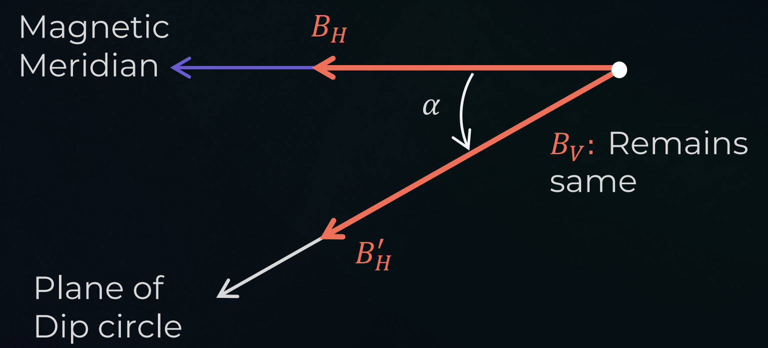
δ' : Apparent Dip

$$\tan\delta = \frac{B_V}{B_H} \qquad \tan\delta' = \frac{B_V}{B'_H} \qquad B'_H = B_H \cos\alpha$$

$$\cot\delta = \frac{B_H}{B_V}$$

$$\cot\delta = \frac{B'_H}{B_V}\frac{1}{\cos\alpha} = \cot\delta' \frac{1}{\cos\alpha}$$

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



Tangent Law

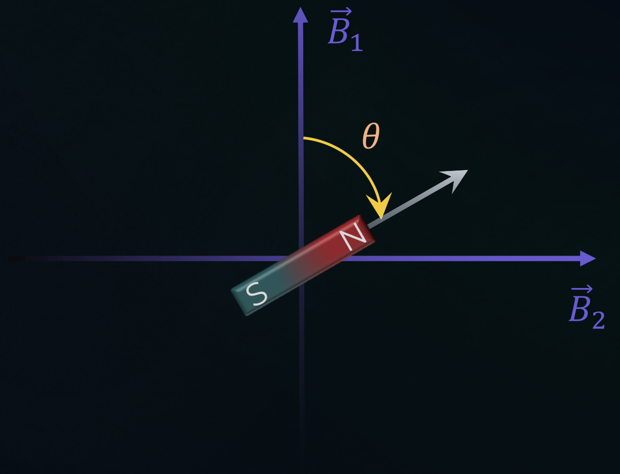
- A dipole is free to rotate in two mutually perpendicular uniform fields $\vec{B}_1$ and $\vec{B}_2$.
- Magnetic moment of the dipole : $\vec{M}$
- For rotational equilibrium :

$$\vec{M} \times \vec{B}_1 = \vec{M} \times \vec{B}_2$$

$$MB_1 \sin\theta = MB_2 \sin(90° - \theta)$$

$$MB_1 \sin\theta = MB_2 \cos\theta$$

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



Deflection Magnetometer : Tan A position

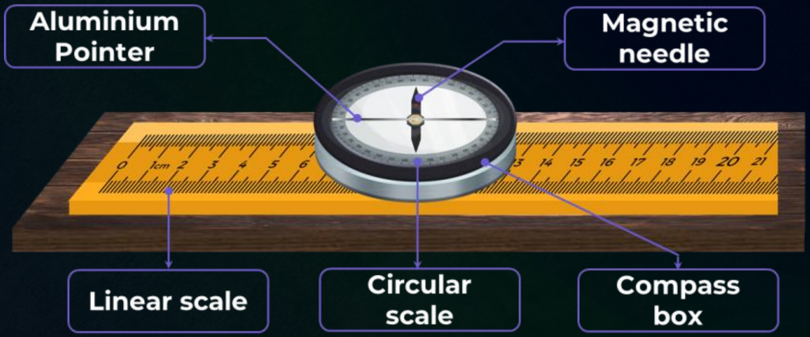
- In this position, the arms of the magnetometer is set along East-West direction i.e., perpendicular to the magnetic meridian.

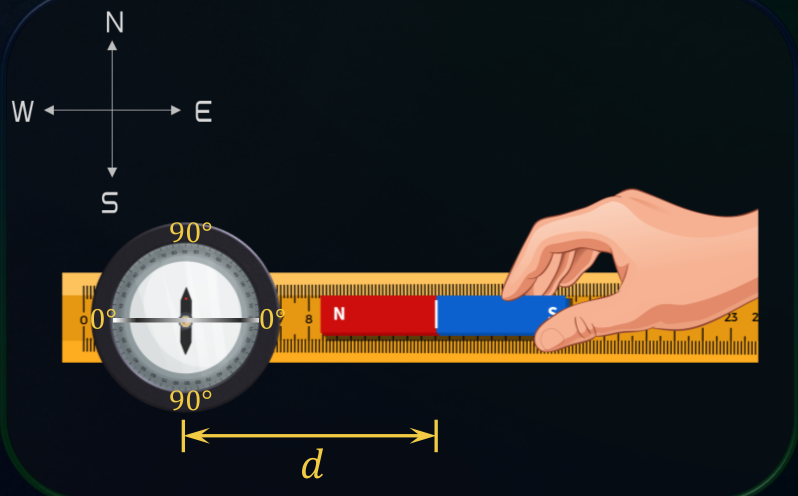
- The external bar magnet in placed with its length parallel to the arm.

- Magnetic field due to a bar magnet at far off point on its axis :

$$B_{bar} = \frac{\mu_0}{4\pi}\left(\frac{2M}{d^3}\right)$$

- The magnetic field B_{bar} due to the bar magnet and Earth's horizontal magnetic field B_H are perpendicular to the each other.





Deflection Magnetometer : Tan A position

- Tangent Law for this situation yields :

$$B_{bar} = B_H \tan\theta$$

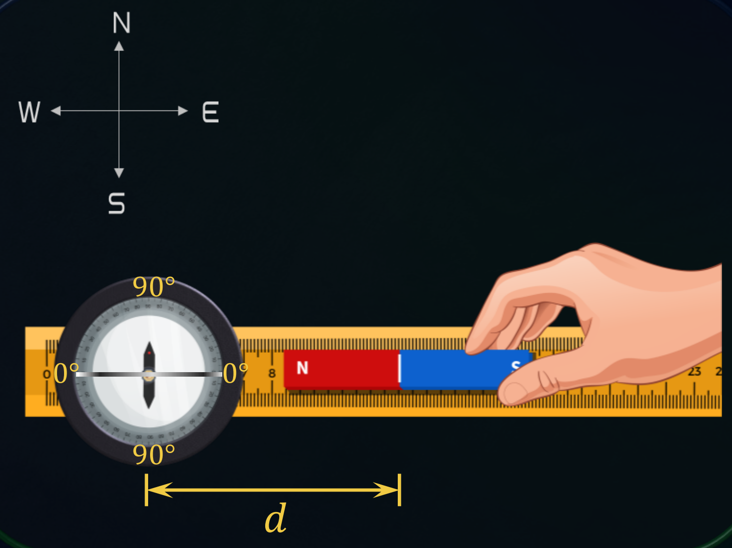
$$\frac{\mu_0}{4\pi}\left(\frac{2M}{d^3}\right) = B_H \tan\theta$$

- Dipole moment of the bar magnet :

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

- For two different bar magnets :

$$\frac{M_1}{M_2} = \frac{\tan\theta_1}{\tan\theta_2} \times \left(\frac{d_1}{d_2}\right)^3$$



Deflection Magnetometer : Tan B position

- In this position, the arms of the magnetometer is set along North-South direction i.e., along to the magnetic meridian.
- The external bar magnet in placed with its length perpendicular to the arm.
- Magnetic field due to a bar magnet at far off point on the equatorial line :

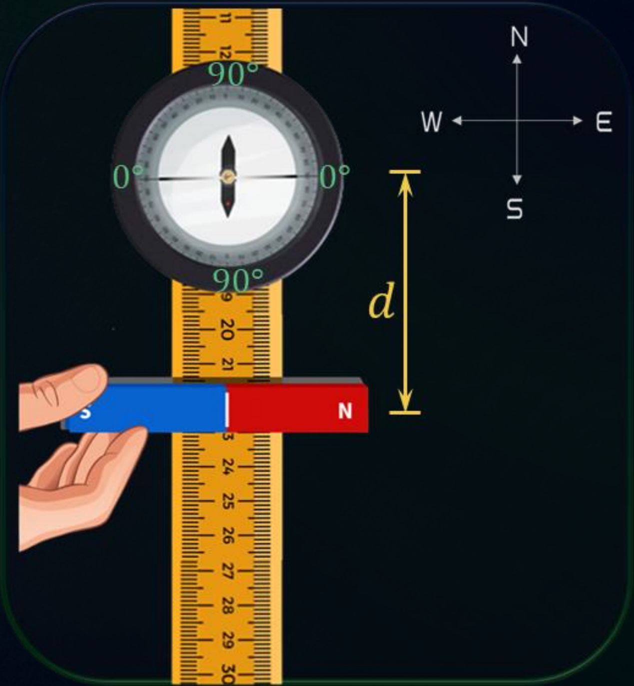
$$B_{bar} = \frac{\mu_0}{4\pi}\left(\frac{M}{d^3}\right)$$

- Tangent Law for this situation yields :

$$B_{bar} = B_H \tan\theta \qquad \frac{\mu_0}{4\pi}\left(\frac{M}{d^3}\right) = B_H \tan\theta$$

- Dipole moment of the bar magnet :

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

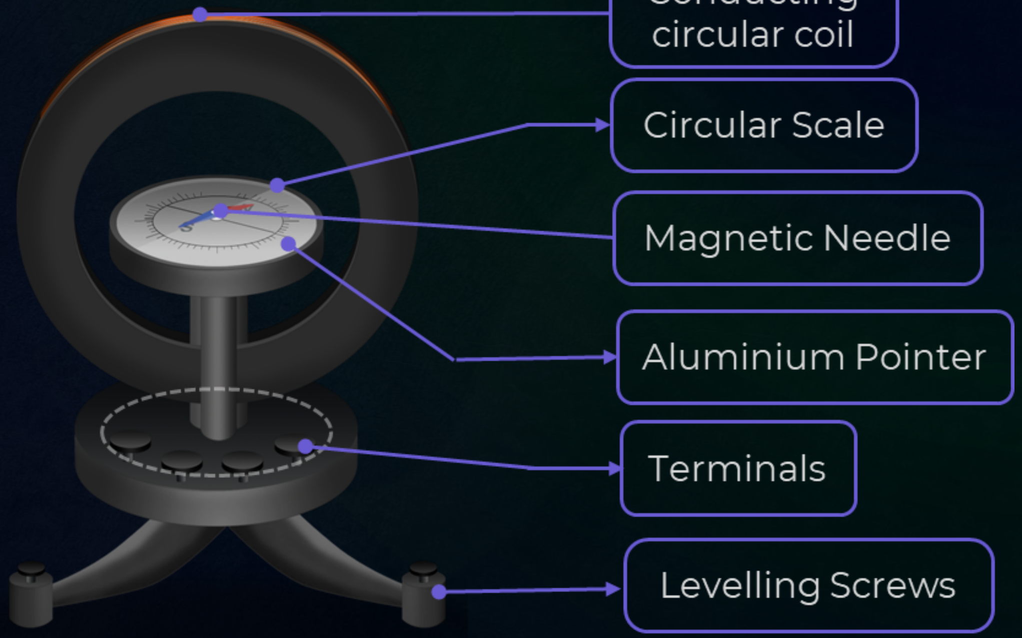


- For two different bar magnets :

$$\frac{M_1}{M_2} = \frac{\tan\theta_1}{\tan\theta_2} \times \left(\frac{d_1}{d_2}\right)^3$$

Tangent Galvanometer : Experimental Setup

- It is an instrument used for the measurement of electric current.
- It uses the Earth's magnetic field to determine the value of the unknown current flowing through the coil.
- It works on the principle of 'tangent law of magnetism'.

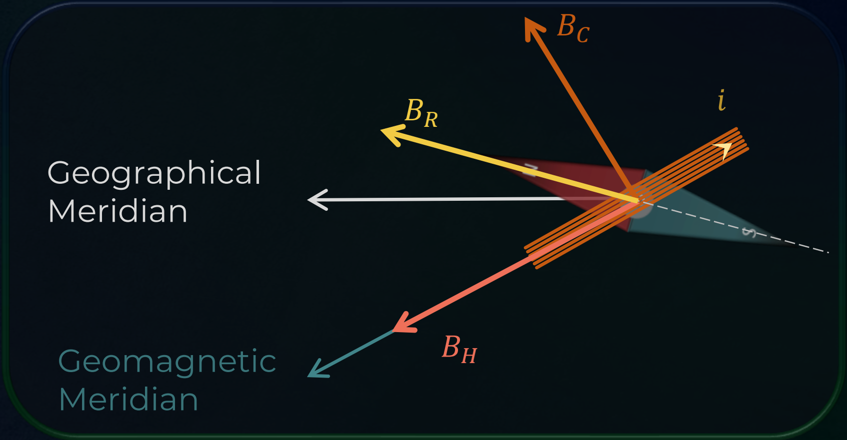


Tangent Galvanometer

Working :

- 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.

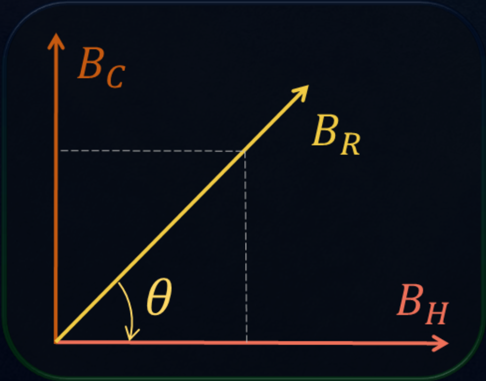
B_C = Magnetic field due to conducting coil
B_H = Magnetic field due to Earth



Resultant magnetic field :

$$B_R = \sqrt{{B_C}^2 + {B_H}^2}$$

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



- θ can be measured on the circular scale.

Tangent Galvanometer : Measurement of Current

$$B_C = B_H \tan\theta$$

$$\frac{\mu_0 n i}{2R} = B_H \tan\theta$$

n = No. of turns in the coil

R = Radius of the coil

$$i = \frac{B_H \tan\theta \; 2R}{\mu_0 n}$$

$$\boxed{i = K \tan\theta}$$

$K = \dfrac{2B_H R}{\mu_0 n} =$ Reduction factor

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., $I_1 = I_2$

$$I_1 = \frac{2rH}{\mu_0 n_1}\tan\theta_1 \qquad I_2 = \frac{2rH}{\mu_0 n_2}\tan\theta_2$$

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

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

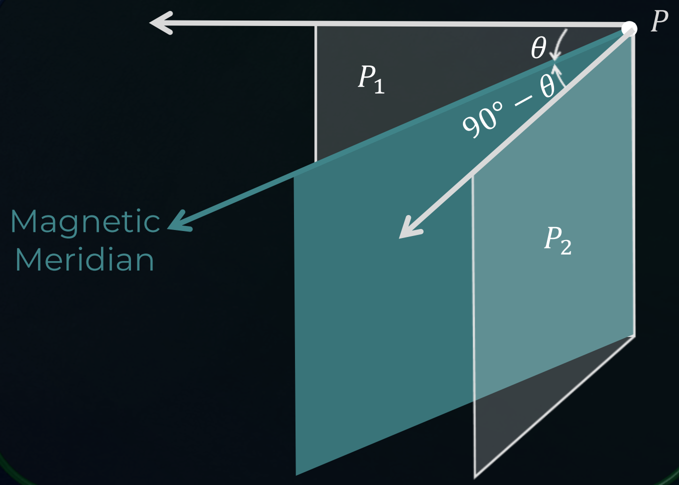
$$\boxed{\frac{n_1}{n_2} = 0.7}$$

The values of apparent angle of dip at two places measured in two mutually perpendicular planes are 30° and 45°. Determine the true angle of dip at the place.

Solution : Apparent dip at plane P_1 : $\delta_1 = 30°$

Apparent dip at plane P_2 : $\delta_2 = 45°$

True dip = δ



$$\tan\delta_1 = \frac{\tan\delta}{\cos\theta} \Rightarrow \cos\theta = \frac{\tan\delta}{\tan\delta_1}$$

$$\tan\delta_2 = \frac{\tan\delta}{\cos(90° - \theta)} = \frac{\tan\delta}{\sin\theta} \Rightarrow \sin\theta = \frac{\tan\delta}{\tan\delta_2}$$

We know : $\sin^2\theta + \cos^2\theta = 1$

$$\frac{\tan^2\delta}{\tan^2\delta_1} + \frac{\tan^2\delta}{\tan^2\delta_2} = 1$$

$$\cot^2\delta_1 + \cot^2\delta_2 = \cot^2\delta$$

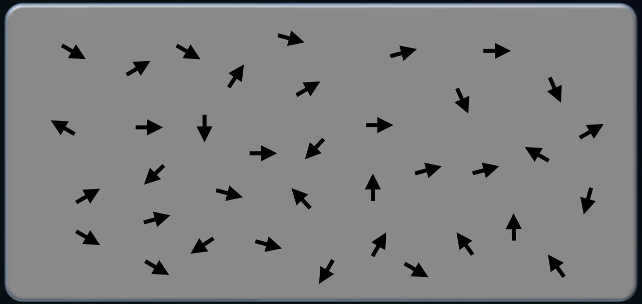
$$\cot^2 30° + \cot^2 45° = \cot^2\delta$$

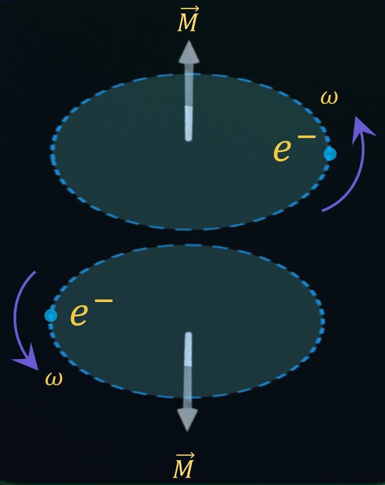
$$\cot\delta = 2$$

$$\boxed{\delta = \tan^{-1}\left(\frac{1}{2}\right)}$$

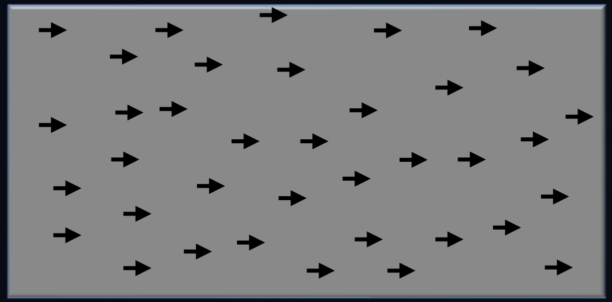
Magnetic Property

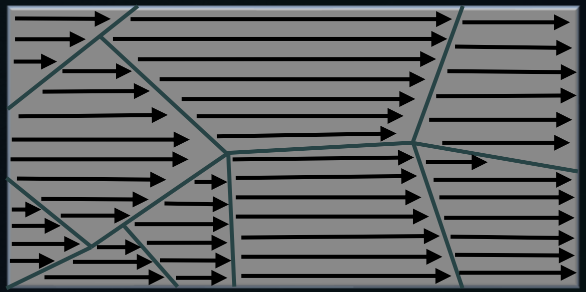
- Every charged particle has an intrinsic property known as "Spin angular momentum".
- Magnetic moment of an atom is due to :
  - Orbital motion of e^-.
  - Magnetic moment due to spin angular moment of e^-.
  - Magnetic moment of nucleus.
- Net magnetic moment ($\vec{M}$) of an atom is a vector sum of magnetic moments.
- Paired electrons cancels the magnetic moment of each other.
- Atoms having only paired electrons can't show magnetic property.
- Atoms having unpaired electrons do have magnetic moment individually, but they are randomly oriented canceling the effect. So, net magnetic moment $\sum \vec{M} = 0$.





Magnetic Property



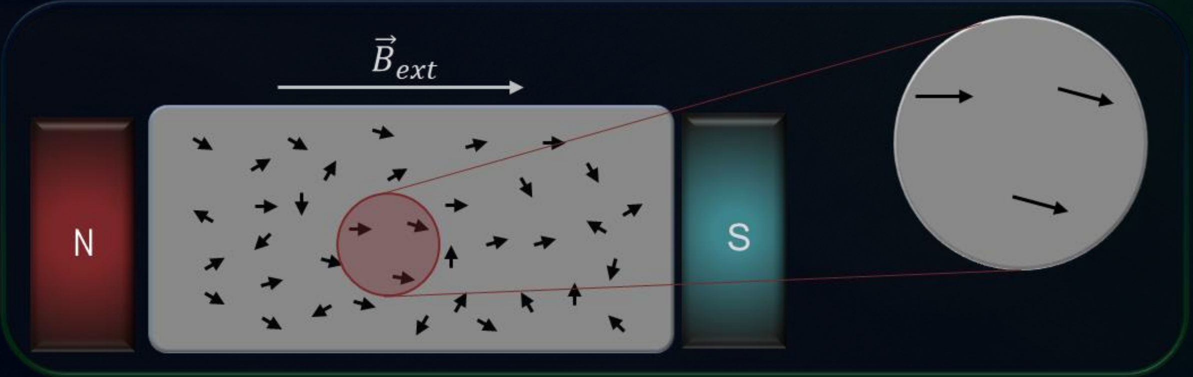


- When atoms having unpaired electrons get aligned in a particular direction, net magnetic moment $\sum \vec{M} \neq 0$ and the material shows magnetic property.
- A cluster of atoms having unpaired electrons is known as "Domain" in which the magnetic moment of the atoms are aligned in same direction.
- When all the domains are aligned in a particular direction, the material shows magnetic property.

Magnetization of Materials

Random alignment of dipoles

$\vec{M} = 0$



Applied external magnetic field → Dipoles get aligned in the direction of external field

$\vec{M} \neq 0$

Intensity of Magnetization ($\vec{I}$)

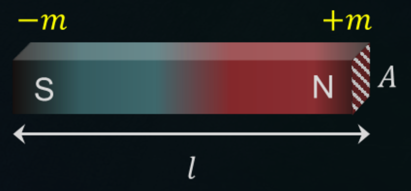
- Intensity of Magnetization :
  Net magnetic moment per unit volume

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

- SI unit: $ampere\ metre^{-1}\ (Am^{-1})$

- $\vec{I}$ depends on nature of material and temperature.

- Intensity of Magnetization for bar magnet :



$$|\vec{I}| = \left|\frac{\vec{M}_{net}}{V}\right| = \frac{m \times l}{A \times l} = \frac{m}{A}$$

- $\vec{I}$ = pole strength per unit cross sectional area.

Magnetic intensity ($\vec{H}$)

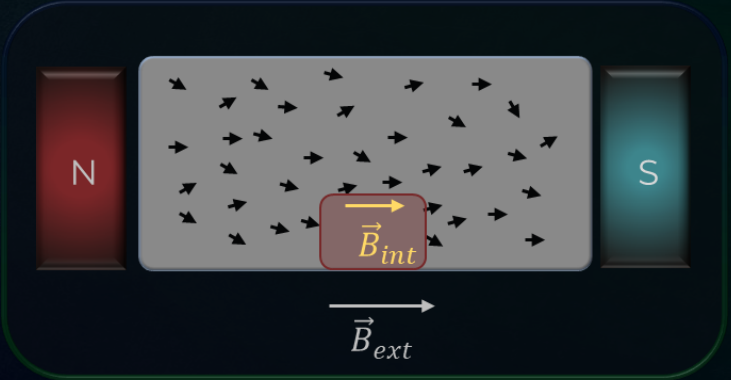
In order to magnetise a magnetic material, it is kept in an external magnetic field B_{ext}. The ratio of the magnetising field to the permeability of free space is known as "Magnetic intensity".

$$\boxed{\vec{H} = \frac{\vec{B}_{ext}}{\mu_0}}$$

- It is a measure of ability of an external magnetic field to magnetize a material medium.
- SI unit : $ampere\ metre^{-1}\ (Am^{-1})$

- Net magnetic field inside the material : $\vec{B} = \vec{B}_{ext} + \vec{B}_{int}$
- Internal factor : $\vec{B}_{int} = \mu_0 \vec{I}$ (Due to alignment of dipoles)
- External factor : $\vec{B}_{ext} = \mu_0 \vec{H}$ (Due to magnetic intensity)

$$\boxed{\vec{B} = \mu_0 \vec{H} + \mu_0 \vec{I}} \quad \text{Or} \quad \boxed{\vec{H} = \frac{\vec{B}}{\mu_0} - \vec{I}}$$



- If no magnetic material is present, $\vec{I} = 0$, in that case;

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

- $\vec{H}$ is a measure of external magnetic field. So, it is independent of nature of medium.

The magnetic intensity H at the centre of a long solenoid carrying a current of $2.0\ A$ is found to be $1500\ Am^{-1}$. Find the number of turns per centimetre of the solenoid?

Solution :

The solenoid is long and no magnetic material is present at its core.

Therefore, magnetic field at the centre :

$$B_0 = \mu_0 ni$$

$$\mu_0 H = \mu_0 ni$$

$$H = ni$$

$$1500 = n \times 2$$

$$n = 750\ turns/metre$$

$$\boxed{n = 7.5\ turns/cm}$$

Magnetic Susceptibility

It is defined as the ratio of the magnitude of "Intensity of magnetization ($\vec{I}$)" to that of "Magnetic intensity ($\vec{H}$)".

$$\boxed{\chi = \frac{I}{H}}$$

- It is a dimensionless and unitless scalar quantity.
- The physical significance of magnetic susceptibility is that it is the degree of ease with which a magnetic material can be magnetised. A material with higher value of χ can easily be magnetized.
- χ depends on nature of material and temperature.

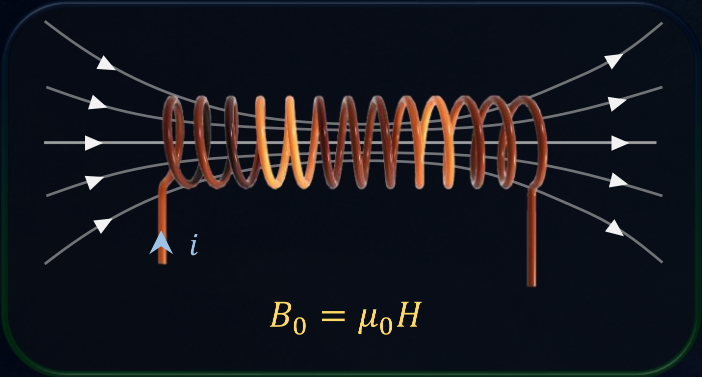
Magnetic Permeability

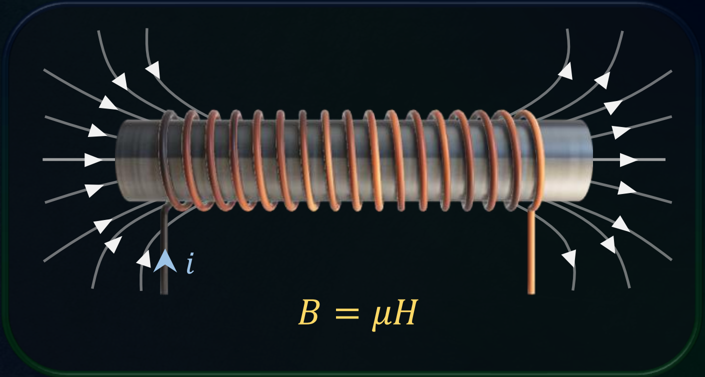
It is defined as the ratio of the magnitude of "total magnetic field ($\vec{B}$)" inside the material to that of "Magnetic intensity ($\vec{H}$)".

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

- It is a scalar quantity.
- SI Unit : Wb/Am^{-1}
- Dimension : $[MLT^{-2}A^{-2}]$
- The physical significance of magnetic permeability is that it measures the extent to which a magnetizing field can penetrate or permeate a given material.

Relative Permeability





- Relative permeability :

  It is defined as the ratio of permeability of a medium (μ) to permeability of free space (μ_0).

$$\boxed{\mu_r = \frac{\mu}{\mu_0} = 1 + \chi}$$

- μ_r is the factor by which magnetic field increases when a material is introduced.

An iron rod of volume $10^{-3}\ m^3$ and relative permeability 1000 is placed as core in a solenoid with $10\ turns/cm$. If a current of $0.5\ A$ is passed through the solenoid, then the magnetic moment of the rod will be :

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For a solenoid having n turns per unit length and carrying a current i, we have :

$$H = ni$$

We have :

$$B = \mu_0(H + I)$$

$$\mu H = \mu_0 H + \mu_0 I$$

$$\mu_0 I = \mu H - \mu_0 H$$

$$I = \left(\frac{\mu}{\mu_0} - 1\right)H$$

$$\boxed{I = (\mu_r - 1)ni}$$

The magnetic moment of the rod :

$$M = I \times V$$

$$M = (\mu_r - 1)ni \times V$$

$$M = (1000 - 1) \times 1000 \times 0.5 \times 10^{-3}$$

$$M = (1000 - 1) \times 1000 \times 0.5 \times 10^{-3}$$

$$M = 499.5 \approx 500\ Am^2$$

$$\boxed{M = 5 \times 10^2\ Am^2}$$

Magnetic Materials

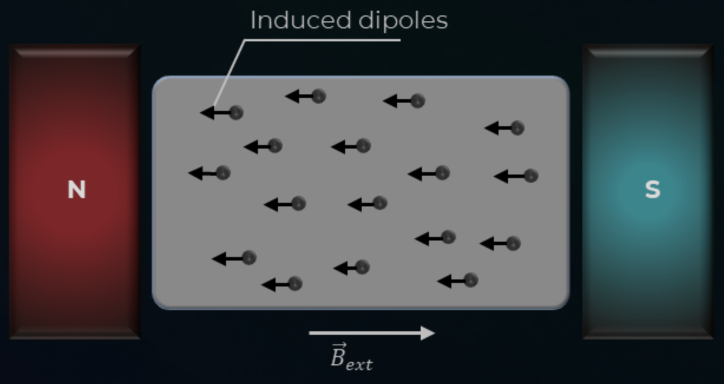
Diamagnetic Materials | Paramagnetic Materials | Ferromagnetic Materials

- Diamagnetic materials have paired electrons only. So, the resultant magnetic moment becomes zero. Hence, diamagnetic materials do not have permanent magnetic dipoles.

- Diamagnetic material is placed in external magnetic field

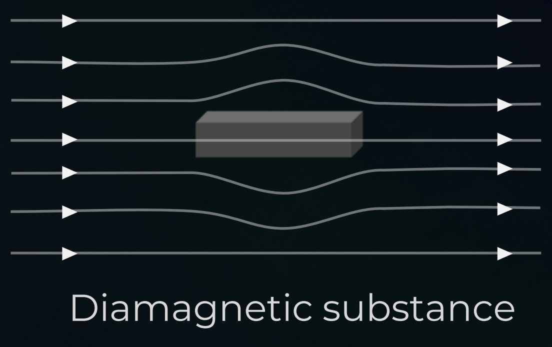
⬇

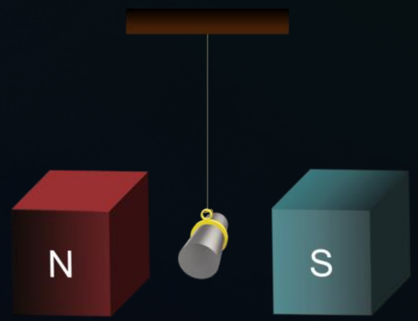
Dipoles are induced but in opposite direction to $\vec{B}_{ext}$.



Diamagnetic Materials

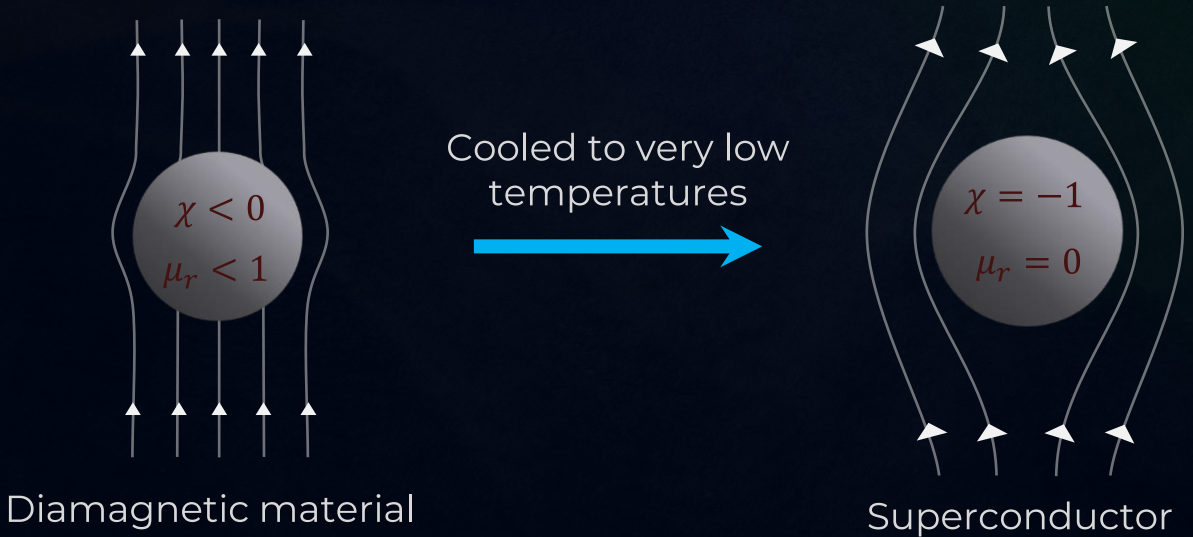
- Magnetic susceptibility : $\boxed{\chi < 0}$ (small and negative)
- Relative permeability : $\boxed{\mu_r < 1}$
- The magnetic field lines are weakly repelled by diamagnetic materials.
- A diamagnetic rod sets itself perpendicular to the field as field is stronger at poles (align itself along weaker field).





Superconductor

- Diamagnetic materials when cooled to very low temperatures exhibit perfect diamagnetism.
- They also show perfect conductivity and thus called Superconductors.
- These superconductors expel the pre-established external field.



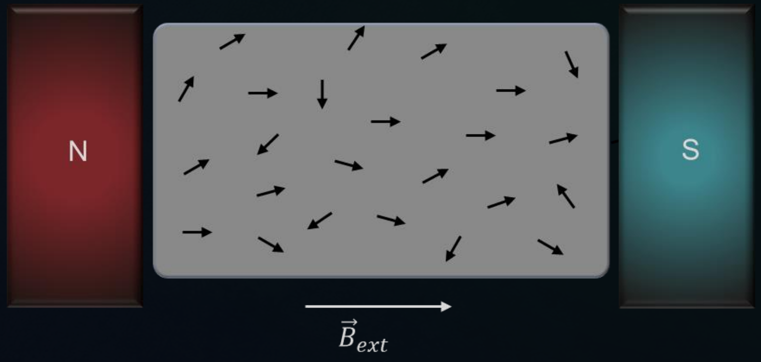
MEISSNER EFFECT

Paramagnetic Materials

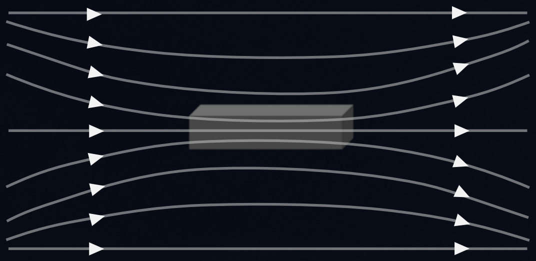
- The substances which get feebly magnetized when placed in external magnetic field, are known as "Paramagnetic substances". E.g., O_2 (at STP), Na, FeO, Al.
- The atoms of these substances have some finite dipole moment.
- Total magnetic moment of the substance is zero due to random orientation in the absence of external magnetic field.
- In presence of external magnetic field, dipoles get aligned in the direction of external magnetic field.

⬇

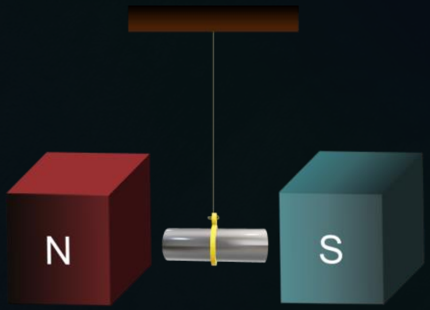
Net magnetization becomes non-zero.



Paramagnetic Materials



Paramagnetic substance



- Magnetic susceptibility : $\boxed{\chi > 0}$ (small and positive)
- Relative permeability : $\boxed{\mu_r > 1}$
- The magnetic field lines become denser inside paramagnetic materials when placed in external magnetic field.

- A paramagnetic rod sets itself parallel to the field as the field is stronger at poles.

A paramagnetic substance in the form of a cube with sides $1\ cm$ has a magnetic dipole moment of $20 \times 10^{-6}\ Am^2$ when a magnetic intensity of $60 \times 10^3\ Am^{-1}$ is applied. Its magnetic susceptibility will be :

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Side length of the paramagnetic cube :

$$a = 1\ cm = 10^{-2}\ m$$

Volume of the paramagnetic cube:

$$V = a^3 = 10^{-6}\ m^3$$

Magnetic dipole moment of the cube:

$$M = 20 \times 10^{-6}\ Am^2$$

So, intensity of magnetization is,

$$I = \frac{M}{V} = \frac{20 \times 10^{-6}}{10^{-6}} = 20\ Am^{-1}$$

Magnetic intensity of the cube:

$$H = 60 \times 10^3\ Am^{-1}$$

Magnetic susceptibility :

$$\chi = \frac{I}{H}$$

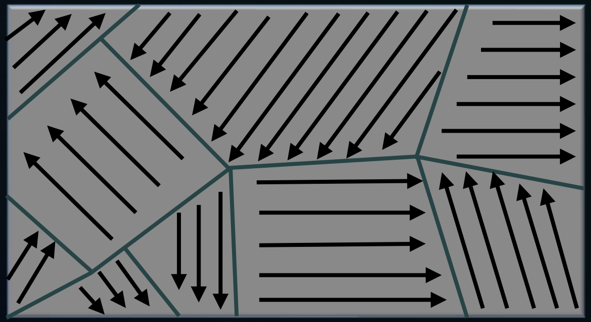
$$\chi = \frac{20}{60 \times 10^3}$$

$$\chi = \frac{1}{3} \times 10^{-3}$$

$$\boxed{\chi = 3.3 \times 10^{-4}}$$

Ferromagnetic Materials

- The substances which get strongly magnetized when placed in an external magnetic field, are known as "Ferromagnetic substances". E.g., Fe, Co, Ni and other alloys.
- Atoms of these substances have permanent dipole moment.
- Domain : It is a macroscopic volume over which the individual dipole moment interacts with one another so that they spontaneously align themselves in a common direction.

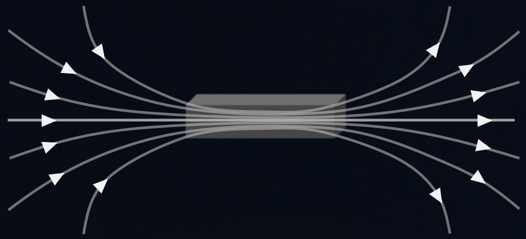


- In the absence of external magnetic field, the domains are randomly oriented.

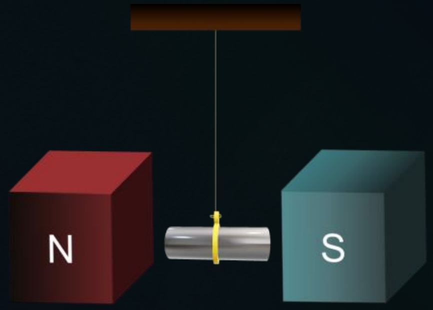
⬇

Net magnetic moment is zero.

Ferromagnetic Materials



Ferromagnetic substance



- Magnetic susceptibility : $\chi \gg 1$
- Relative permeability : $\mu_r \gg 1$
- The magnetic field lines tend to crowd into ferromagnetic materials.

- A ferromagnetic rod quickly sets itself parallel to the field as the field is stronger at poles.

Magnetic Materials

- Diamagnetic Materials
- Paramagnetic Materials
- Ferromagnetic Materials

Diamagnetic	Paramagnetic	Ferromagnetic
$-1 \leq \chi \leq 0$	$0 < \chi < k$	$\chi \gg 1$
$0 \leq \mu_r \leq 1$	$1 < \mu_r < 1 + k$	$\mu_r \gg 1$
$\mu < \mu_0$	$\mu > \mu_0$	$\mu \gg \mu_0$

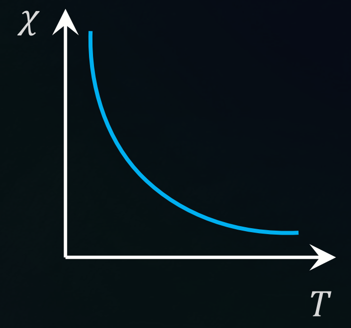
k = Small positive number

Curie's law

- For paramagnetic substances :

  Magnetic susceptibility of a paramagnetic substance is inversely proportional to absolute temperature.

  $\boxed{\chi \propto \frac{1}{T}}$ Or $\boxed{\chi = \frac{C}{T}}$ C: Curie constant



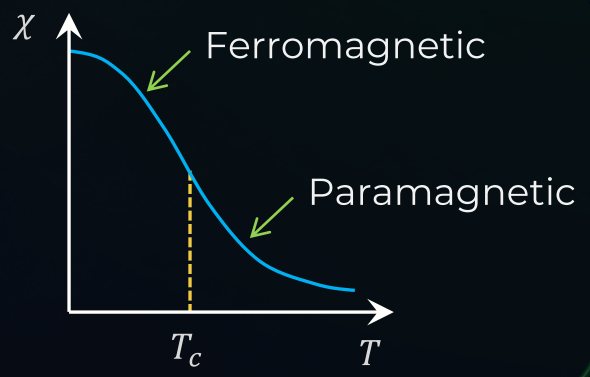
- Curie's temperature :

  The temperature of transition from ferromagnetic to paramagnetic is called the Curie temperature(T_c).

- For ferromagnetic substances :

  At temperature above the curie temperature, a ferromagnetic substance becomes an ordinary paramagnetic substance whose magnetic susceptibility obeys the following law :

  $\boxed{\chi = \frac{C}{T - T_c}}$ C: Curie constant

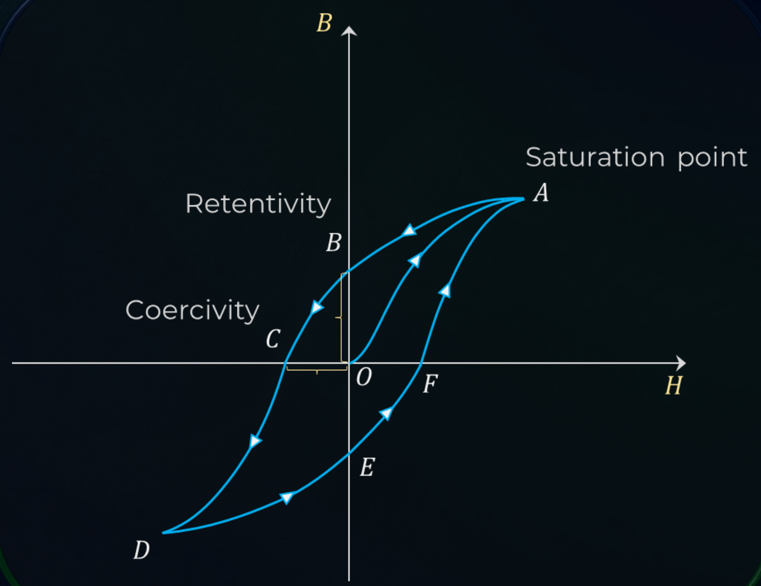


Magnetic Hysteresis

- 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".



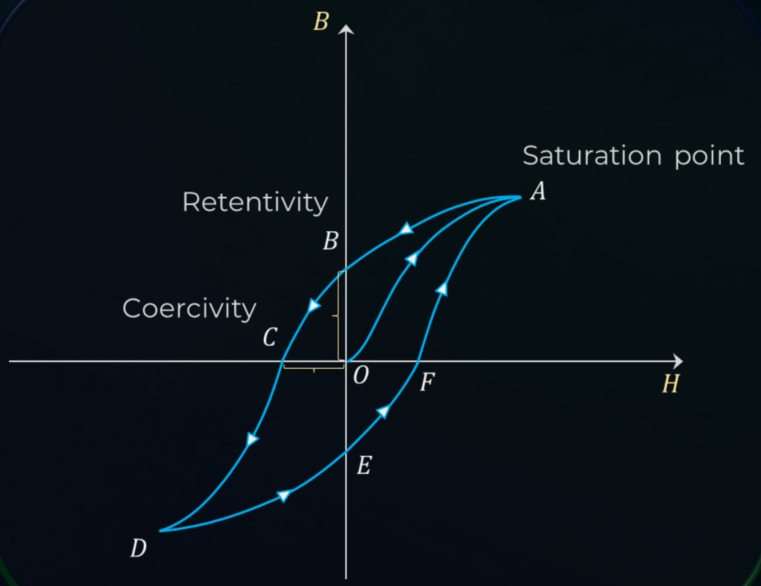
Magnetic Hysteresis

- 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.

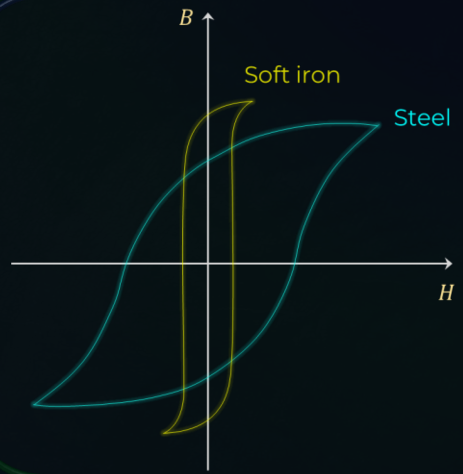
- Area of hysteresis loop ∝ Thermal energy developed per unit volume of the material in a hysteresis cycle.

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



Hard and Soft Magnets

- Hard magnets :
  The ferromagnetic materials which retain magnetisation for a long period of time are hard magnetic materials or hard ferromagnets.
  Examples : Steel, Alnico and naturally occurring lodestone.
- Soft magnets :
  The ferromagnetic materials which retain magnetisation as long as the external field persists are called soft magnetic materials or soft ferromagnets.
  Examples : Soft iron.



Quantity	Steel	Soft iron
Magnetic intensity $(\vec{H})$ for saturation	Very high	Low
Retentivity	Low	High
Coercivity	Very high	Low
Hysteresis loss	High	Low

Permanent Magnet

- The substances which at room temperature retain their magnetization (i.e., ferro-magnetic property) for long period of time are known as "Permanent magnets". E.g., Steel, alnico, cobalt steel and ticonal.
- Substances should have :
    - High retentivity
      (so that the magnet becomes strong)
    - High coercivity
      (so that it couldn't be demagnetized easily)
    - High permeability.
- Uses: In electric clocks, microphones, speakers, generators, motors.

Electromagnet

- An electromagnet is a temporary strong magnet and is just a solenoid with its winding on a material having low retentivity and high permeability. E.g., Soft Iron, aluminium.
- Core material should have :
    - Low retentivity
    - Low coercivity
    - High permeability
- Uses: In electric bells, transformer cores, loudspeakers and telephone diaphragms.