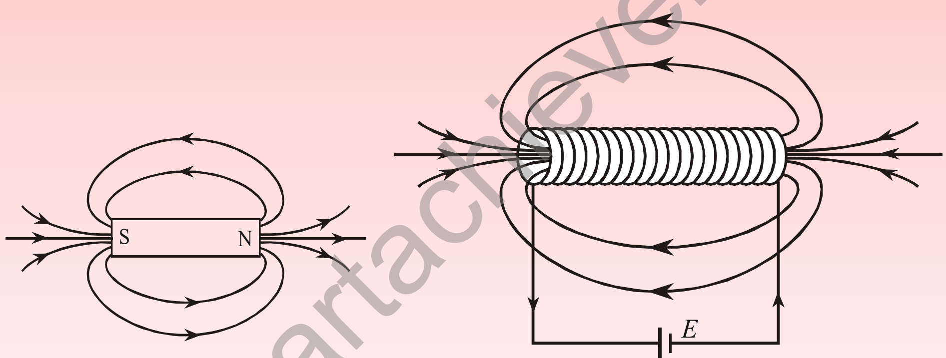
CHAPTER 05

MAGNETISM AND MATTER

Magnetic field due to Bar magnet

- Magnetic field due to a bar magnet is the space around the magnet in which the magnetic effects (of attraction or repulsion) on another small magnet can be experienced.

  The magnetic field produced by a bar magnet and a current carrying solenoid are identical



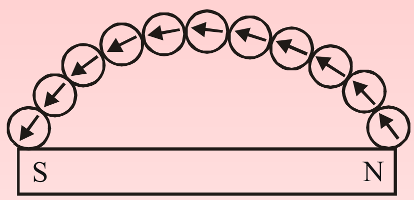
(in figure)

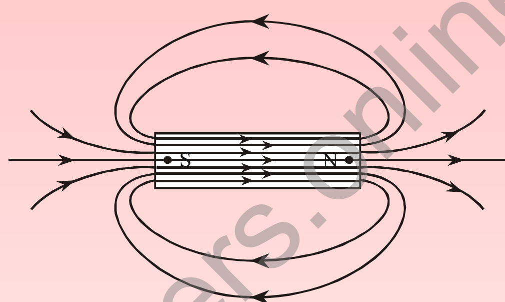
We know that the magnetic field intensity $\vec{B}$ at a point is the force experienced by a unit charge moving with velocity in a direction perpendicular to the magnetic field. We may also define magnetic field intensity $\vec{B}$ at a point as the force experienced by an isolated "hypothetical" unit north pole placed at the point. It is a vector quantity whose direction is the one in which north pole would tend to move if free to do so. It should be noted that the word "hypothetical" has been used because magnetic mono–poles do not exist in reality.

If the magnitude and/or direction of $\vec{B}$ varies in a region, the field is said to be non–uniform. The magnetic field due to a bar magnet is non–uniform and is the strongest at the poles.

Magnetic field lines

- If we place a magnetic compass needle at various points around a bar magnet, starting from one pole and moving towards the other, we get a smooth curve of the type shown in the figure. Each such small curve is called a magnetic field line.





Magnetic field lines are analogous to electric lines of forces. A magnetic field line may be defined as an imaginary line in space such that the tangent at any point in it gives the direction of magnetic field induction $(\vec{B})$ at that point.

❖ **Important properties of magnetic field lines are:**

(i) They are closed, continuous curves extending through the body of the magnet

(ii) The direction of the magnetic field lines is from north pole to south pole outside the body of the magnet while it is from south pole to north pole inside the body of the magnet.

(iii) The tangent to the magnetic field line at any point gives the direction of the magnetic field intensity $\vec{B}$ there.

(iv) The magnetic field lines do not intersect each other as this would mean two different directions of $\vec{B}$ at the same point.

(v) Magnetic field lines crowd together where the field is strong (as at poles) and thin out where it is weak.

Magnetic Dipole moment

➢ It should be recalled that an electric dipole consists of two opposite (unlike) charges of equal magnitude separated by a small distance. Similarly, a magnetic dipole consists of two unlike poles of equal pole–strengths, separated by a small distance.

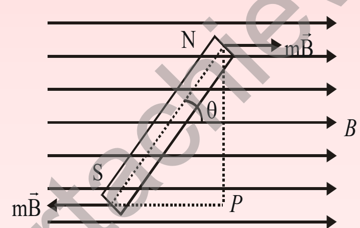
Magnetic dipole moment as the electric dipole moment is defined as the product of the pole strength (equivalent to charge) and the distance between the two poles

$$\vec{M} = m \times 2\vec{l}$$

where $\vec{M}$ is the magnetic dipole moment, m is the pole strength and $2\vec{l}$ is the magnetic length directed from south to north pole.

Magnetic dipole moment is a vector quantity and its direction is from south to north pole within the magnet. It is expressed either in joule per tesla (JT^{-1}) or ampere – metre^2 (Am^2).

❖ TORQUE ON A BAR MAGNET IN A MAGNETIC FIELD



Let a bar magnet NS of magnetic length $2l$ and pole strength m be placed in a uniform magnetic field of strength B. Let the angle between the magnetic axis of the bar magnet and $\vec{B}$ equal θ.

Force on the north pole of the magnet $= m\vec{B}$, along $\vec{B}$.

Force on the south pole of the magnet = $= -m\vec{B}$, opposite to $\vec{B}$.

Since the two forces are equal and opposite, the net force on the bar magnet in a uniform magnetic field is zero. But it should be noted that the two forces have different lines of action and do not act at the same point. So, they constitute a couple which tends to rotate the magnet is the clockwise direction that the magnetic moment $\vec{M}$ and field, $\vec{B}$ are in the same direction.

$\therefore$ Torque (τ) acting on the bar magnet,

$$\vec{\tau} = \vec{r} \times \vec{F} \qquad \text{(From definition)}$$

Here $\vec{r} = 2\vec{l}$ (a vector from S–pole to N–pole)

and $\vec{F} = m\vec{B}$

$\therefore \quad \vec{\tau} = 2\vec{l} \times (m\vec{B})$

$= m(2\vec{l} \times \vec{B})$

Since, $\vec{M} = m(2l)$

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

According to right hand screw rule, the direction of $\vec{\tau}$ is perpendicular to the plane containing $\vec{M}$ and $\vec{B}$. In this case, $\vec{\tau}$ is perpendicular to the plane of the paper and directed inwards.

The magnitude of the torque is given by, $\tau = MB\sin\theta$.

If B = 1, and $\theta = 90°$, then $\tau = M \times 1 \times \sin 90° = M$

or $M = \tau$.

Hence the magnetic dipole moment (M) is numerically equal to the torque on the dipole in a uniform magnetic field of unit strength when held perpendicular to it.

SI unit of magnetic dipole moment is joule per tesla (JT^{-1}).

Torque is maximum, if $\theta = 90°$ $(\sin\theta = 1)$

$\therefore \quad \tau_{max} = MB$

and torque is minimum, if $\theta = 0°$ or $180°$,

$\therefore \quad \tau_{min} = 0$.

Example-1: **A bar magnet has poles of strength 48 amp-m, which are 25 cm apart. What is the magnetic moment of the magnet? What torque is required to hold this magnet on angle of 30° with a uniform field of flux density 0.15 N/A–m? If this magnet is pivoted at the Centre, what force acting perpendicular to the magnet and 6 cm from the pivot is required?**

Solution: Here pole strength m = 48 amp – m separation between pole $2l = 25\,cm = 0.25\,m$.

$\therefore$ Magnetic Moment $M = m.2l = 48 \times .25 = 12\,A - m^2$

Torque, $\tau = MB\sin\theta \quad = 12 \times 0.15 \times \sin 30° \quad = 12 \times 0.15 \times \frac{1}{2} = 9.0\,\text{N} - \text{m} \quad \tau = F.d$

Here d = 6 cm = $6 \times 10^{-2}\,m$

$\therefore$ From $\quad F = \frac{\tau}{d} = \frac{9.0}{6 \times 10^{-2}} = 150\ N$

❖ POTENTIAL ENERGY OF A BAR MAGNET IN A MAGNETIC FIELD

Let a bar magnet NS of magnetic length $2\vec{l}$ and pole strength m be placed in a uniform magnetic field of strength B. Let the angle between the magnetic axis of the bar magnet and $\vec{B}$ equal θ. The magnitude of the torque acting on the magnet is, $\tau = MB\sin\theta$.

This torque tends to align the magnetic dipole in the direction of the field. Work has to be done to rotate the magnet against the action of this torque. The work done is stored in the form of potential energy of the dipole.

The small amount of work done, DW, in rotating the dipole through infinitesimally small angle, $d\theta$, so that the torque can be considered to be constant, is, $dW, = \tau d\theta \ = MB\sin\theta\, d\theta$

Total work done in rotating the dipole from initial position $\theta = \theta_1$ to final position $\theta = \theta_2$, is,

$$W = \int dW = \int_{\theta_1}^{\theta_2} MB\sin\theta\, d\theta$$

$$= MB\,|-\cos\theta\,|_{\theta_1}^{\theta_2} = -MB\,|\cos\theta\,|_{\theta_1}^{\theta_2}$$

Therefore, potential energy of the dipole is,

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

If $\theta_1 = 90°$ and $\theta_2 = \theta$,

$$U = -MB[\cos\theta - \cos 90°] = -MB\cos\theta$$

Vectorially, $U = -\vec{M}.\vec{B}$

It should be noted that:

(i) When $\theta = 0°$, $U = -MB\cos 0° = -MB$ [minimum]

(ii) When $\theta = 90°$, $U = -MB\cos 90° = 0$

(iii) When $\theta = 180°$, $U = -MB\cos 180° = +MB$ [maximum]

Thus, a magnetic dipole has minimum potential energy $(= -MB)$ and no torque acting on it when it is aligned in the direction of field ($\vec{M}$ is parallel to $\vec{B}$) and the magnet is said to be in stable equilibrium.

On the other hand, a magnetic dipole has maximum potential energy $(= +MB)$ and no torque acting on it when it is aligned opposite to the direction of the field ($\vec{M}$ anti parallel to $\vec{B}$) and magnet is said to be in unstable equilibrium.

Gauss's Theorem in Magnetism

- According to Gauss' law in electrostatics, the surface integral of the electric field $\vec{E}$ over any closed surface S, i.e., the total electric flux through the closed surface S in vacuum is $1/\in_0$ times the total charge q inside the surface.

i.e. $$\int_S \vec{E}.d\vec{s} = q/\varepsilon_0$$

If we consider a closed surface S, enclosing an electric dipole, net charge enclosed by the surface becomes zero and hence

$$\int_S \vec{E}.d\vec{s} = 0$$

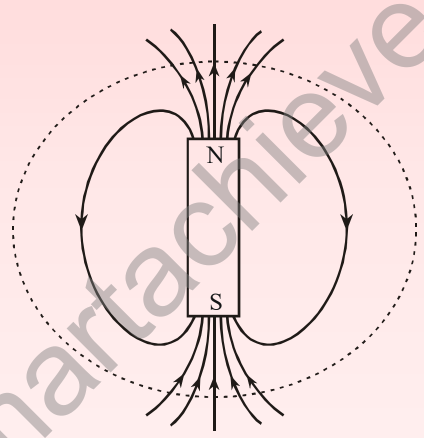
The same principle can be applied to derive Gauss' law in magnetism which has an analogous equation

$$\int_S \vec{B}.d\vec{s} = 0$$

This is so, because magnetic monopoles do not exist and the magnetic poles are always found in pairs of equal strength

So, Gauss' law in magnetism may be stated as the surface integral of the magnetic field intensity $\vec{B}$ over a closed surface is always zero.

Magnetic Flux



Magnetic flux (ϕ_B) through any surface is the number of magnetic lines passing through that surface.

$\phi_B = \vec{B}.\vec{A}$, where $\vec{A}$ is the area vector.

SI unit of magnetic flux is weber (Wb).

1 Wb = $1T \times 1m^2 = 10^8$ maxwell

or $1T = 1Wb/m^2 = 1Wbm^{-2}$

So, magnetic field is sometimes expressed in Wbm^{-2},

Example 2: **A plane loop of irregular shape encloses an area of $7.5\times10^{-4}m^2$ and carries a current of 12 A. The sense of the flow of current appears to be clockwise to an observer. What is the magnitude and direction of the magnetic moment vector associated with the current loop?**

Solution: Here, $A=7.5\times10^{-4}m^2$, $I=12.0\,A$

Magnetic moment, $M=IA=12\times7.5\times10^{-4}=9\times10^{-3}JT^{-1}$

The direction of magnetic moment is perpendicular to the plane of loop, away from the observer [south pole is formed on the face towards the observer].

Example 3: **A circular coil of 300 turns and diameter 14 cm carries a current of 15 A. What is the magnitude of magnetic moment associated with the coil?**

Solution: Here, n = 300; diameter of coil, d = 14 cm = 0.14m; $I=15\,A$, magnetic moment =?

Area of cross section of the coil, $A=\dfrac{\pi d^2}{4}=\dfrac{3.14\times(0.14)^2}{4}=1.54\times10^{-2}m^2$

Now, $M=nIA=300\times15\times1.54\times10^{-2}=69.3\,JT^{-1}$

Example 4: **A short bar magnet placed with its axis at 30° with a uniform external magnetic field of 0.25 T experiences a torque of magnitude equal to $4.5\times10^{-2}J$. What is the magnitude moment of the magnet?**

Solution: Here, $B=0.25T;\theta=30°;\tau=4.5\times10^{-2}J;M=?$

We know that, torque $\tau=MB\sin\theta$

$$\therefore M=\frac{\tau}{B\sin\theta}$$

$$=\frac{4.5\times10^{-2}}{0.25\times\sin30°}=\frac{4.5\times10^{-2}}{0.25\times0.5}=0.36\,JT^{-1}.$$

Example 5: **A magnetized needle of magnetic moment $4.8\times10^{-2}JT^{-1}$ is placed at 30° with the direction of uniform magnetic field of magnitude $3\times10^{-2}T$. What is the torque acting on the needle?**

Solution: Here, magnetic moment, $M=4.8\times10^{-2}JT^{-1}$; $B=3\times10^{-2}T$; $\theta=30°$; torque τ =?

Torque on the needle, $\tau=MB\sin\theta$

$$=4.8\times10^{-2}\times3\times10^{-2}\times\sin30°$$

$$=4.8\times3\times0.5\times10^{-4}=7.2\times10^{-4}J$$

Example 6: **A closely wound solenoid of 800 turns and area of cross–section $2.5\times10^{-4}m^2$ carries a current of 3.0 A. It is free to turn about the vertical direction and a uniform horizontal magnetic field of 0.25 T, is applied. What is the magnitude of the torque on the solenoid when its axis makes an angle of 30° with the direction of the applied field?**

Solution: Here, n = 800; $A=2.5\times10^{-4}m^2$; $I=3.0A$; B= 0.25 T; $\theta=30°$

Now, magnetic moment of the solenoid, M = Nia

$M=800\times3.0\times2.5\times10^{-4}=0.6JT^{-1}$

Torque, $\tau=MB\sin\theta$

$=0.6\times0.25\times\sin30°$

$=0.6\times0.25\times0.5=7.5\times10^{-2}J$

Example 7: **Closely wound solenoid of 2000 turns and area of cross – section $1.6\times10^{-4}m^2$, carrying a current of 4.0 A, is suspended through its Centre, allowing it to turn in a horizontal plane.**

(a) What is the magnetic moment associated with the solenoid?

(b) What is the force and torque on the solenoid if a uniform horizontal magnetic field of $7.5\times10^{-2}T$ is set up at an angle of 30° with the axis of the solenoid?

Solution: Given number of turns of solenoid, N = 2000

Area of cross section, $A=1.6\times10^{-4}m^2$, current I = 4.0 A

(a) Magnetic moment of solenoid $M=NiA=2000\times4.0\times1.6\times10^{-4}=1.28JT^{-1}$

(b) $B=7.5\times10^{-2}T$; $\theta=30°$

Net force on the solenoid in a uniform magnetic field is zero

Net torque on solenoid $\tau=\vec{M}\times\vec{B}=MB\sin\theta$

$=1.28\times7.5\times10^{-2}\times\sin30°=4.8J$

Example 8: **A short bar magnet of magnetic moment $M=0.32JT^{-1}$ is placed in a uniform external magnetic field of 0.15 T. If the bar is free to rotate in the plane of the field, which orientations would correspond to its (i) stable and (ii) unstable equilibrium? What is the potential energy of the magnet in each case?**

Solution: Here $M=0.32JT^{-1}$; $B=0.15T$

For equilibrium of the magnet in an external magnetic field, torque $\tau=0$. There $\theta=0$ or $180°$. $[\because\ \tau=MB\sin\theta]$

Potential energy of the magnet in the magnetic field

$$U = -MB\cos\theta$$

For $\theta = 0$, $U = -MB$

$$= -(0.32)\times(0.15) = -0.048\ J$$

For $\theta = 180°$ $U = +MB = +0.48\ J$

Example 9: **A bar magnet of magnetic moment $1.5\,JT^{-1}$ lies aligned with the direction of a uniform magnetic field of 0.22 T. What is the amount of work required to turn the magnet so as to align its magnetic moment.**

(1) Normal to the field direction,

(ii) Opposite to the field direction?

(b)What is the torque on the magnet in cases (I) and (ii)?

Solution: Here, $M = 1.5\,JT^{-1}$, B = 0.22 T

Initial position of magnet is $\theta = 0°$, as it is aligned.

(a) Work done to move from initial position to final position

$$W = -\left| MB\cos\theta \right|_{\theta=0}^{\theta=\theta} = MB(1-\cos\theta)$$

(i) Here final position is $\theta = 90°$

$\therefore$ Work done is, $W = MB(1-\cos 90°) = MB(1-0) = MB$

$$= 1.5\times 0.22 = 0.33\,J$$

(ii) Here, $\theta = 180°$

$\therefore$ $W = MB(1-\cos 180°) = MB(1-(-1)) = 2MB$

$$= 2\times 0.33 = 0.66\,J$$

(b) Torque, $\tau = MB\sin\theta$

(i) $\theta = 90°$

$\therefore$ $\tau = MB\sin 90° = MB = 0.33\ J$

(ii) $\theta = 180°$

$\therefore$ $\tau = MB\sin 180° = 0$

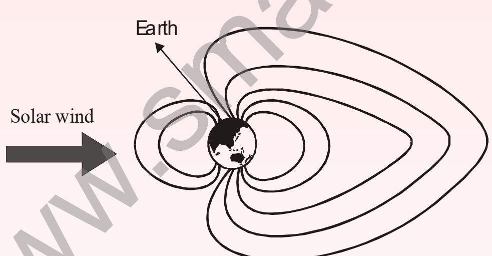
Earth's Magnetism

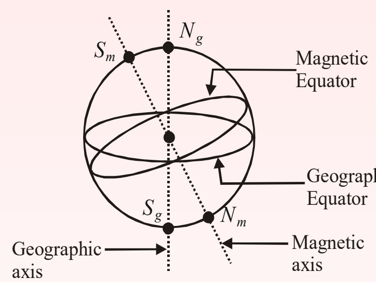
➢ William Gilbert in his book, "De Magnet" in 1600, suggested that the earth itself is a huge magnet and its field is roughly like that of a bar magnet. His conclusion was based on the fact that a freely hanging compass needle, points roughly in the north–south direction. This could be accounted for by a torque on the compass needle exerted by the earth's magnetic field.

❖ PROPERTIES OF EARTH'S MAGNETIC FIELD

1. Earth's magnetic field can be considered to be fairly uniform over the earth's surface. It is more or less what would have been produced by a huge functions bar magnet located inside the earth.
2. The strength of this field at the surface of earth is typically of the order of $10^{-4}T$.
3. This field is not only present on the earth's surface but extends over a distance of more than 32000 km from the surface of the earth. But beyond this distance, the field changes its shape due to solar wind.
4. The south pole of the "earth's magnet", (S_m) is located near the geographical north pole (S_g) . The line joining the two magnetic poles is called the magnetic axis of the earth's magnetic field. The great circle on the earth's surface, perpendicular to this axis is called magnetic equator. It should be noted that the magnetic equator is not same as the geographical equator.

Note: The north pole of a compass needle needs tends to point towards the geographic north and hence the magnetic south pole (S_m), which explains the reason for such alignment (directivity).





❖ CAUSE OF EARTH'S MAGNETISM

The source of geo-magnetism is not any large solid mass of magnetic material 'buried' in it. However, it is believed to be due to an electric current of molten charged metallic fluid inside the earth's core. The radius of the core is about 3500 km, which is approximately half the radius of the earth (6400 km). The high-energy cosmic rays ionize the gas in the earth's atmosphere. As the earth rotates, large electric currents are set up due to these ions. These currents also aid in magnetizing the earth, through the exact role of cosmic rays in geo–magnetism is not yet established.

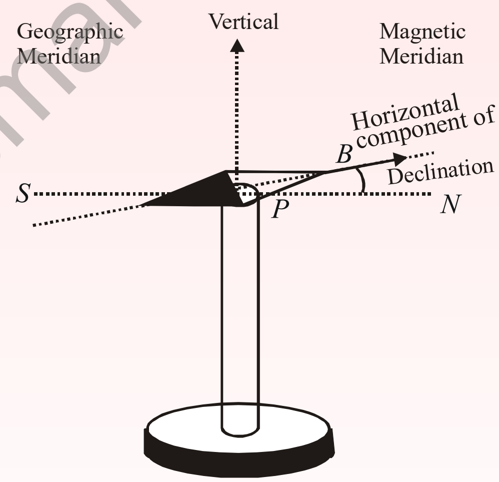
❖ ELEMENTS OF EARTH'S MAGNETIC FIELD

Before taking up the elements of earth magnetic field, we need to introduce certain new terms.

Various components or elements of the earth's magnetic field, at any point on the surface of earth, are:

1. Magnetic declination (θ)
2. Dip angle (δ)
3. Horizontal component of earth's magnetic field (H)

1. **Magnetic Declination:** Magnetic declination at any point is the angle between the magnetic meridian and geographical meridian at that place. In other words, declination is the angle between the horizontal component of B and the north-south direction.

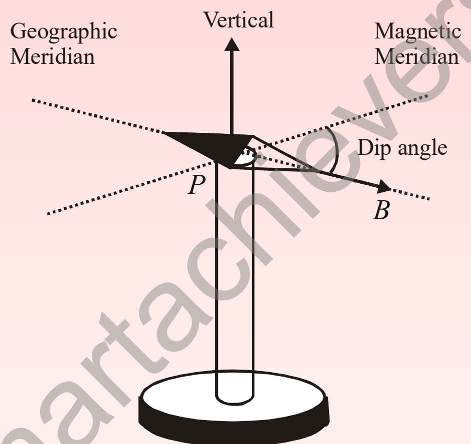


Magnetic declination is not defined at S_m and N_m. At magnetic poles $\vec{B}$ is directly vertically downwards (at S_m) and directed vertically upwards (at N_m), so that the horizontal component is zero at magnetic poles. Therefore, if we place a compass needle free to move in a horizontal plane, it will not point in any particular direction at magnetic poles. Even at N_g and S_g (geographical poles) which are very near to magnetic poles, the value of θ is not well–defined.

2. **Dip angle** (δ) : At any point is the angle between the total intensity of earth's magnetic field (B) and its horizontal component (H). Dip angle is measured using a dip circle.

We know that the earth's magnetic field at any point has two components, a horizontal component (H) and a vertical component (V). The resultant of these two, at any point gives us the resultant intensity of earth's magnetic field (B) at that place.

The angle, which $\vec{B}$ makes with the direction of $\vec{H}$ is called the angle of dip.
It is apparent that to find the dip angle, we must first determine the declination, so that the direction of H is known. So we may say that a dip circle moves in the plane of magnetic meridian.



It should be noted that

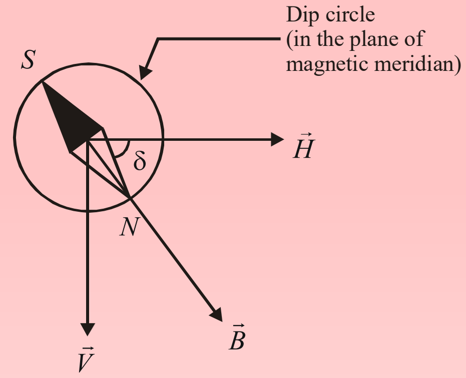
(1) Angle of dip, $\delta = 90°$ at the magnetic poles $(\because H = 0)$.

(ii) Angle of dip, $\delta =$ zero at the magnetic equator $(\because V = 0)$

(iii) In the northern hemisphere, where the south pole of the fictitious magnet lies, the N–pole of the dip circle will "dip–down". And, in the southern hemisphere, the needle "dips–up".

(iv) At any point, near equator, the angle of dip is less (e.g., at southern India, $\delta \simeq 18°$) whereas at a location, near the poles, the angle of dip is more (e.g., at Britain, $\delta \simeq 70°$).

3. Horizontal Component of Earth's Magnetic Field (H) is the component of the total intensity of earth's magnetic field $(\vec{B})$ is the horizontal direction in the plane of magnetic meridian.



It is clear from figure

$$H = B\cos\delta$$

and $$V = B\sin\delta$$

where H is the horizontal component and V is the vertical component of earth's magnetic field.

Squaring and adding, we get

$$H^2 + V^2 = B^2(\cos^2\delta + \sin^2\delta) = B^2(1)$$

$\therefore \quad B^2 = H^2 + V^2 \qquad$ or $\qquad B = \sqrt{(H^2) + (V^2)}$

Dividing the two equations, we get

$$\frac{V}{H} = \frac{B\sin\delta}{B\cos\delta} = \tan\delta$$

$$\therefore \quad \tan\delta = \frac{V}{H}$$

Special cases:

(i) At the magnetic poles, $\delta = 90°$, so $\quad H = B\cos 90° = 0$

(ii) At magnetic equator, $\delta = 0°$, so $H = B\cos 0° = B$

H can be measured using a vibration magnetometer or a deflection magnetometer.

Example-10: **The true value of dip at a place is 30°. The vertical plane carrying the needle is turned through 45° from the magnetic meridian. Calculate the apparent value of the dip.**

Solution: Here, actual value of dip, $\delta = 30°$; $\theta = 45°$; Apparent dip, $\delta_1 = ?$

Let H be the horizontal component of earth's magnetic field in the magnetic meridian, then $\tan\delta = \dfrac{V}{H}$.

Let H_1 be the component of H at 45° to the magnetic meridian, then

$H_1 = H\cos\theta = H\cos 45°$.

$$\therefore \tan\delta_1 = \frac{V}{H_1} = \frac{V}{H\cos 45°} = \frac{\tan\delta}{\cos 45°} = \frac{\tan 30°}{\cos 45°} = \frac{1}{\sqrt{3}} \times \sqrt{2} = 0.8164 \text{ or } \delta_1 = 39°14'$$

Neutral Points

- When a bar magnet is placed along the geo–graphic north–south line and magnetic field lines are traced, the field lines are due to combined field of bar magnet and earth's magnetic field. It is observed that the compass needle rotates freely at some points without pointing along a fixed direction. These points are called neutral points. At such points, the resultant magnetic field is zero and therefore no net force acts on the compass needle.

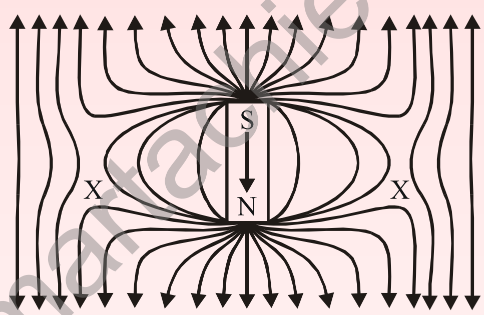
Thus, a neutral point may be defined as a point where the field due to magnet is equal and opposite to the field due to earth or the net field is zero.

If B_m is the field due to a bar magnet and H is the horizontal component of earth magnetic field, then at a neutral point $B_m = H$

As the field of earth is fixed (in magnitude and direction at a place), the position of neutral points for a magnet will depend upon the direction in which the magnet is placed.

Case (i) North pole of the magnet points towards geographic north.

Consider a bar magnet of magnetic length $2l$ and pole strength m placed along the north–south line with its north pole pointing towards the geographic north. If the field lines are plotted, a pattern as shown in figure is obtained. At points marked cross $(\otimes)$, on the equational line of the magnet, the field of the magnet is cancelled by the field of the earth. These are the neutral points.



Let d be the distance of each neutral point from the Centre of the magnet, then the field of the magnet at a distance on the equatorial line of the magnet, is given by,

$$B_m = \frac{\mu_0}{4\pi}\cdot\frac{M}{(d^2+l^2)^{3/2}} \quad \text{.... (i)}$$

At the neutral point, $B_m = H$

$$\therefore \frac{\mu_0}{4\pi}\cdot\frac{M}{(d^2+l^2)^{3/2}} = H \quad \text{... (ii)}$$

For a small magnet,

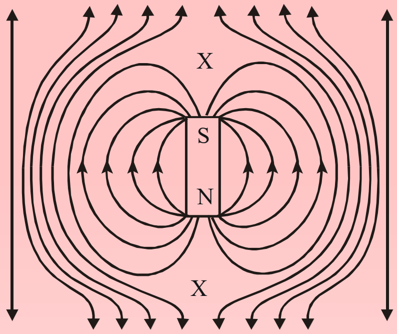
$$B_m = \frac{\mu_0}{4\pi}\cdot\frac{M}{d^3}$$

$$\therefore \frac{\mu_0}{4\pi}\cdot\frac{M}{d^3} = H \quad \text{... (iii)}$$

Knowing d and H, the magnetic moment can be calculated

Case (ii): North pole of the magnet points towards geographic south.

The field lines in this case are shown in figure. Neutral points lie on the axial line of the magnet.



If d is the distance of the neutral point from the Centre of the magnet, then on the axial line of the magnet, $B_m = \frac{\mu_0}{4\pi} \cdot \frac{2Md}{(d^2 - l^2)^2}$.

For a neutral point, $B_m = H$

$$\therefore \quad \frac{\mu_0}{4\pi} \cdot \frac{2Md}{(d^2 - l^2)^2} = H \qquad \text{..... (iv)}$$

For a short magnet, $B_m = \frac{\mu_0}{4\pi} \cdot \frac{2M}{d^3}$

$\therefore$ For a neutral point, $\frac{\mu_0}{4\pi} \cdot \frac{2M}{d^3} = H$

Knowing d and H, magnetic dipole moment can be calculated.

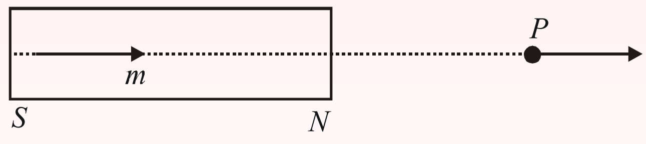
Example-11: **A short bar magnet has a magnetic moment of $0.48\,JT^{-1}$. Give the direction and magnitude of the magnetic field produced by the magnet at a distance of 10 cm from the Centre of the magnet on (i) the axis, (ii) the equatorial line of the magnet.**

Solution: Given magnetic moment $M = 0.48\,JT^{-1}$, $d = 10\,cm = 10^{-1}\,m$

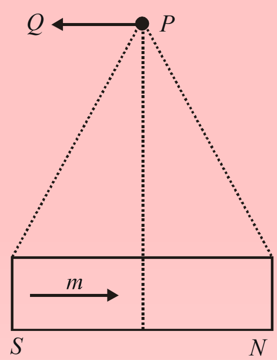
(i) Field at appoint on axis of a short bar magnet is given by

$$B_a = \frac{\mu_0}{4\pi} \cdot \frac{2M}{d^3} = \frac{4\pi \times 10^{-7}}{4\pi} \times \frac{2 \times 0.48}{(10^{-1})^3} = 0.69\,G$$

and is directed along $\vec{NP}$ as shown in figure (a)



(ii) Field at a distance d from Centre of magnet on the equatorial line,

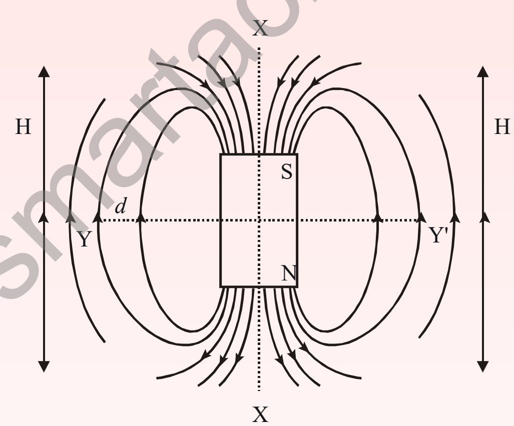


$$B_e = \frac{\mu_0}{4\pi}.\frac{M}{d^3} = \frac{B_a}{2} = 0.48\,G$$

and is directed along PQ, i.e., anti-parallel to the dipole moment of the magnet

Example-12: **A short bar magnet placed in a horizontal plane has its axis aligned along the magnetic north–south direction. Null points are found on the axis of the magnet at 14 cm from the Centre of the magnet. The earth's magnetic field at the place is 0.36 G and the angle of dip is zero. What is the total magnetic field on the normal bisector of the magnet at the same distance as the null points (i.e., 14 cm) from the Centre of the magnet?**

Solution: Given, $H = 0.36\,G; d = 14\,cm$



As shown in the figure, XX are the neutral points lying on the axial line of the magnet. At the neutral point, field due to magnet equals field due to earth, *H* and net field is zero.

$$\therefore \quad B_a = \frac{\mu_0}{4\pi}.\frac{2M}{d^3} = H \qquad \text{... (i)}$$

For a point at a distance 'd' on the normal bisector (YY'), field due to magnet

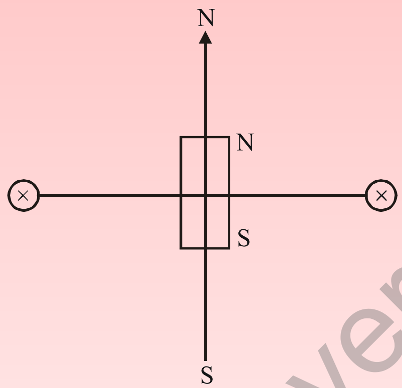
$$B_e = \frac{\mu_0}{4\pi}.\frac{M}{d^3} = \frac{H}{2} \qquad \text{(From equation (i))}$$

The field due to earth at points Y and $Y' = \frac{H}{2} + H = \frac{3}{2}H = \frac{3}{2} \times 0.36 = 0.54\,G$

and is in the direction of earth's magnetic field.

Example-13: **If the bar magnet in example (2) is turned around by 180°, where will be the new null-points be located.**

Solution: In this orientation north pole of the magnet will face north of the earth and therefore neutral points will lie on the equatorial line of the magnet. Let d' be distance of neutral point from the Centre of the magnet.



$\therefore$ For the neutral point

$$\frac{\mu_0}{4\pi}\frac{M}{d'^3} = H \qquad \ldots \text{(i)}$$

In example (2), for the neutral point on the axial line,

$$\frac{\mu_0}{4\pi}\frac{2M}{d^3} = H \qquad \ldots \text{(ii)}$$

$\therefore$ From (i) and (ii)

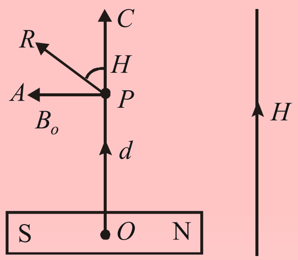
$$\frac{\mu_0}{4\pi}\frac{M}{d'^3} = \frac{\mu_0}{4\pi}\frac{2M}{d^3} \quad \text{or} \quad d'^3 = \frac{d^3}{2}$$

now $d'^3 = \frac{(14)^3}{2}$ or $d = 14 \times 2^{-\frac{1}{3}}\,cm \simeq 11.1\,cm$

Example-14: **A short bar magnet of magnetic moment $5.25 \times 10^{-2}\,JT^{-1}$ is placed with its axis perpendicular to the earth's field direction. At what distance from the Centre of the magnet on (a) its normal bisector (b) its axis, is the resultant field inclined at 45° with the earth's field. Magnitude of the earth's field at the place is given to be 0.42 G. Ignore the length of the magnet in comparison to the distance involved.**

Solution: Given, $M = 5.25 \times 10^{-2}\,JT^{-1}$, $H = 0.42$, $G = 0.42 \times 10^{-4}\,T$.

Solution: Given, $M = 5.25\times10^{-2}\ JT^{-1}$, $H = 0.42$, $G = 0.42\times10^{-4}\ T$.



(a) At a point distance d from the Centre of the magnet along the normal bisector, field of magnet $B_e = \frac{\mu_0}{4\pi}.\frac{M}{d^3}$ and is along the direction PA.

Field due to earth is H and is along, PC

The resultant field at P will make an angle of 45° with H, if

$$\tan 45° = 1 = \frac{H}{B_e}$$

or $\quad B_e = h$

$$\therefore \quad \frac{\mu_0}{4\pi}.\frac{M}{d^3} = H \qquad \text{or} \qquad d = \left(\frac{\mu_0 M}{4\pi H}\right)^{1/3}$$

Substituting values, $d = \left[\frac{4\pi\times10^{-7}\times5.25\times10^{-2}}{4\pi\times0.42\times10^{-4}}\right]^{1/3} = 0.05\,m = 5\,cm$

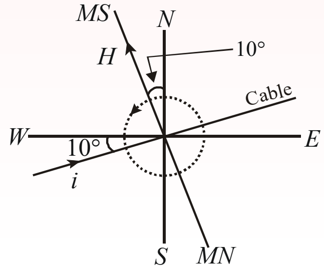
(b) For a point on the axis, resultant field will make an angle of 45° with H if field due to magnet = field H

i.e., $\frac{\mu_0}{4\pi}.\frac{2M}{d_1^3} = H$ or $d_1 = \left(\frac{\mu_0\times 2M}{4\pi H}\right)^{1/3} = 2^{1/3}.\ d$

$d_1 = 2^{1/3}\times5.0 = 6.29\ cm$

Example-15: **A long straight horizontal cable carries a current of 2.5 A in the direction 10° south of west to 10° north to east. The magnetic meridian of the place happens to be 10° west of the geographic meridian. The earth's magnetic field at the location of 0.33 G, and the angle of dip is zero. Locate the line of neutral points (Ignore the thickness of the cable).**

Solution:



This figure shows the magnetic meridian (H) and direction of cable carrying current $i = 2.5\,A$.

$$H = 0.33\,G = 0.33 \times 10^{-4}\,T$$

Let r be the distance of the neutral point from the cable. Then at the neutral point

$$B = \frac{\mu_0 I}{2\pi r} = H \quad \text{or} \quad r = \frac{\mu_0 I}{2\pi H}$$

$$r = \frac{\mu_0 I}{2\pi H} = \frac{4\pi \times 10^{-7} \times 2.5}{2\pi \times 0.33 \times 10^{-4}} = 1.5 \times 10^{-2}\,m = 1.5\,cm$$

By right hand thumb rule, the neutral point lies 1.5 cm above.

Example-16: **A circular coil of 16 turns and radius 10 cm carrying a current of 0.75 A rests with its plane normal to an external field of magnitude $5.0 \times 10^{-2}\,T$. The coil is free to turn about an axis in its plane perpendicular to the field direction. When the coil is turned slightly and released, it oscillates about its stable equilibrium with a frequency of $2.0\,s^{-1}$. What is the moment of inertia of the coil about its axis of rotation?**

Solution: Number of turns n = 16; radius of coil, r = 10 cm = 0.1 m

Current, $i = 0.75\,A$; $B = 5.0 \times 10^{-2}\,T$; $v = 2.0\,s^{-1}$

Area of coil $A = \pi r^2 = \pi \times (0.1)^2 = 0.0314\,m^2$

Magnetic moment of coil $M = niA = 16 \times 0.75 \times 0.0314 = 0.377\,JT^{-1}$

Let I be the moment of inertia of the coil about its axis of rotation. The frequency of rotation is given by

$$v = \frac{1}{2\pi}\sqrt{\frac{MB}{I}} \quad \text{or} \quad I = \frac{MB}{4\pi^2 v^2}$$

Substituting values, we get $I = \dfrac{0.377 \times 5.0 \times 10^{-2}}{4 \times \pi^2 \times (2)^2} = 1.2 \times 10^{-4}\,kg\ m^{-2}$

Example-17: **A magnet makes 30 oscillations per minute at a place where $H = 0.15 \times 10^{-4}\,T$. At another place, it takes 1.5 second to complete one vibration. What is the value of earth's horizontal field at that place?**

Solution: Here frequency $v_1 = 30\ r.p.m = \dfrac{30}{60}\ r.p.s$

$\therefore$ Time period of magnet $T_1 = \dfrac{1}{v_1} = \dfrac{60}{30} = 2\,s$, $H_1 = 0.15 \times 10^{-4}\,T$, $T_2 = 1.5\,s$; $H_2 = ?$

Now $T = 2\pi\sqrt{\dfrac{1}{MH}}$

$\therefore \quad \dfrac{T_1}{T_2} = \sqrt{\dfrac{H_2}{H_1}}$

or $\quad \dfrac{H_2}{H_1} = \dfrac{T_1^2}{T_2^2}$

or $\quad H_2 = \dfrac{T_1^2}{T_2^2} \times H_1$

$$H_2 = \frac{(2)^2}{(1.5)^2} \times 0.15 \times 10^{-4} \quad = 0.26 \times 10^{-4} T$$

Example-18: **A magnet is suspended so that it oscillates in a horizontal plane. It makes 15 oscillations per minute at a place where the angle of dip is 60° and 20 oscillations per minute where the angle of dip is 30°. Compare the earth's total magnetic field at these two places.**

Solution: Here $v_1 = 15$ oscillations/min; $v_2 = 20$ oscillations/min

$\therefore \ T_1 = \dfrac{1}{v_1} = \dfrac{60}{15} = 4\,s$, $T_2 = \dfrac{1}{v_2} = \dfrac{60}{20} = 3\,s$

dip, $\delta_1 = 60°$ and $\delta_2 = 30°$

Let H_1, H_2 be the values of horizontal component of earth's magnetic field and B_1 and B_2 be total field intensities at these two places

$\therefore \ B_1 = \dfrac{H}{\cos\delta_1}$ and $B_2 = \dfrac{H}{\cos\delta_2}$

$\therefore \ \dfrac{B_1}{B_2} = \dfrac{H_1}{H_2}\dfrac{\cos\delta_2}{\cos\delta_1} \ = \dfrac{9}{16}\cdot\dfrac{\cos 30°}{\cos 60°} = \dfrac{9}{16} \times \dfrac{\sqrt{3}}{2} \times \dfrac{2}{1} = \dfrac{9\sqrt{3}}{16}$

Example-19: **The time period of a vibration magnetometer with two magnets in the 'sum' position is 2 seconds. If the polarity of one of the magnets is reversed (i.e., now in the difference position), the time period becomes 3 seconds. Compare the magnetic moments of the two magnets.**

Solution: Here $T_1 = 2\,s$, $T_2 = 3\,s$

Let M_1 and M_2 be the magnetic moments of two magnets, then

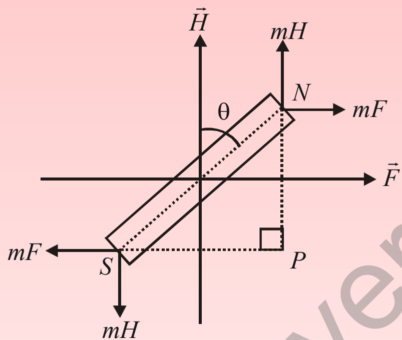
$$\frac{M_2}{M_1} = \frac{T_2^2 - T_1^2}{T_2^2 + T_1^2} \quad = \frac{3^2 - 2^2}{3^2 + 2^2} = \frac{9-4}{9+4} = \frac{5}{13}$$

$\therefore \ M_1 : M_2 = 13 : 5$

Tangent Law in Magnetism

- According to the tangent law, if a magnet is suspended under the combined action of two uniform magnetic fields of intensities H and F, the field being perpendicular to each other, then the magnet comes to rest making an angle θ with the direction of H such that $F = H\tan\theta$

Proof: Let us take a bar magnet NS of magnetic length $2l$, pole strength m and dipole moment M.



When placed under the combined influence of two mutually perpendicular fields H and F, the magnet comes to rest making an angle θ with H. We know that a magnet experiences a torque when a placed in any magnetic field.

Torque due to field $H = mH \times SP$ (anticlockwise)

Torque due to field $F = mF \times NP$ (clockwise)

$\therefore \quad mH \times SP = mF \times NP$

$$\therefore \quad F = H \times \frac{SP}{NP} = H\tan\theta$$

Magnetic Permeability

- As the name suggests, magnetic permeability is a measure of 'how permeable', a material is for the passage of magnetic field lines through it, i.e., a measure of its ability to permit the passage of magnetic field lines through it.

Denoted by μ_m, it is defined as the ratio of the magnetic induction (B) of the magnetized specimen to the strength of the magnetization field (H).

$$\therefore \ \mu_m = \frac{B}{H}$$

The value of μ_m is constant for a given medium and depends solely upon the nature of the medium.

The permeability of the free space (vacuum) is denoted by μ_0,

and $\mu_0 = 4\pi \times 10^{-7}\, TmA^{-1}$ (or $Wb\,A^{-1}m^{-1}$)

The relative magnetic permeability of a magnetic substance (μ_r) is defined as

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

Therefore, μ_r is dimensionless and has no units.

Magnetic susceptibility

- Magnetic susceptibility is a measure of how 'susceptible' a material is to get magnetized i.e., how easily and how strongly a substance can be magnetized by the H – field.

Susceptibility of a magnet material is defined as the ratio of the intensity of magnetization (I) induced in the substance to the strength of the magnetizing field (H) in which it has been placed. It is denoted by χ_m,

Thus, $$\chi_m = \frac{I}{H}$$

Since units of I and H are same $(Am^{-1}), \chi_m$ has no units and is dimensionless.

❖ RELATION BETWEEN RELATIVE PERMEABILITY AND SUSCEPTIBILITY

$B = \mu_0(H + I)$ (considering only the magnitudes)

As $\chi_m = \frac{1}{H}$, $\therefore$ $I = \chi_m H$

$$\therefore \quad B = \mu_0(H + \chi_m H)$$
$$= \mu_0 H(1 + \chi_m)$$

But we know that the permeability of a magnetic material placed in a magnetizing field, is

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

$$\therefore \quad B = \mu H$$

So, $$\mu H = \mu_0 H(1 + \chi_m)$$

or $$\frac{\mu}{\mu_0} = 1 + \chi_m$$

or $$\mu_r = 1 + \chi_m \,. \qquad \text{.... (viii)}$$

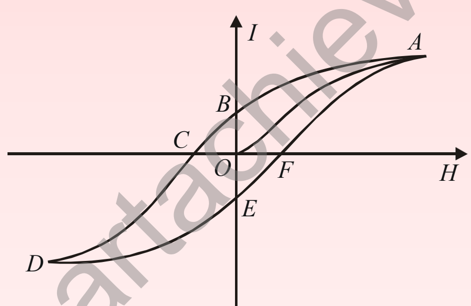
❖ CLASSIFICATION BETWEEN DIA, PARA AND FERRO-MAGNETIC MATERIALS

	Diamagnetic	Paramagnetic	Ferromagnetic
1.	Such substances are repelled weakly by a magnet	Such substances are weakly attracted by a magnet	Such substances are strongly attracted by a magnet
2.	Individual atoms or molecules have no net magnetic moment in the absence of H–field	Individual atoms or molecules have non–zero magnetic moments in the absence of H–field	Individual atoms or molecules have non–zero magnetic moments with 'atomic magnets' organized into domains in the absence of H–field.
3.	When placed in external magnetic field, then within the material, the resultant field is reduced and field lines are repelled by such materials	When placed in uniform external magnetic field, then within the material resultant field is enhanced and field lines concentrate.	When placed in external magnetic field, then within the material, field is strongly enhanced and filed lines are highly concentrated.
4.	When placed in a non–uniform external magnetic field, the substance tends to move from high to low field region	When placed in non–uniform external magnetic field, the para–magnetic substance tends to move from low to high field region	When placed in non–uniform external magnetic field, the substance has strong tendency to move from low to high field region.
5.	μ_r is just less than one	μ_r is just greater than one	$\mu_r >> 1$ (~ 680 for iron)
6.	Susceptibility of Dia-magnetic substance is negative $(\chi_m < 0)$	Susceptibility (χ_m) of paramagnetic substances has small positive value $(\chi_m > 0)$.	Susceptibility for ferro–magnetic substances have large positive values $(\chi_m \simeq 680$ for iron).
7.	Susceptibility does not change with temperature and diamagnetic do not obey Curie law	χ_m varies inversely with the increase of temperature and paramagnetic substances obey Curie law.	Susceptibility decreases with the increase in temperature and beyond Curie temperature, ferro–magnetic substances behave like paramagnetic substances.

Hysterisis

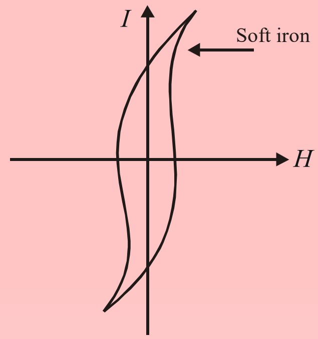
- Consider an iron bar being magnetized slowly by a magnetizing field (H) whose strength can be changed. It is found that the intensity of magnetization (I) increases with the strength of the magnetizing field and then attains a saturated level
- The value of the magnetizing field H which has to be applied to the magnetic material in the reverse direction so as to reduce its residual magnetism to zero, is called its coercivity.

When the strength of the H–field is further increased in the reverse direction, the intensity of magnetization increases along CD till it acquired saturation at point D (points A and D are symmetrical). If we now again change the direction of the field (i.e., make it same as the first case), the intensity of magnetization follows the path DEFA. This closed curve ABCDEFA is called the hysteresis loop and it represents a cycle of magnetization. The word 'hysteresis' literally means lagging behind. We have seen that intensity of magnetization, I, lags behind the magnetizing field, H in a cycle of magnetization (even when H = 0, I does not reduce to zero). This phenomenon of lagging of intensity of magnetization behind the magnetizing field is called hysteresis. The variation between B and H is similar to that between I and H, and it leads to B – H hysteresis loop similar to the I – H hysteresis loop discussed above



- **Hysteresis loss:** In the process of magnetizing of a ferro–magnetic substance through a cycle, there is expenditure of energy. The energy spent in magnetizing of a specimen is not recoverable and there occurs a loss of energy in the form of heat. This is so because, during a cycle of magnetizing, the molecular magnets in the specimen are oriented and reoriented a number of times. This molecular motion results in the production of heat. It has been found that loss of heat energy per unit volume of the specimen in each cycle of magnetizing is equal to the area of the hysteresis loop.

  The shape and size of the hysteresis loop is characteristic of each material, because of the differences in their retentivity, coercivity, permeability, susceptibility and energy losses etc. By studying hysteresis loops of various materials, one can select, materials suitable for different purposes.



❖ USE OF FERROMAGNETIC MATERIALS

1. Permanent magnets:

The idea material for making permanent magnets should possess high retentivity (residual magnetism) and high coercivity so that the magnetization lasts for a longer time. Examples of such substances are steel and alnico (an alloy of Al, Ni and Co).

2. Electromagnets.

Material employed for making an electro–magnet has to undergo cyclic changes. So, the ideal material for making electromagnets has to be one which has to be one which has to be one which has the least hysteresis loss. Moreover, the material should attain high values of magnetization (I) at low values of magnetizing field (H).

Soft iron is preferred for making electro–magnets as it has this hysteresis loop [small area, therefore less hysteresis loss] and it attains high values of I and B at low values of magnetizing field (H). [μ and χ are large for soft iron at low magnetizing fields]

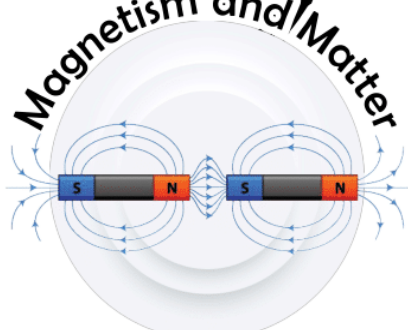
3. Core of the transformer:

A material used for making transformer cores is subjected to cyclic changes very rapidly. And also, the material must have a large value of magnetic induction (B) or magnetization (I). Therefore, the material with thin and tall hysteresis loops like soft–iron is ideal. Some alloys with low hysteresis loss are: radio–metals, perm–alloy and mu–metal. The requirements for materials used for making chokes and diaphragms of telephones are also similar.

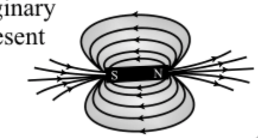
4. Magnetic tapes and memory store: Magnetization of a magnet depends not only on the magnetizing field but also on the history of magnetization of the specimen (i.e., the cycles of magnetization it has undergone). Thus, the value of magnetization of the specimen is a record of the cycles of magnetization it has undergone. So, such a system can act as a device for storing memory.

Ferromagnetic materials have been used for coating magnetic tapes in a cassette player and for building a memory store in a modern computer. Examples of such substances are: Ferrites, e.g., $Fe.Fe_2O$, $MnFe_2O_4$.

Magnetism and Matter



- **Magnetic terms**
  - Time period oscillating bar magnet: $T = 2\pi\sqrt{\frac{I}{MB}}$
  - Intensity of magnetization: $I = \frac{M}{V}$
  - Magnetic Susceptibility: $\chi = \frac{I}{H}$
  - Magnetic permeability: $\mu = \mu_0(1+\chi_m)$
  - Magnetic intensity: $H = \frac{B_0}{\mu}$
- **Magnetic substance**
  - Para-magnetism: Tendency to increase the magnetic field due to magnetization, e.g., *Al, Mn* (χ_m low and $-ve$, $\mu_r > 1$)
  - Ferromagnetism: Tendency of strong magnetization in the direction of magnetic field. e.g., *Fe, Co, Ni*, ($\mu_r, \chi_m >> 1$)
  - Diamagnetism: Tendency to magnetise in a direction opposite to direction of magnetic field e.g., *Bi, Cu, Hg, Ag* ($\mu_r, \chi_m < 1$)
- **Magnetic field lines**
  - Continuous imaginary lines which represent the direction of magnetic field.



- **Solenoid**
  - $\mu = NIA$, N = Number of turns, I = Current, A = Area
- **Bar magnet**
  - **Magnetic field intensity**
    - End–on–position $= \frac{\mu_0}{4\pi}\frac{2M}{d^3}$, $M = 2ml$, $d >>> l$
    - Broad-side Position, $B = \frac{\mu_0}{4\pi}\frac{M}{(d^2+l^2)^{3/2}}$. For $d >>> l$, $B = \mu_0 M/4\pi d^3$
  - Potential energy of a Field-Magnet System: $U_\theta = U_\theta - U_{90^\circ} = -MB\cos\theta = -\vec{M}.\vec{B}$, we take P.E. at $\theta = 90^\circ$ to be zero
  - Torque: $\vec{\tau} = \vec{M} \times \vec{B} = MB\sin\theta$, $M = 2ml$, B = Magnetic field

Trace the Mind Map
- First Level
- Second Level
- Third Level

PRACTICE QUESTIONS

1. A magnet is suspended in the magnetic meridian with an untwisted wire. The upper end of wire is rotated through 180° to deflect the magnet by 30° from magnetic meridian. When this magnet is replaced by another magnet, the upper end of wire is rotated through 270° to deflect the magnet 30° from magnetic meridian. The ratio of magnetic moments of magnets is

a)1 : 5 b) 1 : 8 c) 5 : 8 d) 8 : 5

2. If a magnetic substance is kept in a magnetic field, then which of the following substance is thrown out?

a) Paramagnetic b) Ferromagnetic c) Diamagnetic d) Antiferromagnetic

3. A magnet performs 10 oscillations per minute in a horizontal plane at a place where the angle of dip is 45° and the total intensity is 0.707 CGS units. The number of oscillations per minute at a place where dip angle is 60° and total intensity is 0.5 CGS units will be

a) 5 b) 7 c) 9 d) 11

4. Two identical bar magnets are placed one above the other such that they are mutually perpendicular and bisect each other. The time period of this combination in a horizontal magnetic field is T. The time period of each magnet in the same field is

a) $\sqrt{2}\,T$ b) $2^{\frac{1}{4}}\,T$ c) $2^{\frac{1}{4}}\,T$ d) $2^{\frac{1}{2}}\,T$

5. Ratio of magnetic intensities for an axial point and a point on broad side-on position at equal distance d from the centre of magnet will be or the magnetic field at a distance d from a short bar magnet in longitudinal and transverse positions are in the ratio

a) 1 : 1 b) 2 : 3 c) 2 : 1 d) 3 : 2

6. A magnetic dipole is placed at right angles to the direction of lines of force of magnetic induction B. If it is rotated through an angle of 180°, then the work done is

a) MB b) $2\,MB$ c) $-2\,MB$ d) Zero

7. A domain in a ferromagnetic substance is in the form of a cube of side length 1 μm. If it contains 8×10^{10} atoms and each atomic dipole has a dipole moment of $9 \times 10^{-24}\ A\ m^2$, then magnetization of the domain is

a) 7.2×10^5 A m^{-1} b) 7.2×10^3 A m^{-1} c) 7.2×10^9 A m^{-1} d) 7.2×10^{12} A m^{-1}

8. A bar magnet is placed north-south with its north pole due north. The points of zero magnetic field will be in which direction from center of magnet

a) North and south
b) East and west
c) North-east and south-west
d) North-east and south-east

9. If a magnetic dipole of dipole moment M rotated through an angle θ with respect to the direction of the field H, then the work done is

a) $MH\sin\theta$ b) $MH(1-\sin\theta)$ c) $MH\cos\theta$ d) $MH(1-\cos\theta)$

10. The magnetic moment of a magnet is 0.1 amp × m^2. It is suspended in a magnetic field of intensity3×10^{-4} Wbm^{-2}. The couple acting upon it when deflected by 30° from the magnetic field is

a)1×10^{-5}N m b) 1.5×10^{-5}N m c) 2×10^{-5}N m d) 2.5×10^{-5}N m

11. A small bar magnet A oscillates in a horizontal plane with a period T at a place where the angle of dip is 60°. When the same needle is made to oscillate in a vertical plane coinciding with the magnetic meridian, its period will be

a) $\frac{T}{\sqrt{2}}$ b) T c) $\sqrt{2}T$ d) $2T$

12. A magnet oscillating in a horizontal plane has a time period of 2 $second$ at a place where the angle of dip is 30° and 3 $seconds$ at another place where the angle of dip is 60°. The ratio of resultant magnetic fields at the two places is

a)$\frac{4\sqrt{3}}{7}$ b) $\frac{4}{9\sqrt{3}}$ c) $\frac{9}{4\sqrt{3}}$ d) $\frac{9}{\sqrt{3}}$

13. A straight wire carrying current i is turned into a circular loop. If the magnitude of magnetic moment associated with it in M.K.S. unit is M, the length of wire will be

a) $4\pi iM$ b) $\sqrt{\frac{4\pi M}{i}}$ c) $\sqrt{\frac{4\pi i}{M}}$ d) $\frac{M\pi}{4i}$

14. The magnetising field required to be applied in opposite direction to reduce residual magnetism to zero is called

a) Coercivity b) Retentivity c) Hysteresis d) None of these

15. What happens to the force between magnetic poles when their pole strength and the distance between them are both doubled

a) Force increases to two times the previous value
b) No change
c) Force decreases to half the previous value
d) Force increases to four times the previous value

16. Two short magnets having magnetic moments in the ratio 27 : 8, when placed on opposite sides deflection magnetometer, produce no deflection. If the distance of the weaker magnet is 0.12 m centre of deflection magnetometer, the distance of the stronger magnet from the centre is

a)0.06 m b) 0.08 m c) 0.12 m d) 0.18 m

17. A magnet 20 cm long with its poles concentrated at its ends is placed vertically with its north pole on the table. At a point due 20 cm south (magnetic) of the pole, a neutral point is obtained. If H =0.3 G, then the pole strength of the magnet is approximately

a)185 ab-amp-cm b) 185 amp-m c) 18.5 ab-amp-cm d) 18.5 amp-cm

18. A magnetic needle lying parallel to a magnetic field requires W units of work to turn it through 60°. The torque required to keep the needle in this position will be

$a)$ $2W$ b) W c) $\frac{W}{\sqrt{2}}$ d) $\sqrt{3}W$

19. Which of the following statements is incorrect about hysteresis

a) This effect is common to all ferromagnetic substances

b) The hysteresis loop area is proportional to the thermal energy developed per unit volume of the material

c) The hysteresis loop area is independent of the thermal energy developed per unit volume of the material

d) The shape of the hysteresis loop is characteristic of the material

20. The area of hysteresis loop of a material is equivalent to 250 $joule$. When 10 kg material is magnetized by an alternating field of 50 Hz then energy lost in one hour will be (density of material is 7.5 gm/cm^3)

$a)$ $6 \times 10^4 J$ b) $6 \times 10^4 erg$ c) $3 \times 10^2 J$ d) $3 \times 10^2 erg$

21. The effective length of a magnet is 31.4 cm and its pole strength is 0.5 Am. Calculate its magnetic moment. If it is bent in form of semicircle, then magnetic moment will be

a) 0.157 Am^2, 0.01 Am^2 b) 0.357 Am^2, 0.01 Am^2

c) 1.157 Am^2, 1.01 Am^2 d) None of these

22. A short bar magnet of magnetic moment 255 JT^{-1} is placed with its axis perpendicular to earth's field direction. At what distance from the center of the magnet, the resultant field is inclined at 45° with earth's field, $H = 0.4 \times 10^{-4}$ T ?

a) 5 m b) 0.5m c) 2.5 m d) 0.25 m

23. When a piece of a ferromagnetic substance is put in a uniform magnetic field, the flux density inside it is four times the flux density away from the piece. The magnetic permeability of the material (in $\mathrm{N/A}^2$) is

a) 1 b) 2 c) 3 d) 4

24. Each atom of an iron bar ($5cm \times 1cm \times 1cm$) has a magnetic moment $1.8 \times 10^{-23} Am^2$. Knowing that the density of iron is $7.78 \times 10^3\ kg\ m^{-3}$, atomic weight is 56 and Avogadro's number of 6.02×10^{23} the magnetic moment of bar in the state of magnetic saturation will be

$a)$ 4.75 Am^2 b) 5.74 Am^2 c) 7.54 Am^2 d) 75.4 Am^2

25. Susceptibility of ferromagnetic substance is

a) >1 b) <1 c) Zero d) 1

26. The period of oscillations of a magnet is 2 s. When it is magnetized that the pole strength is 4 times, its period will be

a) 4 s b) 1 s c) 2 s d) $\frac{1}{2}$ s

27. The needle of a deflection galvanometer shows a deflection of 60° due to a short bar magnet at a certain distance in tan *A* position. If the distance is double the deflection is

a) $\sin^{-1}\left[\frac{\sqrt{3}}{8}\right]$ b) $\cos^{-1}\left[\frac{\sqrt{3}}{8}\right]$ c) $\tan^{-1}\left[\frac{\sqrt{3}}{8}\right]$ d) $\cot^{-1}\left[\frac{\sqrt{3}}{8}\right]$

28. Magnets A and B are geometrically similar but the magnetic moment of A is twice that of B. If T_1 and T_2 be the time periods of the oscillation when their like poles and unlike poles are kept together respectively, then $\frac{T_1}{T_2}$ will be

a) $\frac{1}{3}$ b) $\frac{1}{2}$ c) $\frac{1}{\sqrt{3}}$ d) $\sqrt{3}$

29. A vibration magnetometer placed in magnetic meridian has a small bar magnet. The magnet executes oscillations with a time period of 2 sec in earth's horizontal magnetic field of 24 micro-Tesla. When a horizontal field of 18 micro-Tesla is produced opposite to the earth's field by placing a current carrying wire, the new time period of magnet will be

a) $4s$ b) $1s$ c) $2s$ d) $3s$

30. A bar magnet is situated on a table along east-west direction in the magnetic field of earth. The number of neutral points, where the magnetic field is zero, are

a) 2 b) 0 c) 1 d) 4

31. The magnetic susceptibility of a material of a rod is 499. The absolute permeability of vacuum is $4\pi \times 10^{-7}$ HM^{-1}. The absolute permeability of the material of a road is

$a)$ $\pi \times 10^{-4}$ HM^{-1} b) $2\pi \times 10^{-4}$ HM^{-1} c) $3\pi \times 10^{-4}$ HM^{-1} d) $4\pi \times 10^{-4}$ HM^{-1}

32. A frog can be levitated in magnetic field produced by a current in a vertical solenoid placed below the frog. This is possible because the body of the frog behaves as

a) Paramagnetic b) Diamagnetic c) Ferromagnetic d) Anti-ferromagnetic

33. A short bar magnet placed with its axis at 30° with a uniform external magnetic field of 0.16 tesla experiences a torque of magnitude 0.032 J. The magnetic moment of bar magnet will be

a) 0.23 J/T b) 0.40 J/T c) 0.80 J/T d) Zero

34. Which of the following is represented by the area enclosed by a hysteresis loop (*B*-*H* curve)?

a) Permeability
b) Retentivity
c) Heat energy lost per unit volume in the sample
d) Susceptibility

35. The magnetic potential at a point on the axial line of a bar magnet of dipole moment M is V. What is the magnetic potential due to a bar magnet of dipole moment $\frac{M}{4}$ at the same point

$a)$ $4\,V$ b) $2V$ c) $\frac{V}{2}$ d) $\frac{V}{4}$

36. A wire of length L metre carrying current i, ampere is bent in the form of a circle. What is the magnitude of magnetic of magnetic dipole moment?

$a)$ $iL^2/4\pi$ b) $i^2L^2/4\pi$ c) $i^2L/8\pi$ d) $iL^2/8\pi$

37. If the magnetic is cut into four equal parts such that their lengths and breadths are equal. Pole strength of each part is

$a)$ m b) *m/2* c) *m/4* d) *m/8*

38. To shield an instrument from external magnetic field, it is placed inside a cabin made of

a) Wood b) Ebonite
b) Iron d) Diamagnetic substance

39. The magnetic susceptibility of any paramagnetic material changes with absolute temperature T as

a) Directly proportional to T b) Remains constant
c) Inversely proportional to T d) Exponentially decaying with T

40. Magnetic susceptibility of a diamagnetic substance

a) Decreases with temperature b) Is not affected by temperature
c) Increases with temperature d) First increase then decrease with temperature

41. Lines which represent places of constant angle of dip are called

a) Isobaric lines b) Isogonic lines c) Isoclinic lines d) Isodynamic lines

42. The hysteresis cycle for the material of a transformer core is

a) Short and wide b) Tall and narrow c) Tall and wide d) Short and narrow

------------------------------ Answer Key ------------------------------------

1)	c	2)	c	3)	b		
4)	c	5)	c	6)	d	7)	a
8)	b	9)	d				
10)	b	11)	a	12)	c	13)	b
14)	a	15)	b	16)	d	17)	a
18)	d	19)	c	20)	a		
21)	a	22)	b	23)	d	24)	c
25)	b	26)	c	27)	c		
28)	a	29)	b	30)	b	31)	b
32)	b	33)	c	34)	d	35)	a
36)	b	37)	c	38)	c	39)	b
40)	c	41)	c	42)	b		

HINTS AND SOLUTIONS

1. (c)
Let M_1 and M_2 be the magnetic moments of magnets and H the horizontal component of earth's field. We have $\tau = MH\sin\theta$. If ϕ is the twist of wire, then $\tau = C\phi$, C being restoring couple per unit twist of wire
$\Rightarrow C\phi = MH\sin\theta$
Here $\phi_1 = (180° - 30°) = 150° \times \frac{\pi}{180} rad$
$\phi_2 = (270° - 30°) = 240° = 240 \times \frac{\pi}{180} rad$
So, $C\phi_1 = M_1 H \sin\theta$ [For deflection $\theta = 30°$ of I magnet]
$C\phi_2 = M_2 H \sin\theta$ [For deflection $\theta = 30°$ of II magnet]
Dividing $\frac{\phi_1}{\phi_2} = \frac{M_1}{M_2}$

$$\Rightarrow \frac{M_1}{M_2} = \frac{\phi_1}{\phi_2} = \frac{150 \times \left(\frac{\pi}{180}\right)}{240 \times \left(\frac{\pi}{180}\right)} = \frac{15}{24} = \frac{5}{8}$$

$$\Rightarrow M_1 : M_2 = 5 : 8$$

2. (c)
Magnetic substance when kept in a magnetic field is feebly repelled or thrown out if the substance is diamagnetic.

3. (b)
Here, $n_1 = 10$ oscillations per min
$\delta_1 = 45°, T_1 = 0.707$ CGS units
$n_2 = ?, \delta_2 = 60°, R_2 = 0.5$ CGS units

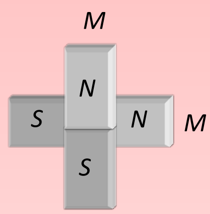
$$\frac{n_2}{n_1} = \sqrt{\frac{H_2}{H_1}} = \sqrt{\frac{R_2 cos\delta_2}{R_1 cos\delta_1}}$$

$$\frac{n_2}{10} = \sqrt{°\frac{0.5cos60°}{0.707cos45°}} = \sqrt{\frac{0.5 \times 1/2}{0.5 \times \sqrt{2} \times 1/\sqrt{2}}} = \frac{1}{\sqrt{2}}$$

$$n_2 = \frac{10}{\sqrt{2}} = 7.07$$

4. (c)
Time period of combination

$$T = 2\pi\sqrt{\frac{2I}{\sqrt{2}M.H}} \quad \text{... (i)}$$



and time period of each magnet

$$T' = 2\pi\sqrt{\frac{I}{MH}} \quad \text{... (ii)}$$

From (i) and (ii), we get

$$T' = \frac{T}{2^{1/4}} = 2^{-1/4}T$$

5. (c)

$$B_1 = \frac{2M}{d^3}, B_2 = \frac{M}{d^2}; \therefore \frac{B_1}{B_2} = 2 : 1$$

6. (d)
$\theta_1 = 90°, \theta_2 = 270°$,
$W = -MB[\cos 270° - \cos 90°] =$zero

7. (a)
The volume of the cubic domain is
$V(10^{-6} m)^3 = 10^{-18}\ m^3$
Net dipole moment $m_{net} = 8 \times 10^{10} \times 9 \times 10^{-24}$ A m^2
$= 72 \times 10^{-14}$ A m^2
Magnetization, $M = \frac{m_{net}}{\text{Domain volume}}$

$$= \frac{72 \times 10^{-14} A\ m^2}{10^{-18}\ m^3} = 72 \times 10^4\ A\ m^{-1}$$

$$= 7.2 \times 10^5\ A\ m^{-1}$$

8. (b)
Points of zero magnetic field *ie*, neutral points lie on equatorial line of magnetic *ie*, along east and west.

9. (d)
The potential energy of a magnetic dipole of magnetic moment M placed in magnetic field H is given as
$U_\theta = -\mathbf{M}.\mathbf{H} = -MH\cos\theta$
Where θ is angle between the vector **M** and **H**.
Initially the dipole possesses minimum potential energy U_0, therefore work requires to turn through angle θ is
$$W = U_\theta - U_0$$
$$= -MH\cos\theta - (-MH\cos\theta)$$
$$= -MH\cos\theta + MH$$
$$W = MH(1-\cos\theta)$$

10. (b)
$\tau = MB\sin\theta = 0.1 \times 3 \times 10^{-4}\sin 30°$
$= 1.5 \times 10^{-5}$ N-m

11. (a)
$$T = 2\pi\sqrt{\frac{1}{MB}} \Rightarrow \frac{T}{T'} = \sqrt{\frac{B'}{B}} = \sqrt{\frac{B}{B_H}}$$
$$\frac{T}{T'} = \sqrt{\frac{1}{\cos\phi}} = \sqrt{\frac{1}{\cos 60°}} = \sqrt{2} \Rightarrow T' = \frac{T}{\sqrt{2}}$$

12. (c)
$$T \propto \frac{1}{\sqrt{B_H}} \propto \frac{1}{\sqrt{B\cos\phi}} \Rightarrow \frac{T_1}{T_2} = \sqrt{\frac{B_2\cos\phi_2}{B_1\cos\phi_1}}$$
$$\Rightarrow \frac{B_1}{B_2} = \frac{T_2^2}{T_1^2} \times \frac{\cos\phi_2}{\cos\phi_1} = \left(\frac{3}{2}\right)^2 \times \left(\frac{\cos 60°}{\cos 30°}\right) \Rightarrow \frac{B_1}{B_2} = \frac{9}{4\sqrt{3}}$$

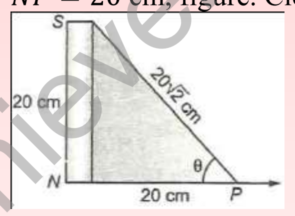
13. (b)
Magnetic moment of circular loop carrying current
$$M = IA = I(\pi R^2) = I\pi\left(\frac{L}{2\pi}\right)^2 = \frac{IL^2}{4\pi} \Rightarrow L = \sqrt{\frac{4\pi M}{I}}$$

14. (a)
This magnetising field is a measure of coercivity of the material.

15. (b)
$$F \propto \frac{m_1 m_2}{r^2}$$

16. (d)
$$\frac{M_1}{M_2} = \left(\frac{d_1}{d_2}\right)^3 \Rightarrow \frac{27}{8} = \left(\frac{d_1}{0.12}\right)^3$$
$$\Rightarrow \frac{3}{2} = \frac{d_1}{0.12} \Rightarrow 0.18\, m$$

17. (a)
NS is a magnet held vertically with its north pole on the table. P is neutral point, where $NP = 20$ cm, figure. Clearly,



18. (d)
$$W = mB\cos\theta$$
$$= mB\cos 60°$$
$$= mB \times \frac{1}{2}$$
$$\tau = mB\sin\theta$$
$$= mB\sin 60°$$
$$= \sqrt{3}\,W \qquad [\because mB = 2W]$$

19. (c)
The energy lost per unit volume of a substance in a complete cycle of magnetization is equal to the area of the hysteresis loop

20. (a)
$$E = nAVt = nA\frac{m}{d}t$$
$$= \frac{50 \times 250 \times 10 \times 3600}{7.5 \times 10^3} = 6 \times 10^4 J$$

21. (a)

The effective length of magnet $2l =$ 31.4 cm = 0.314 m

Pole strength $m = 0.5$ Am

So, the magnetic moment, $M = m \times 2l$

$= (0.5 \times 0.314)\text{Am}^2$

$= 0.157\ \text{Am}^2$

When magnet is bent in the form of semicircle (of diameter d), then length of magnet $= \pi \frac{d}{2}$

$$\therefore \quad 31.4 = \frac{\pi d}{2}$$

$$\Rightarrow \quad d = \frac{31.4 \times 2}{3.14} = 20 \text{ cm}$$

$\therefore$ Effective length of magnet

$2l' = d = 20$ cm $= 0.2$ cm

Hence, its magnetic moment will be

$M' = m \times 2l'$

$= 0.5 \times 0.2 = 0.1\ \text{Am}^2$

22. (b)

Since, B and H are perpendicular to each other and the resultant field is inclined at an angle 45° with.

So, $B = H$

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

$$\therefore r^3 = \frac{\mu_0}{4\pi}\frac{2M}{H} = 0.5 \text{ m}$$

23. (d)

Permeability is given by

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

When B is magnetic flux density and H the auxiliary field strength.

Given, $B = 4H$,

$$\therefore \ \mu = \frac{4H}{H} = 4\text{NA}^{-2}$$

24. (c)

The number of atoms per unit volume in a specimen

$$n = \frac{\rho N_A}{A}$$

For iron, $\rho = 7.8 \times 10^3 kgm^{-3}$,

$N_A = 6.02 \times 10^{26}/kgmol, A = 56$

$$\Rightarrow n = \frac{7.8 \times 10^3 \times 6.02 \times 10^{26}}{56}$$

$= 8.38 \times 10^{28} m^{-3}$

Total number of atoms in the bar is

$N_0 = nV = 8.38 \times 10^{28} \times (5 \times 10^{-2} \times 1 \times 10^{-2} \times 1 \times 10^{-2})$

$N_0 = 4.19 \times 10^{23}$

The saturated magnetic moment of bar

$= 4.19 \times 10^{23} \times 1.8 \times 10^{-23}$

$= 7.54\ Am^2$

25. (b)

When pole strength becomes 4 times, magnetic moment M becomes four times.

As $T \propto \frac{1}{\sqrt{M}}$

$\therefore T$ becomes $\frac{1}{\sqrt{4}} = \frac{1}{2}$ times

$T = \frac{2}{2} =$1 s.

26. (c)

For short bar magnet in tan A position

$$\frac{\mu_0}{4\pi}\frac{2M}{d^3} = H \tan\theta \qquad \ldots\text{(i)}$$

When distance is doubled, then new deflection θ' is given by

$$\frac{\mu_0}{4\pi}\frac{2M}{(2d)^3} = H \tan\theta' \qquad \ldots\text{(ii)}$$

$$\therefore \ \frac{\tan\theta'}{\tan\theta} = \frac{1}{8}$$

$$\Rightarrow \quad \theta' = \frac{\tan\theta}{8} = \frac{\tan 60°}{8} = \frac{\sqrt{3}}{8}$$

$$\Rightarrow \quad \theta' = \tan^{-1}\left[\frac{\sqrt{3}}{8}\right]$$

27. (c)

$$T_{Sum} = 2\pi\sqrt{\frac{(I_1 + I_2)}{(M_1 + M_2)B_H}}$$

$$T_{diff} = 2\pi\sqrt{\frac{I_1 + I_2}{(M_1 - M_2)B_H}}$$

$$\Rightarrow \frac{T_s}{T_d} = \frac{T_1}{T_2} = \sqrt{\frac{M_1 - M_2}{M_1 + M_2}} = \sqrt{\frac{2M - M}{2M + M}} = \frac{1}{\sqrt{3}}$$

28. (a)

$$T = 2\pi\sqrt{\frac{1}{MB_H}}, T' = 2\pi\sqrt{\frac{1}{M(B_H - B)}} \Rightarrow T' = 2T = 4s$$

29. (b)
Absolute permeability of material of rod
$\mu = \mu_r \mu_0 = (1 + X_m)\mu_0$
$\therefore \ \mu = (1 + 499) \times 4\pi \times 10^{-7}$
$= 2\pi \times 10^{-4}\ \text{Hm}^{-1}$

30. (b)
Frog is leveited in magnetic field produced by the current in vertical solenoid below the frog due to repulsion, so body of frog behaves as diamagnetic substance.

31. (b)
32. (b)
Torque, $\tau = MB_H \sin\theta$
$\Rightarrow \ 0.032 = M \times 0.16 \sin 30°$
$\Rightarrow \quad M = 0.4\ \text{J/T}$

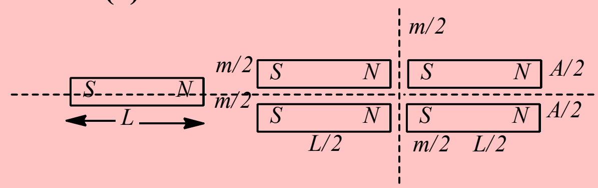
33. (c)
Area enclosed by $B - H$ curve represents energy lost. If the area of hysteresis loop is less energy loss is low whereas if the area of hysteresis loop is large energy loss is high.

34. (d)
Magnetic potential at a distance d from the bar magnet on it's axial line is given by
$$V = \frac{\mu_0}{4\pi} \cdot \frac{M}{d^2} \Rightarrow V \propto M \Rightarrow \frac{V_1}{V_2} = \frac{M_1}{M_2}$$
$$\Rightarrow \frac{V}{V_2} = \frac{M}{M/4} \Rightarrow V_2 = \frac{V}{4}$$

35. (a)
The magnetic dipole moment of the current loop (M) is directly proportional to (i) strength of current(i) through the loop and (ii) area (A) enclosed by the loop.
ie, $\quad M \propto i$ and $M \propto A$
$\therefore \quad M = kiA \quad$ ... (i)
Where k is constant of proportionality.
If we define unit magnetic dipole moment as that of a small one turn loop of unit area carrying unit current, then from Eq.(i)
$1 = k \times 1 \times 1$ or $k = 1$

$\therefore$ From Eq.(i)
$$M = iA$$
For N such turns
$$M = NiA$$

36. (b)



For each part $m' = \frac{m}{2}$

37. (c)
Cabin must be made of iron, which has large permeability.
38. (c)

39. (b)

Magnetic susceptibility is given as
$$X_m = \frac{I}{H}$$
Large value of X_m implies that the material is more susceptible to the field and hence can be easily magnetized. For diamagnetic substance X_m is small and negative and is independent of temperature

40. (c)

41. (c)

42. (b)
Transformer core is of soft iron which has large retentivity and small coercivity. Therefore, its hysteresis loop is tall and narrow.