

Chapter 5 : Magnetism and Matter (Notes)

by - Tomar Sir

Notes

GSEB and CBSE Board Exam preparation subjective notes · Class 12 Physics · NCERT Chapter 5

Q.1 State the commonly known basic properties of magnetism. (2 Marks)

- i. **The Earth behaves as a magnet**, with its magnetic field pointing approximately from the geographic south to the geographic north.
- ii. A **freely suspended bar magnet points in the north-south direction**. The tip pointing to the geographic north is the **north pole**; the other is the **south pole**.
- iii. **Like poles repel and unlike poles attract** each other.
- iv. **Isolated poles do not exist**. If a bar magnet is broken into two halves, we get two similar (weaker) bar magnets. Unlike electric charges, isolated magnetic north and south poles — **magnetic monopoles** — do not exist.
- v. Magnets can be made out of **iron and its alloys**.

Key Examination Points for Full Marks:

- The word *magnet* comes from *Magnesia*, an island in Greece where magnetic ore deposits were found around 600 BC.
- Moving charges (currents) produce magnetic fields — Oersted, Ampere, Biot and Savart.

Q.2 What are magnetic field lines? State their properties. (3 Marks)

Iron filings sprinkled on a sheet of glass over a short bar magnet arrange themselves in a pattern (Fig. 5.1). The pattern suggests the magnet has **two poles**, like an electric dipole. The field lines are a visual and intuitive representation of the magnetic field.

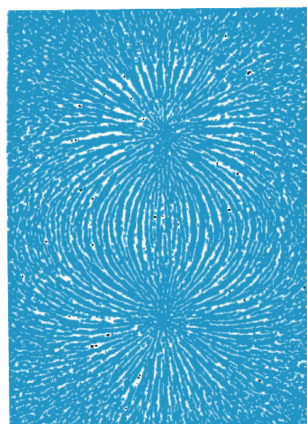


Fig. 5.1: Iron filings around a bar magnet. The pattern mimics magnetic field lines and suggests the bar magnet is a magnetic dipole

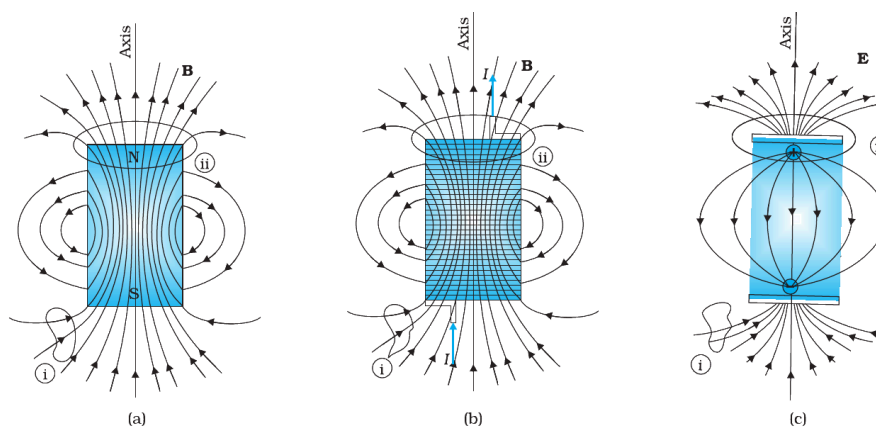


Fig. 5.2: Field lines of (a) a bar magnet, (b) a current-carrying finite solenoid and (c) an electric dipole. At large distances the field lines are very similar. Curves ① and ② are closed Gaussian surfaces

Properties of magnetic field lines:

- i. They form **continuous closed loops** — unlike electric dipole field lines, which begin on a positive charge and end on a negative charge (or escape to infinity).
- ii. The **tangent** to a field line at a point gives the **direction** of the net field **B** at that point.
- iii. The **larger the number of field lines crossing per unit area**, the stronger the magnetic field.
- iv. Field lines **never intersect**; otherwise the field would have two directions at the point of intersection.

Key Examination Points for Full Marks:

- Outside a magnet, field lines go from N to S; **inside, from S to N**.
- Field lines can be plotted with a small compass needle placed at various positions.
- They are not “lines of force”: unlike electrostatics, magnetic field lines do not give the direction of the force on a moving charge.

Q.3 Explain how a bar magnet behaves as an equivalent solenoid. Give (3 Marks) the axial field of a bar magnet.

Ampere’s hypothesis: All magnetic phenomena can be explained in terms of circulating currents. A current loop acts as a magnetic dipole.

The field lines of a bar magnet and a current-carrying solenoid are very similar (Fig. 5.2). So **a bar magnet may be thought of as a large number of circulating currents**, like a solenoid:

- Cutting a bar magnet in half is like cutting a solenoid — we get two smaller solenoids (magnets) with weaker properties.
- Field lines emerge from one face of the solenoid and enter the other.
- A small compass needle is deflected similarly near a bar magnet and near a finite solenoid.

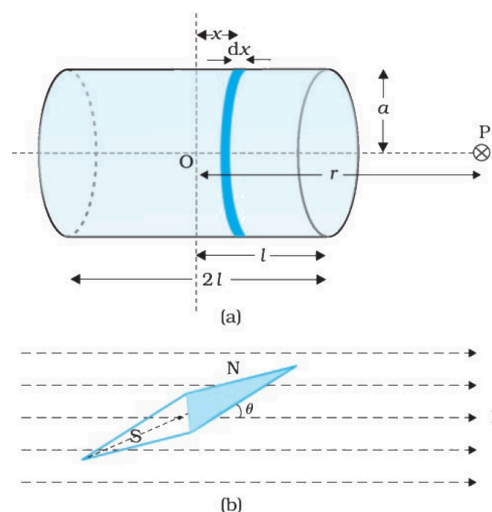


Fig. 5.3: (a) Calculating the axial field of a finite solenoid to show its similarity to that of a bar magnet. (b) A magnetic needle in a uniform magnetic field B

Axial field: The field at a far point P on the axis of a finite solenoid of magnetic moment m (Fig. 5.3(a)) is

$$B = \frac{\mu_0}{4\pi} \frac{2m}{r^3}$$

This is also the far axial field of a bar magnet found experimentally. Hence **the magnetic moment of a bar magnet equals that of the equivalent solenoid** producing the same field.

Key Examination Points for Full Marks:

- Magnetic moment of a solenoid: $m = NIA$, directed along its axis (right-hand rule). Unit: $\text{A m}^2 (= \text{J T}^{-1})$.
- The direction of $\vec{m}$ of a bar magnet is from its **S-pole to N-pole**.

Q.4 Derive the torque and potential energy of a magnetic dipole in a uniform magnetic field. When is it in stable equilibrium? (3 Marks)

Place a small compass needle of magnetic moment $\vec{m}$ in a uniform field $\vec{B}$ (Fig. 5.3(b)).

Torque: The forces on the two poles are equal and opposite (**net force = 0**) but form a couple:

$$\vec{\tau} = \vec{m} \times \vec{B}, \quad \tau = mB \sin \theta$$

where θ is the angle between $\vec{m}$ and $\vec{B}$. This is a **restoring torque**.

Potential energy: The magnetic potential energy is the work done against this torque:

$$U_m = \int \tau(\theta) d\theta = \int mB \sin \theta d\theta = -mB \cos \theta$$

$$U_m = -\vec{m} \cdot \vec{B}$$

The zero of PE is chosen at $\theta = 90^\circ$ ($\vec{m}$ perpendicular to $\vec{B}$).

- $\theta = 0^\circ$ ($\vec{m}$ parallel to $\vec{B}$): $U = -mB$ (**minimum**) — **most stable** equilibrium.
- $\theta = 180^\circ$ ($\vec{m}$ antiparallel to $\vec{B}$): $U = +mB$ (**maximum**) — **most unstable** equilibrium.

Key Examination Points for Full Marks:

- Work done in rotating a dipole from θ_1 to θ_2 : $W = mB (\cos \theta_1 - \cos \theta_2)$. From 0° to 180° : $W = 2mB$.
- For small oscillations of a needle of moment of inertia I : $T = 2\pi \sqrt{\frac{I}{mB}}$ (used to find m or B).
- A magnet in a uniform field feels only a torque; in a **non-uniform** field it also feels a net force.

Q.5 Explain the electrostatic analog of a bar magnet. Write the fields on its axis and equator. (2 Marks)

The equations for a magnetic dipole can be obtained from those of an electric dipole by the replacements

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

For a bar magnet of size l at a distance $r \gg l$ from its centre:

$$\text{Equatorial field: } \vec{B}_E = -\frac{\mu_0 \vec{m}}{4\pi r^3}, \quad \text{Axial field: } \vec{B}_A = \frac{\mu_0 2\vec{m}}{4\pi r^3}$$

Property	Electrostatics	Magnetism
Constant	$1/\epsilon_0$	μ_0
Dipole moment	p	m
Equatorial field (short dipole)	$-\mathbf{p}/4\pi\epsilon_0 r^3$	$-\mu_0 \mathbf{m}/4\pi r^3$
Axial field (short dipole)	$2\mathbf{p}/4\pi\epsilon_0 r^3$	$\mu_0 2\mathbf{m}/4\pi r^3$
Torque in external field	$\mathbf{p} \times \mathbf{E}$	$\mathbf{m} \times \mathbf{B}$
Energy in external field	$-\mathbf{p} \cdot \mathbf{E}$	$-\mathbf{m} \cdot \mathbf{B}$

Key Examination Points for Full Marks:

- At the same distance, $B_A = 2B_E$.
- The equatorial field is **opposite** to $\vec{m}$; the axial field is **along** $\vec{m}$.

Q.6 State and explain Gauss's law for magnetism. How does it differ from Gauss's law of electrostatics? (2 Marks)

For a small vector area element $\Delta \vec{S}$ of a closed surface S , the magnetic flux is $\Delta \phi_B = \vec{B} \cdot \Delta \vec{S}$ (Fig. 5.5). The net flux through S is

$$\phi_B = \sum_{\text{all}} \Delta \phi_B = \sum_{\text{all}} \vec{B} \cdot \Delta \vec{S} = 0$$

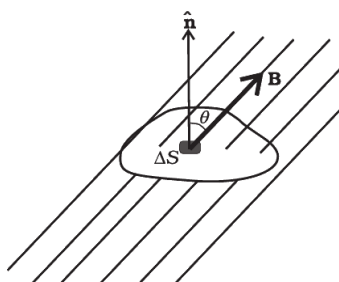


Fig. 5.5: Magnetic flux through a small area element ΔS

Statement: The net magnetic flux through any closed surface is zero.

Explanation: Magnetic field lines are continuous closed loops. For any closed surface (e.g. ① or ② in Fig. 5.2(a), (b)), the number of field lines leaving the surface equals the number entering it.

Comparison with electrostatics: $\sum \vec{E} \cdot \Delta \vec{S} = \frac{q}{\epsilon_0}$, where q is the enclosed charge. The difference arises because **isolated magnetic poles (monopoles) do not exist** — there are no sources or sinks of $\mathbf{B}$. The simplest magnetic element is a dipole or current loop.

Key Examination Points for Full Marks:

- If monopoles existed, the law would become $\oint \vec{B} \cdot d\vec{S} = \mu_0 q_m$, where q_m is the enclosed magnetic charge.

Q.7 Define magnetisation, magnetic intensity, susceptibility and permeability. Derive the relations between them. (3 Marks)

Magnetisation (M): The net magnetic moment per unit volume of a sample:

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

Unit: $A\ m^{-1}$; dimensions $[L^{-1} A]$; vector.

Consider a long solenoid (n turns per unit length, current I). The field inside is $B_0 = \mu_0 nI$. If the interior is filled with a material, the field becomes $\vec{B} = \vec{B}_0 + \vec{B}_m$, where the extra field is proportional to the magnetisation:
 $\vec{B}_m = \mu_0 \vec{M}$.

Magnetic intensity (H):

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

H has the same unit as M ($A\ m^{-1}$). H represents the contribution of external factors (current in the solenoid); M represents the contribution of the material.

Magnetic susceptibility (χ): For a linear material,

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

χ is dimensionless; it measures how a material responds to an external field. χ is small and positive for paramagnetic materials, small and negative for diamagnetic materials.

Relative permeability and permeability:

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

$$\mu_r = 1 + \chi, \quad \mu = \mu_0 \mu_r = \mu_0 (1 + \chi)$$

μ_r is dimensionless (analog of the dielectric constant); μ has the same unit as μ_0 ($T\ m\ A^{-1} = N\ A^{-2}$). Given any one of χ , μ_r , μ , the other two can be found.

Key Examination Points for Full Marks:

- Example 5.5:** Core with $\mu_r = 400$, $n = 1000\ m^{-1}$, $I = 2\ A$: $H = nI = 2 \times 10^3\ A/m$; $B = \mu_r \mu_0 H = 1.0\ T$;
 $M = (\mu_r - 1) H \approx 8 \times 10^5\ A/m$; magnetising current $I_M = 794\ A$.

Q.8 Classify magnetic materials on the basis of susceptibility. Compare diamagnetic, paramagnetic and ferromagnetic substances. (3 Marks)

A material is **diamagnetic** if χ is negative, **paramagnetic** if χ is small and positive, and **ferromagnetic** if χ is large and positive.

Property	Diamagnetic	Paramagnetic	Ferromagnetic
Susceptibility χ	$-1 \leq \chi < 0$	$0 < \chi < \varepsilon$ (small)	$\chi \gg 1$
Relative permeability μ_r	$0 \leq \mu_r < 1$	$1 < \mu_r < 1 + \varepsilon$	$\mu_r \gg 1$
Permeability μ	$\mu < \mu_0$	$\mu > \mu_0$	$\mu \gg \mu_0$
Behaviour in a magnet's field	Weakly repelled	Weakly attracted	Strongly attracted
In a non-uniform field, moves	Strong $\rightarrow$ weak field	Weak $\rightarrow$ strong field	Weak $\rightarrow$ strong field
Field lines	Expelled (field inside reduced)	Slightly concentrated	Highly concentrated
Atomic magnetic moment	Zero	Non-zero (permanent)	Non-zero; aligned in domains
Examples	Bi, Cu, Pb, Si, N ₂ , water, NaCl	Al, Na, Ca, O ₂ , CuCl ₂	Fe, Co, Ni, Gd, alnico

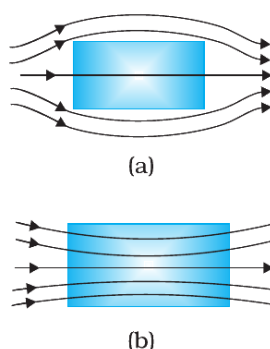


Fig. 5.7: Field lines near (a) a diamagnetic and (b) a paramagnetic substance

Key Examination Points for Full Marks:

- For diamagnetic materials $\chi \approx -10^{-5}$; for paramagnetic $\chi \approx +10^{-5}$. A tiny difference in χ gives radically different behaviour.
- Diamagnetism is universal** — present in all materials, but masked in para- and ferromagnetic ones.

Q.9 Explain diamagnetism. What is the Meissner effect?

(2 Marks)

Diamagnetic substances tend to move from the stronger to the weaker part of an external field — they are repelled by a magnet. The field lines are expelled and the field inside is reduced (by about 1 part in 10^5) (Fig. 5.7(a)).

Explanation: Orbiting electrons behave like current loops with orbital magnetic moments. In a diamagnetic atom, the **resultant magnetic moment is zero**. When a field is applied, electrons whose orbital moment is along the field **slow down** and those with the opposite moment **speed up** (induced currents, by Lenz's law). The substance develops a net magnetic moment **opposite to the applied field**, hence repulsion.

Superconductors and the Meissner effect: Metals cooled to very low temperatures show both **perfect conductivity** and **perfect diamagnetism** — the field lines are completely expelled: $\chi = -1$ and $\mu_r = 0$. A superconductor repels a magnet. **The phenomenon of perfect diamagnetism in superconductors is called the Meissner effect.**

Key Examination Points for Full Marks:

- Application: superconducting magnets for magnetically **levitated superfast trains**.
- The BCS theory (Bardeen, Cooper and Schrieffer, 1957) explains superconductivity.

Q.10 Explain paramagnetism. How does it depend on temperature? (2 Marks)

Paramagnetic substances get weakly magnetised in an external field and tend to move from a weak-field region to a strong-field region — they are **weakly attracted** to a magnet.

Explanation: Each atom (or ion or molecule) has a **permanent magnetic dipole moment**. Due to random thermal motion, the moments point randomly and there is no net magnetisation. In a strong enough external field B_0 , at low temperatures, the atomic moments align along B_0 . The field lines get concentrated inside the material and the field is enhanced (by about 1 part in 10^5) (Fig. 5.7(b)).

Temperature dependence: For a paramagnetic material, χ and μ_r depend on the material **and on temperature**. As the field is increased or the temperature lowered, the magnetisation increases until it reaches **saturation**, when all dipoles are aligned with the field.

Key Examination Points for Full Marks:

- **Curie's law:** $M = C \frac{B_0}{T}$, i.e. $\chi \propto \frac{1}{T}$ — magnetisation is directly proportional to the applied field and inversely proportional to the absolute temperature.
- Examples: aluminium, sodium, calcium, oxygen (at STP), copper chloride.

Q.11 Explain ferromagnetism using domains. Distinguish between hard and soft ferromagnets. (3 Marks)

Ferromagnetic substances get strongly magnetised in an external field and are strongly attracted to a magnet.

Domain theory: The atoms possess dipole moments, but they **interact** so that they spontaneously align in a common direction over a macroscopic volume called a **domain** (size ≈ 1 mm, containing about 10^{11} atoms). Each domain has a net magnetisation.

- Without an external field, the magnetisation varies randomly from domain to domain — no bulk magnetisation (Fig. 5.8(a)).
- When a field B_0 is applied, the domains orient along B_0 and the domains already aligned with B_0 **grow in size**. Finally they amalgamate into a single “giant” domain (Fig. 5.8(b)).

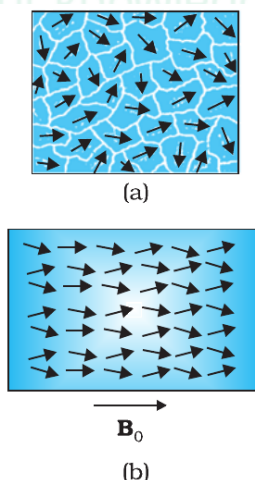


Fig. 5.8: (a) Randomly oriented domains, (b) aligned domains

Domains can be seen under a microscope using a liquid suspension of powdered ferromagnetic substance.

Hard ferromagnets: The magnetisation **persists** after the external field is removed. Examples: **alnico** (Fe, Al, Ni, Co, Cu), naturally occurring **lodestone**. Used to make **permanent magnets** (e.g. compass needles).

Soft ferromagnets: The magnetisation **disappears** on removing the external field. Example: **soft iron**. Used in electromagnets and transformer cores.

Key Examination Points for Full Marks:

- Ferromagnetic elements: iron, cobalt, nickel, gadolinium. $\mu_r > 1000$.
- **At high enough temperature** (the Curie temperature), a ferromagnet becomes a **paramagnet** — the domain structure disintegrates gradually with temperature.
- Electromagnet core: **high permeability, low retentivity** (soft iron). Permanent magnet: **high retentivity and coercivity** (steel, alnico).

Formula Sheet — Magnetism and Matter

Quantity	Formula	SI Unit
Magnetic moment (bar magnet)	$m = q_m \times 2l$ (S → N)	A m ²
Magnetic moment (solenoid/loop)	$m = NIA$	A m ²
Axial field ($r \gg l$)	$B_A = \frac{\mu_0 2m}{4\pi r^3}$	T
Equatorial field ($r \gg l$)	$B_E = -\frac{\mu_0 m}{4\pi r^3}$	T
Torque on a dipole	$\vec{\tau} = \vec{m} \times \vec{B}$; $\tau = mB \sin \theta$	N m
Potential energy	$U = -\vec{m} \cdot \vec{B} = -mB \cos \theta$	J
Work in rotating	$W = mB (\cos \theta_1 - \cos \theta_2)$	J
Time period of oscillation	$T = 2\pi \sqrt{\frac{I}{mB}}$	s
Gauss's law (magnetism)	$\phi_B = \oint \vec{B} \cdot d\vec{S} = 0$	Wb
Magnetisation	$M = \frac{m_{net}}{V}$	A m ⁻¹
Magnetic intensity	$H = \frac{B}{\mu_0} - M$; in a solenoid $H = nI$	A m ⁻¹
Field in material	$B = \mu_0 (H + M) = \mu_0 \mu_r H = \mu H$	T
Susceptibility	$M = \chi H$	—
Relative permeability	$\mu_r = 1 + \chi$; $\mu = \mu_0 \mu_r$	—
Curie's law (paramagnets)	$\chi = \frac{C\mu_0}{T}$, i.e. $\chi \propto \frac{1}{T}$	—
Earth's field	$B_H = B \cos \delta$, $B_V = B \sin \delta$, $\tan \delta = \frac{B_V}{B_H}$	T

Constants: $\mu_0 = 4\pi \times 10^{-7} \text{ T m A}^{-1}$; $\frac{\mu_0}{4\pi} = 10^{-7} \text{ T m A}^{-1}$; $1 \text{ G} = 10^{-4} \text{ T}$.

Dimensions: B [M T⁻² A⁻¹]; magnetic moment [L² A]; M and H [L⁻¹ A]; magnetic flux [M L² T⁻² A⁻¹]; μ, μ_0 [M L T⁻² A⁻²].

NEET / JEE Quick Points and Tricks

1. **Cutting a magnet perpendicular to its axis into n parts:** pole strength unchanged, m becomes m/n. **Cut along the axis (lengthwise):** pole strength becomes q_m/n , m becomes m/n.

2. **Bending a magnet (or a wire with moment) into an arc of angle θ :** $m' = m \frac{2 \sin (\theta/2)}{\theta}$. Semicircle:

$$m' = \frac{2m}{\pi}; 60^\circ \text{ arc: } \frac{3m}{\pi}; \text{ bent at the middle into an L (90°): } \frac{m}{\sqrt{2}}; \text{ into a 60° V: } \frac{m}{2}.$$

3. **Magnetic length** $\approx \frac{5}{6} \times$ geometric length.
4. **Axial vs equatorial field** at the same distance: $B_A = 2B_E$; directions are opposite relative to $\vec{m}$.
5. **Work to turn a dipole** from the stable position by θ : $W = mB (1 - \cos \theta)$. By 90° : $W = mB$; by 180° : $W = 2mB$. Torque is maximum (mB) at 90° .
6. **Equilibrium**: $\vec{m}$ parallel to $\vec{B}$ — stable ($U = -mB$); antiparallel — unstable ($U = +mB$).
7. **Net force on a magnet in a uniform field is zero**; in a non-uniform field there is a net force too (e.g. an iron nail is attracted to a magnet).
8. **Magnetic monopoles do not exist** — field lines form closed loops and $\oint \vec{B} \cdot d\vec{S} = 0$ always.
9. **Signs of χ** : diamagnetic -ve ($\chi = -1$ for a superconductor), paramagnetic small +ve, ferromagnetic large +ve.
10. **Temperature**: χ of a diamagnet is independent of T ; paramagnet $\chi \propto 1/T$ (Curie); ferromagnet becomes a paramagnet above the Curie temperature.
11. **Which way does a sample move in a non-uniform field?** Para/ferro $\rightarrow$ towards the strong field; dia $\rightarrow$ towards the weak field. A diamagnetic liquid in a U-tube between poles is **depressed**; a paramagnetic liquid **rises**.
12. **Soft iron** (high μ , low retentivity, low coercivity, small hysteresis loss) $\rightarrow$ electromagnets, transformer cores.
Steel/alnico (high retentivity and coercivity) $\rightarrow$ permanent magnets.
13. **Angle of dip**: $\tan \delta = B_V/B_H$; $\delta = 0^\circ$ at the magnetic equator, 90° at the magnetic poles. If $B_V = B_H$, $\delta = 45^\circ$.
14. **Solenoid with core**: $B = \mu_0 \mu_r nI$, $H = nI$ (independent of the core), $M = (\mu_r - 1) nI$.

