The Collegedunia NCERT Notes

The Ultimate NCERT Revision Notes for Class 12 Physics

Chapter 5: Magnetism and Matter

1 Introduction to Magnetism

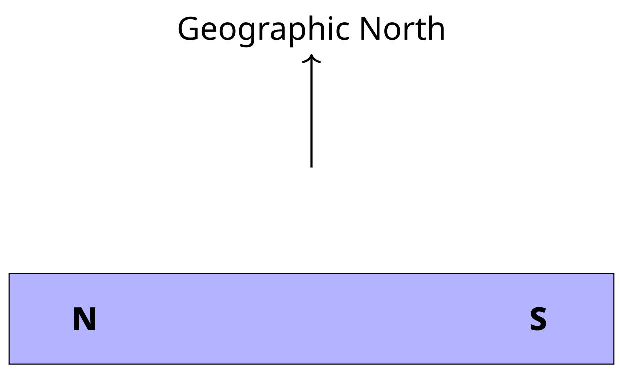
1.1 Bar Magnet

A bar magnet is a rectangular piece of magnetic material having two opposite magnetic poles at its ends.

It is the simplest example used to study magnetism.

Properties of a Bar Magnet

- It has two poles: North (N) and South (S).
- Like poles repel each other.
- Unlike poles attract each other.
- Magnetic poles always exist in pairs.
- Magnetic monopole does not exist.
- A freely suspended magnet aligns itself in North–South direction.



Bar Magnet Aligning in N–S Direction

Magnetic Field Lines of a Bar Magnet

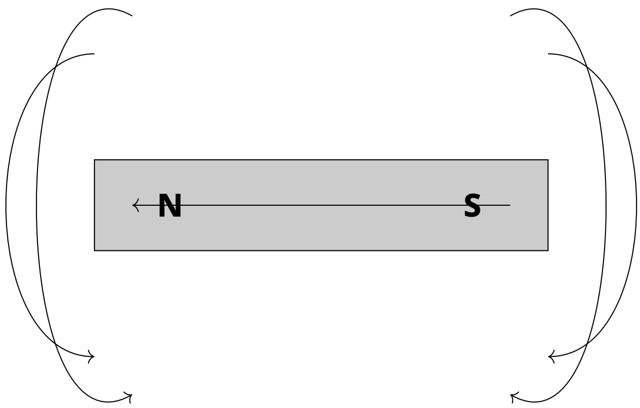
Magnetic field lines represent the magnetic field around a magnet.
Direction:

- Outside magnet: N $\Rightarrow$ S
- Inside magnet: S $\Rightarrow$ N

Properties:

- Closed loops
- Strongest at poles
- Never intersect

Magnetic Field Lines of Bar Magnet



1.2 Magnetic Dipole

A magnetic dipole consists of two equal and opposite magnetic poles separated by a small distance.
A bar magnet behaves like a magnetic dipole.

Magnetic Dipole Moment of Bar Magnet

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

where:

- m = magnetic pole strength
- $2l$ = magnetic length

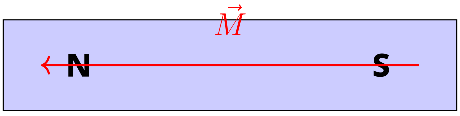
Vector Nature of Magnetic Dipole Moment

Direction:

- From South to North inside the magnet.

Unit:

$$\boxed{A \cdot m^2}$$



Direction of Magnetic Dipole Moment

Concept Summary

- Bar magnet has two poles.
- Field lines form closed loops.
- $\vec{M} = m(2l)$.
- Direction of $\vec{M}$ is S $\Rightarrow$ N inside magnet.
- Unit: A·m².

2 Bar Magnet as Equivalent Solenoid

2.1 Magnetic Field Due to Bar Magnet

A bar magnet behaves like a magnetic dipole.
Its magnetic field at a distant point (where $r \gg l$) is similar to that of a short current loop.
Let:

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

where M is magnetic dipole moment.

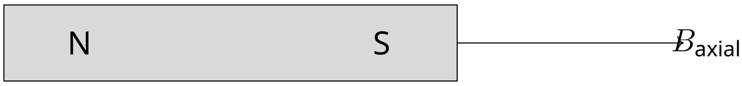
Field on Axial Line

Axial line is the line passing through the poles of the magnet.
For a point at distance r from centre of magnet (where $r \gg l$):

$$\boxed{B_{\text{axial}} = \frac{\mu_0}{4\pi}\frac{2M}{r^3}}$$

Direction:

- Along the axis of magnet.
- Outside magnet: from North to South.



Axial Line

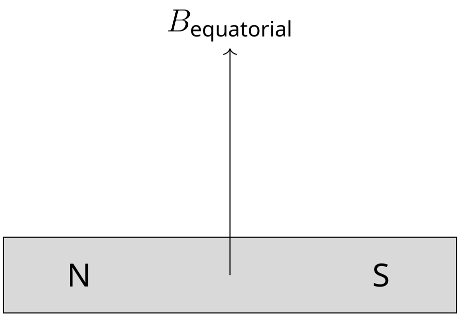
Field on Equatorial Line

Equatorial line is the perpendicular bisector of the magnet.
For a point at distance r from centre:

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

Direction:

- Opposite to magnetic dipole moment.



Equatorial Line

Comparison of Axial and Equatorial Fields

$$B_{\text{axial}} = \frac{\mu_0}{4\pi}\frac{2M}{r^3}$$

$$B_{\text{equatorial}} = \frac{\mu_0}{4\pi}\frac{M}{r^3}$$

Therefore:

$$\boxed{B_{\text{axial}} = 2B_{\text{equatorial}}}$$

Important observations:

- Both decrease as $\frac{1}{r^3}$.

- Axial field is twice the equatorial field at same distance.
- Direction of axial and equatorial fields are opposite.

Concept Summary

- $B_{\text{axial}} = \frac{\mu_0}{4\pi}\frac{2M}{r^3}$
- $B_{\text{equatorial}} = \frac{\mu_0}{4\pi}\frac{M}{r^3}$
- $B_{\text{axial}} = 2B_{\text{equatorial}}$
- Both vary as $\frac{1}{r^3}$

3 Bar Magnet as Equivalent Solenoid

3.1 Concept

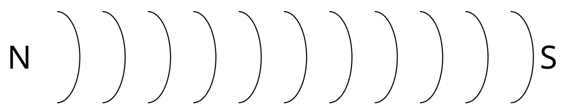
A bar magnet can be considered equivalent to a current carrying solenoid.
Reason:

- A current loop behaves like a magnetic dipole.
- A solenoid consists of many closely wound current loops.
- The combined effect produces a strong dipole field.

Thus:

- One end of solenoid behaves like North pole.
- Other end behaves like South pole.

The magnetic field pattern of a long solenoid is very similar to that of a bar magnet.



Solenoid Acting as Bar Magnet

3.2 Magnetic Dipole Moment of Solenoid

For a current carrying loop:

$$m = IA$$

For a solenoid having:

- N turns
- Current I
- Cross-sectional area A

Magnetic dipole moment:

$$\boxed{m = NIA}$$

Direction:

- Given by right-hand rule.
- Along axis of solenoid.

Thus:

- Solenoid behaves like a giant magnetic dipole.

3.3 Why Magnetic Monopole Does Not Exist

If magnetism were due to isolated poles:

- Cutting a magnet should produce separate North and South poles.

But experimentally:

- Cutting a magnet produces two smaller magnets.
- Each piece has both North and South poles.

Mathematically:

$$\nabla \cdot \vec{B} = 0$$

This implies:

- Magnetic field lines are continuous.
- They form closed loops.

Hence:

$$\boxed{\text{Magnetic monopole does not exist}}$$

Concept Summary

- Solenoid behaves like bar magnet.
- Magnetic dipole moment of solenoid: $m = NIA$
- Magnetic monopole does not exist.
- Magnetic field lines form closed loops.

4 Torque on a Magnetic Dipole

4.1 Torque on Bar Magnet in Uniform Magnetic Field

When a bar magnet (magnetic dipole) is placed in a uniform magnetic field, it experiences a torque.

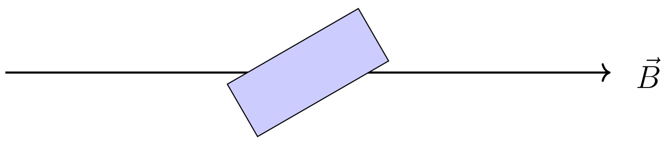
This torque tries to align the magnetic dipole moment $\vec{m}$ with the magnetic field $\vec{B}$.

Vector form:

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

There is no net force in a uniform field, only rotational effect.

Magnet in Uniform Field



4.2 Magnitude of Torque

$$\boxed{\tau = mB \sin\theta}$$

where:

- m = magnetic dipole moment
- B = magnetic field
- θ = angle between $\vec{m}$ and $\vec{B}$

Special cases:

- $\theta = 0^\circ \Rightarrow \tau = 0$
- $\theta = 90^\circ \Rightarrow \tau = mB$ (maximum)
- $\theta = 180^\circ \Rightarrow \tau = 0$

4.3 Stable and Unstable Equilibrium

Stable Equilibrium

Occurs when:

$$\theta = 0^\circ$$

- $\vec{m}$ parallel to $\vec{B}$

- Potential energy minimum
- Small displacement produces restoring torque

Unstable Equilibrium
Occurs when:

$$\theta = 180^\circ$$

- $\vec{m}$ anti-parallel to $\vec{B}$
- Potential energy maximum
- Small displacement increases torque away from position

4.4 Potential Energy of Magnetic Dipole

Work done in rotating dipole against magnetic field is stored as potential energy.

$$\boxed{U = -\vec{m} \cdot \vec{B}}$$

or

$$\boxed{U = -mB\cos\theta}$$

Important cases:

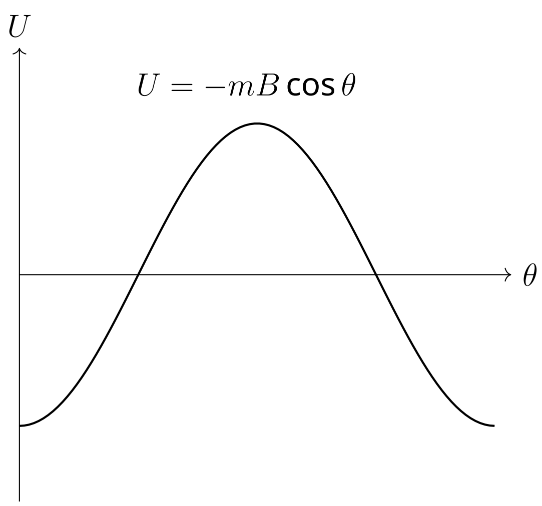
- $\theta = 0^\circ \Rightarrow U = -mB$ (minimum)
- $\theta = 90^\circ \Rightarrow U = 0$
- $\theta = 180^\circ \Rightarrow U = +mB$ (maximum)

4.5 Graph: U vs θ

Since:

$$U = -mB\cos\theta$$

Graph is cosine curve.



Concept Summary

- $\vec{\tau} = \vec{m} \times \vec{B}$
- $\tau = mB \sin\theta$
- $U = -mB \cos\theta$
- Minimum energy $\Rightarrow$ Stable equilibrium
- Maximum energy $\Rightarrow$ Unstable equilibrium

5 Earth's Magnetism

5.1 Earth's Magnetic Field

The Earth behaves like a giant magnet.

It produces a magnetic field similar to that of a bar magnet placed inside the Earth.

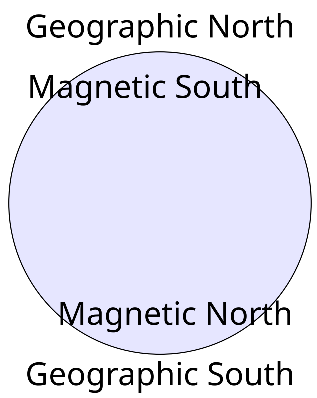
Earth as a Giant Magnet

Important facts:

- Magnetic south pole of Earth lies near geographic north.
- Magnetic north pole of Earth lies near geographic south.

Reason:

- The north pole of a compass needle is attracted toward geographic north.
- Therefore, geographic north must behave like a magnetic south pole.



Earth as a Giant Magnet

5.2 Magnetic Elements

To describe Earth's magnetic field at a place, three magnetic elements are used.

Magnetic Declination (D)

Magnetic declination is the angle between:

- Geographic meridian (true north–south line)
- Magnetic meridian (direction of compass needle)

Declination varies from place to place.

Magnetic Inclination or Dip (I)

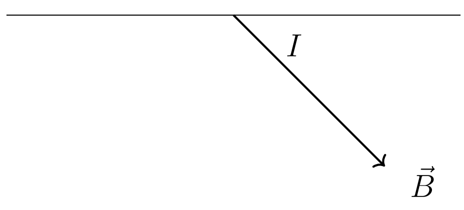
Magnetic inclination (dip) is the angle made by Earth's magnetic field with the horizontal plane.
At equator:

$$I = 0^\circ$$

At poles:

$$I = 90^\circ$$

Angle of Dip



Horizontal Component (B_H)

If total magnetic field is B and dip angle is I:

$$\boxed{B_H = B\cos I}$$

Vertical component:

$$B_V = B\sin I$$

5.3 Relation Between Magnetic Elements

From right triangle formed by components:

$$\tan I = \frac{B_V}{B_H}$$

$$\boxed{\tan I = \frac{B_V}{B_H}}$$

Thus:

- If dip increases $\Rightarrow$ vertical component increases.

5.4 Variation of Dip with Latitude

Important results:

- At magnetic equator:
$$I = 0^\circ$$
Field is horizontal.
- At magnetic poles:
$$I = 90^\circ$$
Field is vertical.

As latitude increases:

- Dip increases gradually.

Concept Summary

- Earth behaves like giant magnet.
- $B_H = B \cos I$
- $B_V = B \sin I$
- $\tan I = \frac{B_V}{B_H}$
- Dip = 0° at equator
- Dip = 90° at poles

6 Magnetisation

6.1 Magnetisation

When a magnetic material is placed in an external magnetic field, the atomic dipoles inside it tend to align.
As a result, the material becomes magnetised.
The extent to which a material gets magnetised is described by magnetisation.

Definition

Magnetisation is defined as magnetic dipole moment per unit volume.

$$\boxed{\vec{M} = \frac{\text{Magnetic dipole moment}}{\text{Volume}}}$$

If total magnetic moment of specimen is m and its volume is V:

$$\boxed{M = \frac{m}{V}}$$

Nature of Magnetisation

- Magnetisation is a vector quantity.
- Its direction is same as magnetic dipole moment.
- It represents alignment of microscopic dipoles.

SI Unit

$$\boxed{\text{Ampere per meter (A/m)}}$$

Reason:

$$m \text{ has unit } A \cdot m^2$$

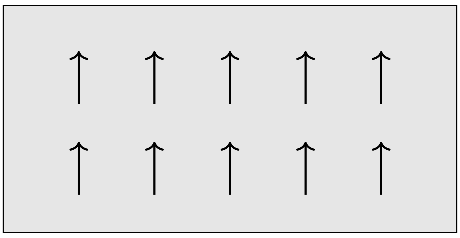
Dividing by volume (m^3):

$$\frac{A \cdot m^2}{m^3} = A/m$$

Physical Meaning

- Larger $M \Rightarrow$ stronger magnetisation.
- If $M = 0 \Rightarrow$ no net magnetic alignment.
- In ferromagnetic materials, M can be very large.

Aligned Magnetic Dipoles in Material



Concept Summary

- $\vec{M} = \frac{m}{V}$
- Magnetisation = dipole moment per unit volume.
- Vector quantity.
- SI unit: A/m.

7 Magnetic Intensity ($\vec{H}$)

7.1 Magnetic Intensity

Magnetic intensity (or magnetising field) represents the magnetic field strength produced by an external source (like current or magnetising coil).

It describes the cause of magnetisation.

Symbol:

$$\vec{H}$$

Definition

Magnetic intensity is the magnetic field produced by free currents, independent of the material response.

In simple terms:

- $\vec{H}$ is the external magnetic field.
- $\vec{M}$ represents material response.
- $\vec{B}$ is the total magnetic field inside material.

Relation Between B, H and M

When a magnetic material is placed in a magnetic field:

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

where:

- $\vec{B}$ = magnetic flux density
- $\vec{H}$ = magnetic intensity
- $\vec{M}$ = magnetisation
- μ_0 = permeability of free space

Special Case: Linear Magnetic Material

If:

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

Substitute into equation:

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

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

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

where:

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

SI Unit of Magnetic Intensity

From relation:

$$B = \mu_0 H$$

Since:

$$B \text{ has unit Tesla}$$

$$\mu_0 \text{ has unit T·m/A}$$

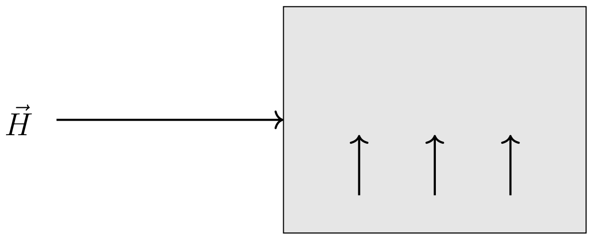
Therefore:

$$\boxed{H \text{ has unit } A/m}$$

Physical Meaning

- $\vec{H}$ represents magnetising cause.
- $\vec{M}$ represents material response.
- $\vec{B}$ represents total magnetic field inside material.

External Field and Magnetisation



Concept Summary

- $\vec{H}$ = external magnetising field.
- $\vec{M}$ = magnetisation.
- $\vec{B} = \mu_0(\vec{H} + \vec{M})$.
- For linear material: $\vec{B} = \mu\vec{H}$.
- Unit of H = A/m.

8 Magnetic Susceptibility (χ)

8.1 Magnetic Susceptibility

When a magnetic material is placed in an external magnetic field $\vec{H}$, it becomes magnetised and develops magnetisation $\vec{M}$.

Magnetic susceptibility measures how easily a material gets magnetised.

Definition

Magnetic susceptibility is defined as the ratio of magnetisation to magnetic intensity:

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

Vector form (for linear materials):

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

Nature of Magnetic Susceptibility

- It is a dimensionless quantity.
- It indicates the strength of magnetic response.
- It depends on the nature of the material.

Since:

$$M \text{ has unit } A/m$$

$$H \text{ has unit } A/m$$

Therefore:

$$\boxed{\chi \text{ has no unit}}$$

Physical Interpretation

- Large $\chi \Rightarrow$ material strongly magnetised.
- Small $\chi \Rightarrow$ weak magnetisation.

Depending on value of χ:

- $\chi < 0 \Rightarrow$ Diamagnetic material
- $\chi > 0$ (small) $\Rightarrow$ Paramagnetic material
- $\chi \gg 1 \Rightarrow$ Ferromagnetic material

Relation with Permeability

From earlier relation:

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

Substitute:

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

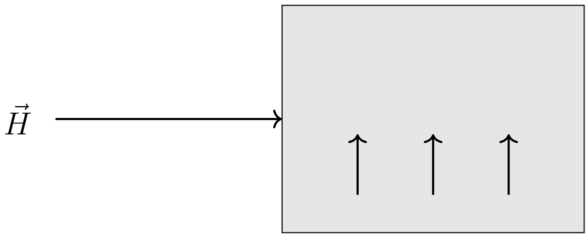
$$\vec{B} = \mu_0(1 + \chi)\vec{H}$$

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

Relative permeability:

$$\mu_r = 1 + \chi$$

Magnetisation due to External Field



Concept Summary

- $\chi = \frac{M}{H}$
- Dimensionless quantity
- $\vec{M} = \chi\vec{H}$
- $\mu = \mu_0(1 + \chi)$
- Determines type of magnetic material

9 Magnetic Permeability (μ)

9.1 Magnetic Permeability

Magnetic permeability measures the ability of a material to allow magnetic field lines to pass through it.

It describes how easily a material supports magnetic field within itself.

Definition

From relation:

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

Magnetic permeability is defined as:

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

where:

- $\vec{B}$ = magnetic flux density
- $\vec{H}$ = magnetic intensity

Relation with Magnetic Susceptibility

We know:

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

and

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

Substitute:

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

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

Comparing with:

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

we get:

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

Thus, permeability depends on magnetic susceptibility.

9.2 Relative Permeability

Relative permeability is defined as the ratio of permeability of material to permeability of free space.

$$\boxed{\mu_r = \frac{\mu}{\mu_0}}$$

Using previous relation:

$$\boxed{\mu_r = 1 + \chi}$$

Nature of μ_r

- If $\chi < 0 \Rightarrow \mu_r < 1$ (diamagnetic)
- If $\chi > 0$ (small) $\Rightarrow \mu_r > 1$ (paramagnetic)
- If $\chi \gg 1 \Rightarrow \mu_r \gg 1$ (ferromagnetic)

SI Unit of Permeability

Since:

$$B \text{ has unit Tesla}$$

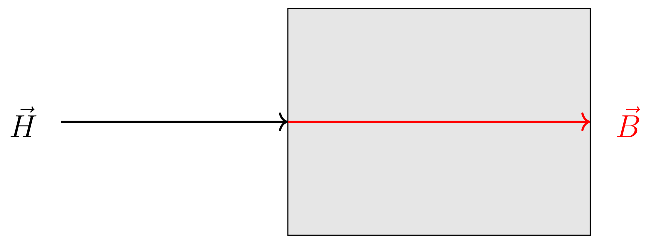
$$H \text{ has unit A/m}$$

$$\boxed{\mu \text{ has unit T·m/A}}$$

Permeability of free space:

$$\mu_0 = 4\pi \times 10^{-7} \text{ T·m/A}$$

Magnetic Field Inside Material



Concept Summary

- $\mu = \frac{B}{H}$
- $\mu = \mu_0(1 + \chi)$
- $\mu_r = 1 + \chi$
- Determines magnetic response of material
- $\mu_0 = 4\pi \times 10^{-7}$ T·m/A

10 Classification of Magnetic Materials

10.1 Diamagnetic Substances

Diamagnetic substances are those materials which are weakly repelled when placed in an external magnetic field.

They exhibit diamagnetism, which is a universal property of all materials but is very weak in most cases.

Properties of Diamagnetic Substances

- Weakly repelled by magnetic field.
- Magnetic susceptibility χ is small and negative.
- Relative permeability $\mu_r < 1$.
- Magnetisation is opposite to applied magnetic field.
- Effect is independent of temperature.

Mathematically:

$$\chi < 0$$

$$\mu_r = 1 + \chi < 1$$

Since χ is very small:

$$|\chi| \approx 10^{-5}$$

Examples

Common diamagnetic substances:

- Bismuth
- Copper

- Silver
- Water

Cause of Diamagnetism

In diamagnetic substances:

- Atoms have no permanent magnetic dipole moment.
- All electrons are paired.

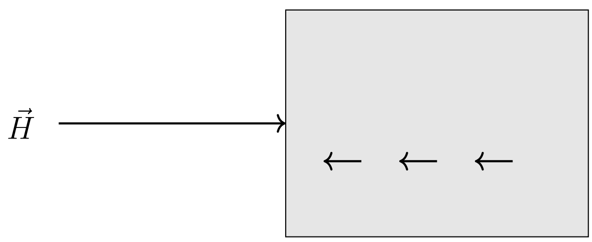
When external magnetic field is applied:

- Small induced dipoles are created.
- Induced dipoles oppose the applied field (Lenz's law).

Thus:

$$\boxed{\text{Induced magnetisation is opposite to applied field}}$$

Induced Dipoles Oppose Field



Concept Summary

- Diamagnetic $\Rightarrow$ weakly repelled.
- χ small and negative.
- $\mu_r < 1$.
- No permanent dipole moment.
- Induced dipoles oppose external field.

11 Paramagnetic Substances

11.1 Paramagnetic Substances

Paramagnetic substances are those materials which are weakly attracted when placed in an external magnetic field.

They exhibit paramagnetism due to the presence of permanent magnetic dipoles in their atoms.

Properties of Paramagnetic Substances

- Weakly attracted by magnetic field.
- Magnetic susceptibility χ is small and positive.
- Relative permeability $\mu_r > 1$ (slightly greater than 1).
- Magnetisation is in the same direction as applied field.
- Susceptibility decreases with increase in temperature.

Mathematically:

$$\chi > 0$$

$$\mu_r = 1 + \chi > 1$$

Typically:

$$\chi \approx 10^{-5} \text{ to } 10^{-3}$$

Cause of Paramagnetism

In paramagnetic materials:

- Atoms possess permanent magnetic dipole moments.
- Due to unpaired electrons.

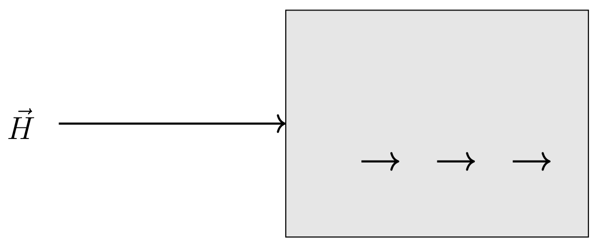
In absence of field:

- Dipoles are randomly oriented.
- Net magnetisation is zero.

In presence of external field:

- Dipoles partially align with the field.
- Weak magnetisation is produced.

Partial Alignment of Dipoles



11.2 Curie's Law

For paramagnetic materials, susceptibility varies inversely with temperature.

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

where:

- C = Curie constant
- T = absolute temperature

Thus:

- As temperature increases, χ decreases.
- Thermal agitation disturbs alignment.

Examples

Common paramagnetic substances:

- Aluminium
- Platinum
- Oxygen

Concept Summary

- Paramagnetic $\Rightarrow$ weakly attracted.
- χ small and positive.
- $\mu_r > 1$.
- $\chi = \frac{C}{T}$ (Curie's law).
- Alignment decreases with temperature.

12 Ferromagnetic Substances

12.1 Ferromagnetic Substances

Ferromagnetic substances are materials which are strongly attracted by an external magnetic field.

They show very strong magnetic behaviour compared to diamagnetic and paramagnetic substances.

Properties of Ferromagnetic Substances

- Strongly attracted by magnetic field.
- Magnetic susceptibility χ is very large and positive.
- Relative permeability $\mu_r \gg 1$.
- Can retain magnetisation even after removing external field.
- Show hysteresis.

Mathematically:

$$\chi \gg 1$$

$$\mu_r = 1 + \chi \gg 1$$

Examples:

- Iron
- Cobalt
- Nickel

12.2 Domain Theory

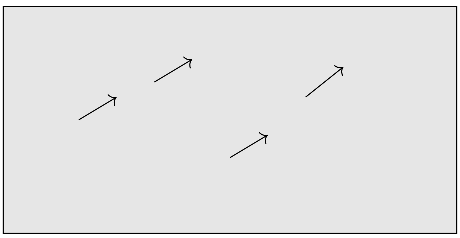
Ferromagnetism is explained using domain theory.
According to domain theory:

- A ferromagnetic material is divided into small regions called domains.
- Each domain is fully magnetised.
- In absence of magnetic field, domains are randomly oriented.
- Net magnetisation becomes zero.

When external magnetic field is applied:

- Domains align in the direction of field.
- Magnetisation increases rapidly.

Domains in Absence of Field

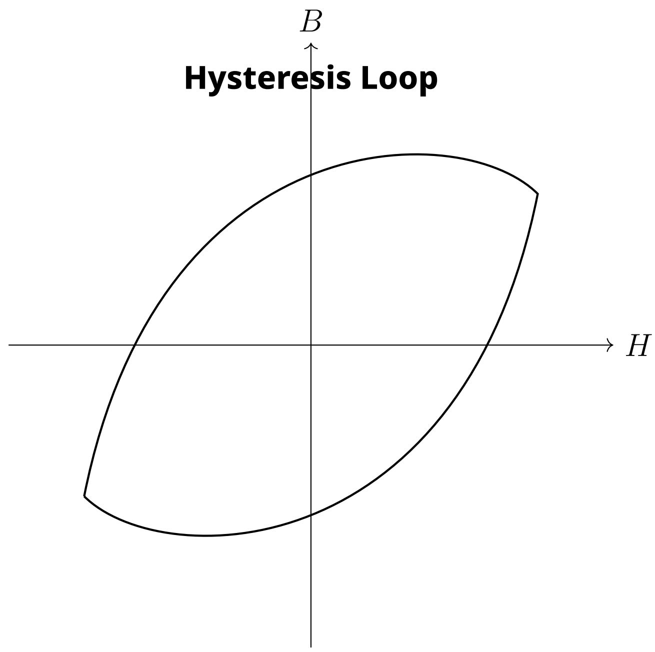


12.3 Hysteresis

When a ferromagnetic material is magnetised and demagnetised, the B–H curve forms a loop called hysteresis loop.

This shows lagging of magnetisation behind applied magnetic field.

Hysteresis Loop



Important Terms

Saturation

- All domains align.
- Maximum magnetisation reached.

Remanence (Retentivity)

- Magnetisation remaining when $H = 0$.

Coercivity

- Reverse magnetic field required to reduce magnetisation to zero.

Area of hysteresis loop represents energy loss per cycle.

12.4 Applications

Soft Iron $\Rightarrow$ Electromagnets

- Low coercivity
- Low retentivity
- Narrow hysteresis loop
- Easily magnetised and demagnetised

Used in:

- Electromagnets
- Transformers

Steel $\Rightarrow$ Permanent Magnets

- High coercivity
- High retentivity
- Wide hysteresis loop
- Difficult to demagnetise

Used in:

- Permanent magnets
- Compass needles

Concept Summary

- Ferromagnetic $\Rightarrow$ strongly attracted.
- χ very large.
- Domains align in external field.
- Hysteresis loop shows remanence and coercivity.
- Soft iron $\Rightarrow$ electromagnets.
- Steel $\Rightarrow$ permanent magnets.

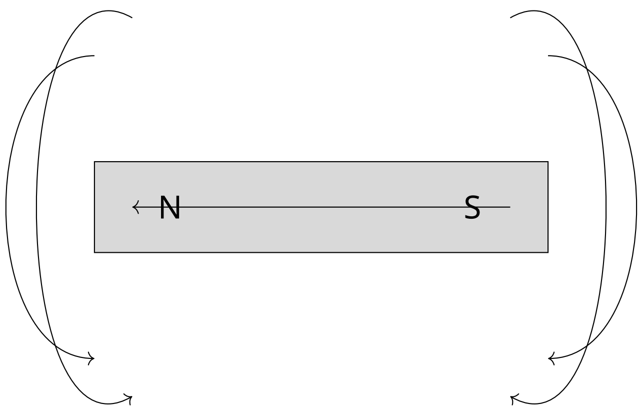
13 Important Graphs in Magnetism

13.1 Field Lines of Bar Magnet

Magnetic field lines:

- Outside magnet: N ⇒ S
- Inside magnet: S ⇒ N
- Closed loops

Field Lines of Bar Magnet



13.2 Axial vs Equatorial Field Variation

For distant point:

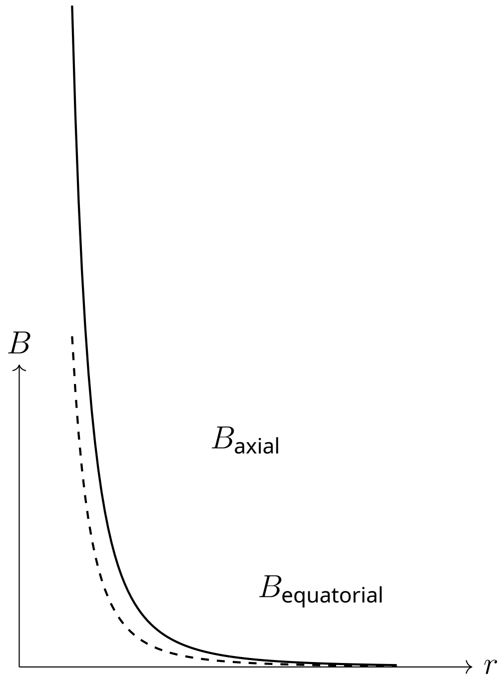
$$B_{\text{axial}} = \frac{\mu_0}{4\pi}\frac{2M}{r^3}$$

$$B_{\text{equatorial}} = \frac{\mu_0}{4\pi}\frac{M}{r^3}$$

$$B_{\text{axial}} = 2B_{\text{equatorial}}$$

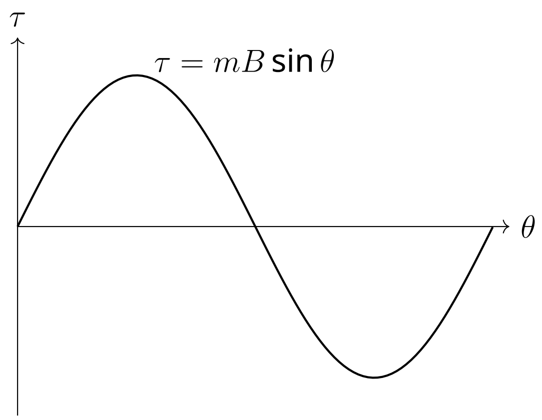
Both vary as:

$$\propto \frac{1}{r^3}$$



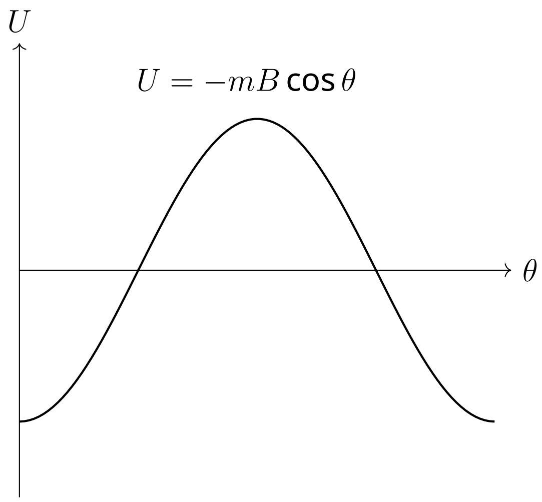
13.3 Torque vs Angle

$$\tau = mB \sin \theta$$

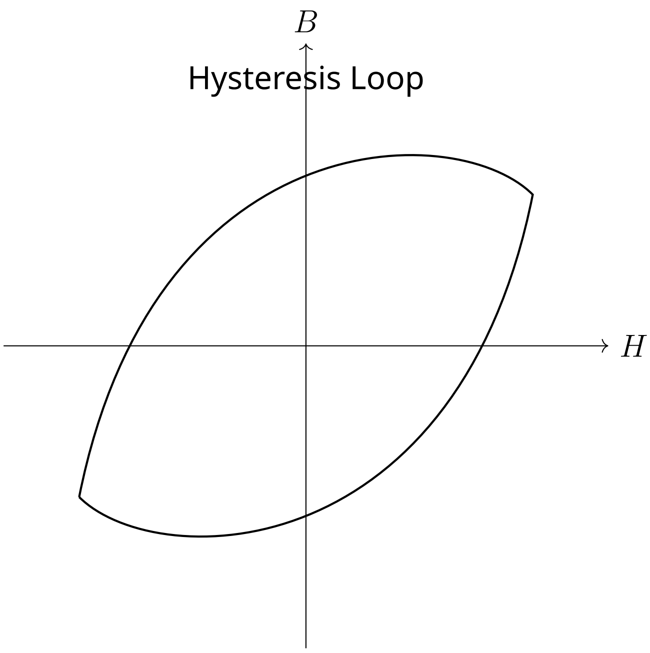


13.4 Potential Energy vs Angle

$$U = -mB \cos \theta$$



13.5 Hysteresis Loop

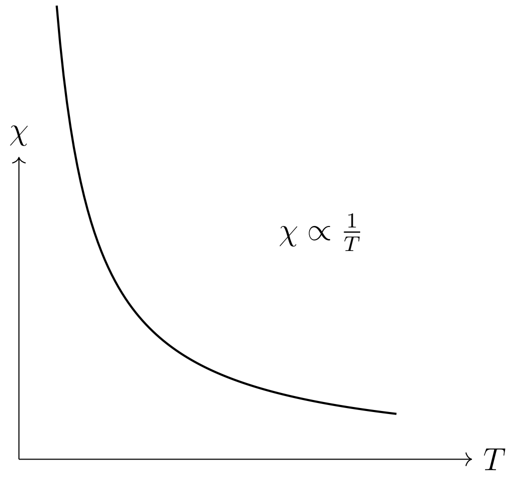


13.6 χ vs T for Paramagnetic Material

From Curie's law:

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

$$\chi \propto \frac{1}{T}$$



Graph Summary

- Field lines of bar magnet
- Axial vs equatorial field comparison
- τ vs θ
- U vs θ
- Hysteresis loop
- χ vs T (paramagnetic)

14 Important Derivations in Magnetism

14.1 Field on Axial Line of a Magnetic Dipole

Consider a bar magnet of magnetic moment $M = m(2l)$.

For a point at distance r from centre on axial line (where $r \gg l$):

Magnetic field due to North pole:

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

Magnetic field due to South pole:

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

Net field:

$$B = B_N - B_S$$

Using binomial approximation for $r \gg l$:

$$\boxed{B_{\text{axial}} = \frac{\mu_0}{4\pi}\frac{2M}{r^3}}$$

14.2 Field on Equatorial Line of a Magnetic Dipole

For a point at distance r on equatorial line:
Net magnetic field:

$$B = 2\left(\frac{\mu_0}{4\pi}\frac{ml}{r^3}\right)$$

Using $M = m(2l)$:

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

Direction is opposite to magnetic dipole moment.
Comparison:

$$\boxed{B_{\text{axial}} = 2B_{\text{equatorial}}}$$

14.3 Torque on Magnetic Dipole

Consider dipole of magnetic moment $\vec{M}$ placed in uniform magnetic field $\vec{B}$.
Forces on poles are equal and opposite.
These forces form a couple.
Torque magnitude:

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

Vector form:

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

14.4 Potential Energy of Magnetic Dipole

Work done in rotating dipole through small angle $d\theta$:

$$dW = \tau d\theta$$

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

Integrating from reference position:

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

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

Minimum at $\theta = 0°$, maximum at $\theta = 180°$.

14.5 Relation Between B, H and M

Magnetic field inside material:

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

If material is linear:

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

Substitute:

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

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

14.6 Curie's Law (Paramagnetic Materials)

In paramagnetic materials:
Magnetisation:

$$M \propto \frac{H}{T}$$

Since:

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

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

where:

- C = Curie constant
- T = absolute temperature

Thus susceptibility decreases with increase in temperature.

Derivation Summary

- $B_{\text{axial}} = \frac{\mu_0}{4\pi}\frac{2M}{r^3}$
- $B_{\text{equatorial}} = \frac{\mu_0}{4\pi}\frac{M}{r^3}$
- $\vec{\tau} = \vec{M} \times \vec{B}$
- $U = -\vec{M} \cdot \vec{B}$
- $\vec{B} = \mu_0(\vec{H} + \vec{M})$
- $\chi = \frac{C}{T}$

15 Important Comparisons in Magnetism

15.1 Electric Dipole vs Magnetic Dipole

Electric Dipole	Magnetic Dipole
Two equal and opposite electric charges separated by small distance	Equivalent to a current loop or bar magnet
Dipole moment: $p = qd$	Dipole moment: $M = IA$ or $M = m(2l)$
Electric field lines start from + and end at –	Magnetic field lines form closed loops
Electric monopole exists	Magnetic monopole does not exist
Field at large distance $\propto \frac{1}{r^3}$	Field at large distance $\propto \frac{1}{r^3}$

15.2 Diamagnetic vs Paramagnetic vs Ferromagnetic

Property	Diamagnetic	Paramagnetic	Ferromagnetic
Response to field	Weakly repelled	Weakly attracted	Strongly attracted
Susceptibility χ	Small negative	Small positive	Very large positive
Relative permeability μ_r	< 1	Slightly > 1	$\gg 1$
Temperature dependence	Independent	$\chi = \frac{C}{T}$	Above Curie temp becomes paramagnetic
Examples	Cu, Bi, Ag	Al, Pt, O_2	Fe, Co, Ni

15.3 Solenoid vs Bar Magnet

Solenoid	Bar Magnet
Current carrying coil	Permanent magnet
Magnetic moment $M = NIA$	Magnetic moment $M = m(2l)$
Field depends on current	Field exists without external current
Polarity can be reversed by reversing current	Polarity fixed unless remagnetised
Field pattern similar to bar magnet	Field pattern similar to solenoid

15.4 Magnetic Field Lines vs Electric Field Lines

Magnetic Field Lines	**Electric Field Lines**
Form closed loops	Start on + and end on – charges
No magnetic monopole	Electric monopole exists
Direction: N $\Rightarrow$ S outside magnet	Direction: + $\Rightarrow$ –
Never intersect	Never intersect
$\nabla \cdot \vec{B} = 0$	$\nabla \cdot \vec{E} \neq 0$

Quick Revision Summary

- Electric dipole ≠ Magnetic dipole (no magnetic monopole).
- Diamagnetic < Paramagnetic < Ferromagnetic (in strength).
- Solenoid behaves like bar magnet.
- Magnetic field lines are closed loops; electric field lines are not.