

CUET · PHYSICS · CLASS XII · CODE 322

Magnetism and Matter

CUET unit: Magnetism and Matter

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Snapshot

- Establishes the bar magnet as the prototype magnetic dipole and shows it is equivalent to a current-carrying solenoid — every magnetic phenomenon reduces to circulating currents (Ampere's hypothesis).
- Derives torque ($\tau = m \times B$) and potential energy ($U = -m \cdot B$) of a magnetic dipole in a uniform field, with stable/unstable equilibrium positions.
- States Gauss's law for magnetism (net flux through any closed surface = 0) as a consequence of the non-existence of magnetic monopoles.
- Defines magnetisation M , magnetic intensity H , susceptibility χ and relative permeability μ_r , and classifies materials as diamagnetic, paramagnetic and ferromagnetic.
- CUET tests this chapter for short numerical computations (axial/equatorial field, torque, U), conceptual classification of materials, and properties of field lines.

Detailed Notes

2.1 Core concepts

Magnetism is older than the science of it. The word "magnet" comes from Magnesia, a region in Greece where lodestone (a naturally magnetic form of magnetite) was found around 600 BC. Magnetic compasses guided ships across the medieval world long before the laws of electromagnetism were written down. The Earth itself behaves like a giant bar magnet whose field points approximately from geographic south to geographic north, which is what a compass needle responds to (NCERT §5.1, p. 136).

Some basic facts emerge from simple experiments with a bar magnet (NCERT §5.1, p. 137). A freely suspended bar magnet aligns itself along the geographic north–south direction; the end pointing to geographic north is the **north pole** (N), the other the **south pole** (S). Like poles repel, unlike poles attract — a Coulomb-like rule. Sprinkling iron filings around a bar magnet traces a family of curves running from N to S externally and from S to N internally, identical in shape to the lines of force of a current-carrying solenoid. Most importantly, **magnetic monopoles do not exist**: cutting a bar magnet across its length produces two smaller bar magnets, each with its own N and S, no matter how many times you cut. The simplest magnetic element is therefore a **dipole**, not a charge.

The deep theoretical statement underlying this is **Ampere's hypothesis**: every magnetic effect is ultimately due to circulating electric currents. A bar magnet is equivalent to a stack of microscopic current loops, each loop carrying a tiny circulating current (NCERT §5.2.2, p. 138). Hence a bar magnet of magnetic moment m and a long solenoid carrying an appropriate current produce the same field pattern far away. The far axial field of a finite solenoid worked out from the Biot–Savart law is $\mathbf{B} = \frac{\mu_0}{4\pi} \frac{2m}{r^3}$, identical to that of a bar magnet of dipole moment m (NCERT §5.2.2, Eq. 5.1, p. 139).

Properties of magnetic field lines (NCERT §5.2.1, p. 137–138). (i) Magnetic field lines form continuous closed loops, unlike electric field lines which start on positive charges and end on negative charges. (ii) The tangent to a field line at any point gives the direction of \mathbf{B} there. (iii) The density of field lines per unit area perpendicular to them is proportional to $|\mathbf{B}|$, so closely spaced lines indicate strong field. (iv) Field lines never intersect — if they did, \mathbf{B} would have two directions at the same point.

Torque and energy of a dipole in a uniform field (NCERT §5.2.3, p. 139).

Consider a bar magnet placed in a uniform external field \mathbf{B} at angle θ to it. The forces on the N and S poles are equal and opposite, so the net force is zero; but they form a couple producing a torque

$$\tau = m \times \mathbf{B}, \text{ with magnitude } \tau = mB \sin \theta \text{ (Eq. 5.2, p. 139).}$$

Doing work against this restoring torque to rotate the dipole stores potential energy

$$U = -m \cdot \mathbf{B} = -mB \cos \theta \text{ (Eq. 5.3, p. 139).}$$

The zero of energy is chosen at $\theta = 90^\circ$. The minimum $U = -mB$ is at $\theta = 0^\circ$ (m parallel to \mathbf{B} — **most stable** orientation); the maximum $U = +mB$ is at $\theta = 180^\circ$ (m anti-parallel — **most unstable**). These results, with $\tau \rightarrow 0$ at both extremes, look exactly like an electric dipole in an electric field. The general electrostatic-magnetic analogy is summarised in NCERT Table 5.1, p. 141: replacing $\mathbf{E} \rightarrow \mathbf{B}$, $p \rightarrow m$ and $1/(4\pi\epsilon_0) \rightarrow \mu_0/4\pi$ converts every electrostatic dipole formula into its magnetic counterpart. For a short bar magnet on the axis at distance r from the centre, $\mathbf{B} = \frac{\mu_0}{4\pi} \frac{2m}{r^3}$, and on the equatorial plane $\mathbf{B} = -\frac{\mu_0}{4\pi} \frac{m}{r^3}$ (NCERT §5.2.4, Eqs. 5.4–5.5, p. 140). The equatorial field is anti-parallel to m and half the axial field's magnitude — a frequent CUET trap.

Gauss's law for magnetism (NCERT §5.3, p. 142–143). Because magnetic field lines form closed loops, every line entering a closed surface must also exit it. Hence the net magnetic flux through any closed surface is zero:

$$\oint \mathbf{B} \cdot d\mathbf{S} = 0 \text{ (Eq. 5.6, p. 143).}$$

This is the magnetic analog of Gauss's law for electricity, but with the right-hand side zero — a direct statement that no magnetic monopoles exist (no sources or sinks of \mathbf{B}). In Maxwell's equations this becomes $\nabla \cdot \mathbf{B} = 0$.

Magnetisation, intensity and permeability (NCERT § 5.4, p. 145–146). Inside a magnetic material, the dipoles of individual atoms produce a net magnetic moment per unit volume:

$$M = m_{\text{net}} / V \text{ (Eq. 5.7, p. 145), units } A \text{ m}^{-1}.$$

Inside a solenoid of n turns per metre carrying current I , the field would be $B_0 = \mu_0 nI$ in vacuum. When the bore is filled with a magnetic material, the material contributes an additional field $B_m = \mu_0 M$, so the total field is $\mathbf{B} = \mathbf{B}_0 + \mathbf{B}_m = \mu_0(nI + M)$. To separate the contribution of free conduction currents from that of the material, one defines the **magnetic intensity** (or magnetising field)

$$H = B/\mu_0 - M \text{ (Eq. 5.10, p. 146), units } A \text{ m}^{-1}.$$

Equivalently $B = \mu_0(H + M)$. For linear, isotropic materials the magnetisation is proportional to H :

$$M = \chi H \text{ (Eq. 5.13, p. 146),}$$

where χ is the dimensionless **magnetic susceptibility**. Substituting back gives $B = \mu_0(1 + \chi)H = \mu_0 \mu_r H = \mu H$, where $\mu_r = 1 + \chi$ is the **relative permeability** (dimensionless) and $\mu = \mu_0 \mu_r$ is the **magnetic permeability** of the material.

Classification of magnetic materials (NCERT § 5.5, p. 147, Table 5.2). All materials fall into three broad classes:

- **Diamagnetic** ($-1 \leq \chi < 0$, $0 \leq \mu_r < 1$, $\mu < \mu_0$). Atoms have zero net moment; on applying B , induced currents (a manifestation of Lenz's law) produce a moment that **opposes** B . The substance is feebly repelled by a magnet, moves from regions of strong to weak field, and the field lines tend to be expelled from its interior (NCERT § 5.5.1, p. 147–148, Fig. 5.7a). Examples: bismuth, copper, lead, silicon, nitrogen at STP, water, sodium chloride. **Superconductors** are perfect diamagnets with $\chi = -1$, $\mu_r = 0$; they completely expel the magnetic field, a phenomenon known as the **Meissner effect**.
- **Paramagnetic** ($0 < \chi < \epsilon$, $1 < \mu_r < 1 + \epsilon$, μ slightly $> \mu_0$). Each atom carries a permanent magnetic moment, but thermal motion randomises them, so the bulk substance has no net M in zero field. An external B partially aligns the moments along itself; the field lines crowd into the material (Fig. 5.7b), the substance is feebly attracted by a magnet and moves from weak to strong field regions. Susceptibility and μ_r depend on temperature (Curie's law). Examples: aluminium, sodium, calcium, oxygen at STP, copper chloride (NCERT § 5.5.2, p. 148).
- **Ferromagnetic** ($\chi \gg 1$, $\mu_r \gg 1$). Quantum mechanical exchange interaction causes atomic moments to align spontaneously over macroscopic regions called **domains** (~ 1 mm size, $\sim 10^{11}$ atoms each). In an unmagnetised piece the domains are randomly oriented and cancel out; an applied B grows favourably-oriented domains at the expense of others, until they merge into one giant domain at saturation (NCERT Fig. 5.8, p. 149). The resulting M can be enormous, $\mu_r > 1000$. **Hard** ferromagnets (Alnico, lodestone) retain their magnetisation when the external field is removed —

these are used as **permanent magnets**. **Soft** ferromagnets (soft iron) lose their magnetisation almost completely — used in transformer and motor cores. Above a critical (Curie) temperature, thermal motion destroys the domain order and a ferromagnet becomes paramagnetic. Examples: iron, cobalt, nickel, gadolinium.

Diamagnetism is universal — every substance has a small diamagnetic contribution from induced currents — but in paramagnetic or ferromagnetic materials the much stronger paramagnetic/ferromagnetic response masks it.

2.2 Definitions to memorise

Term	Definition	Page
Magnetic dipole moment (m)	Property of a bar magnet/current loop characterising its strength as a magnetic source; vector, units $A\ m^2$	137, 145
North/South pole	Ends of a freely suspended bar magnet that point to geographic north/south	137
Magnetic field lines	Continuous closed loops whose tangent gives B direction and density gives B magnitude; never intersect	137–138
Magnetic monopole	Hypothetical isolated N or S magnetic charge — does not exist	137
Ampere's hypothesis	All magnetic phenomena are due to circulating electric currents	138
Torque on dipole (τ)	$\tau = m \times B$; magnitude $mB \sin \theta$	139
Magnetic potential energy (U)	$U = -m \cdot B$; minimum at $\theta = 0^\circ$, maximum at $\theta = 180^\circ$	139
Axial field of short bar magnet	$B_A = (\mu_0/4\pi)(2m/r^3)$	140
Equatorial field of short bar magnet	$B_E = -(\mu_0/4\pi)(m/r^3)$	140
Magnetic flux (ϕ_B)	$\phi_B = \int B \cdot dS$ over a surface	142
Gauss's law for magnetism	$\oint B \cdot dS = 0$ over any closed surface	143
Magnetisation (M)	Net magnetic dipole moment per unit volume; $A\ m^{-1}$	145
Magnetic intensity (H)	$H = B/\mu_0 - M$; $A\ m^{-1}$	146
Magnetic susceptibility (χ)	$M = \chi H$; dimensionless	146
Relative permeability (μ_r)	$\mu_r = 1 + \chi$; dimensionless	146
Magnetic permeability (μ)	$\mu = \mu_0 \mu_r = \mu_0(1 + \chi)$	146

Term	Definition	Page
Diamagnetic	$\chi < 0$; $\mu_r < 1$; weakly repelled; e.g. Bi, Cu, water	147
Paramagnetic	$\chi > 0$ (small); $\mu_r > 1$; weakly attracted; e.g. Al, Na, O ₂	148
Ferromagnetic	$\chi \gg 1$; $\mu_r \gg 1$; strongly attracted; e.g. Fe, Co, Ni	149
Domain	Macroscopic region (~1 mm) of aligned atomic moments in a ferromagnet	149
Hard / soft ferromagnet	Retains / loses magnetisation when external field removed	149
Meissner effect	Complete expulsion of B from a superconductor ($\chi = -1$, $\mu_r = 0$)	148
Curie temperature	Temperature above which a ferromagnet becomes paramagnetic	149
Permanent magnet	Hard ferromagnetic object retaining its magnetisation	149

2.3 Diagrams / processes to remember

- **Fig. 5.1 (p. 137):** Iron filings around a bar magnet — shows the dipole field pattern, concentrated near the poles.
- **Fig. 5.2 (p. 138):** Field lines of (a) bar magnet, (b) finite current-carrying solenoid (identical pattern), (c) electric dipole, with hypothetical Gaussian surfaces marked.
- **Fig. 5.3 (p. 138):** Axial field calculation for a finite solenoid (analogy with bar magnet); compass needle in uniform B.
- **Fig. 5.5 (p. 142):** A vector area element ΔS of a closed surface S used to define magnetic flux $\phi_B = \sum B \cdot \Delta S$, which is zero for any closed surface.
- **Fig. 5.7 (p. 147):** Behaviour of field lines near (a) a diamagnetic specimen — lines are expelled, less dense inside; (b) a paramagnetic specimen — lines concentrate inside, more dense.
- **Fig. 5.8 (p. 149):** Domains in a ferromagnet — (a) randomly oriented (no bulk M); (b) aligned in external B (single giant domain).
- **Table 5.1 (p. 141):** Electrostatics \leftrightarrow Magnetism dipole analogy table — the key cheat-sheet for converting electric-dipole results to magnetic ones.
- **Table 5.2 (p. 147):** χ , μ_r , μ ranges for dia-, para- and ferromagnetic materials.

2.4 Common confusions / NTA trap points

- Magnetic field lines are NOT lines of force on a moving charge — the magnetic force $qv \times B$ is perpendicular to B, not along the field lines (NCERT Example 5.4(a), p. 144).
- B_E and B_A differ by a factor of 2: $B_A = 2 \times |B_E|$ for a short bar magnet on the same r. Watch the sign of B_E (anti-parallel to m on the equatorial line).

- Diamagnetism is present in **all** substances but is masked in para-/ferromagnets — students often pick "only some substances" as a distractor (NCERT Points to Ponder 6, p. 151).
- For diamagnetic materials, χ is **negative** (so M and H are anti-parallel) and $\mu_r < 1$ — easy to confuse with paramagnetic.
- "Bar magnet exerts torque on itself" — NO. An element of a body does not exert a force/torque on itself due to its own field (Example 5.4(c), p. 145).
- Magnetic flux through a closed surface is always zero — even if it appears to enclose a "north pole" — because monopoles don't exist (NCERT §5.3, p. 143).
- Forgetting $\mu_r = 1 + \chi$ (not $1 - \chi$ or $\chi - 1$) — the $+\chi$ sign is a frequent NTA distractor.
- Confusing "soft" with "soft material" — in magnetism "soft" means **easy to demagnetise** (soft iron), not mechanically soft.
- Mixing up B and H : B has units T ($= \text{Wb m}^{-2}$) while H has units A m^{-1} — they are different physical quantities related by $B = \mu H$ for linear media.
- Treating a current loop's magnetic moment vector as scalar — $m = IA \hat{n}$ where \hat{n} is the right-hand-rule normal to the loop area.
- Above the Curie temperature ferromagnets become paramagnetic — they do **not** become diamagnetic.
- Superconductors are **perfect** diamagnets ($\chi = -1$) — a common appearance in assertion-reason items.

2.5 Key formulas table

Symbol	Formula	Meaning	NCERT page
m	$m = NIA$ (loop)	Magnetic moment of a current loop	145
τ	$\tau = m \times B$	Torque on a dipole in uniform field	139, Eq. 5.2
τ (mag)	$\tau = mB \sin \theta$	Magnitude of torque	139
U	$U = -m \cdot B$	Potential energy of dipole	139, Eq. 5.3
U_{\min}, U_{\max}	$-mB$ ($\theta = 0^\circ$), $+mB$ ($\theta = 180^\circ$)	Stable and unstable orientations	139
B_A	$(\mu_0/4\pi)(2m/r^3)$	Axial far-field of short bar magnet	140, Eq. 5.4
B_E	$-(\mu_0/4\pi)(m/r^3)$	Equatorial far-field of short bar magnet	140, Eq. 5.5
Gauss (B)	$\oint B \cdot dS = 0$	Net magnetic flux through closed surface	143, Eq. 5.6

Symbol	Formula	Meaning	NCERT page
M	$M = m_{\text{net}} / V$	Magnetisation	145, Eq. 5.7
H	$H = B/\mu_0 - M$	Magnetic intensity	146, Eq. 5.10
B (linear)	$B = \mu_0(H + M)$	Relation in a magnetic medium	146
M (linear)	$M = \chi H$	Definition of susceptibility	146, Eq. 5.13
μ_r	$\mu_r = 1 + \chi$	Relative permeability	146, Eq. 5.14
μ	$\mu = \mu_0 \mu_r$	Magnetic permeability	146, Eq. 5.15
Solenoid field	$B = \mu_r \mu_0 n I$	Field inside long solenoid with core	146 (Example 5.5)
Far solenoid axial	$B = (\mu_0/4\pi)(2m/r^3)$	Equivalent bar-magnet formula	139, Eq. 5.1
Meissner	$\chi = -1, \mu_r = 0$	Superconductor	148
Diamagnetic range	$-1 \leq \chi < 0, \mu_r < 1$	Class boundary	147, Table 5.2
Paramagnetic range	$0 < \chi \ll 1, \mu_r \gtrsim 1$	Class boundary	147, Table 5.2
Ferromagnetic range	$\chi \gg 1, \mu_r \gg 1$	Class boundary	147, Table 5.2
Curie point	T_C above which ferro \rightarrow para	Temperature transition	149

Practice MCQs

PYQ Alignment

This chapter is a steady contributor to CUET (UG) Physics — typically 1–2 questions appear each year, often a numerical on axial/equatorial field or torque/U on a dipole, plus one conceptual MCQ on classifying materials (dia-/para-/ferromagnetic) or on properties of magnetic field lines. Susceptibility-permeability relations ($\mu_r = 1 + \chi$) and Gauss's law for magnetism are recurring statement-based question themes.

CUET 2025 — Actual PYQs from this chapter

Q.16 (CUET 2025) A bar magnet of magnetic moment 5.0 A m^2 has poles 20 cm apart. Pole strength is:

- A) 2.0 A m B) 30 A m C) 1 A m D) 2.5 A m Tests: Magnetic dipole — pole strength from M and $2l$ Answer: Not in extracted key

Q.17 (CUET 2025) Match the following: List I List II Magnetic field $J T^{-1}$ Magnetic moment $T m A^{-1}$ Pole strength $J T^{-1} m^{-1}$ Permeability $Wb m^{-2}$ Choose correct combination.

- (options not in extracted source — see official paper) **Tests:** Units — B (T), m (J/T), pole strength (A·m), μ_0 (T·m/A) **Answer:** Not in extracted key

CUET 2024 — Actual PYQs from this chapter

Q.8 (CUET 2024) Increasing order of magnetic susceptibility:

- A) Paramagnetic, Diamagnetic, Ferromagnetic B) Ferromagnetic, Paramagnetic, Diamagnetic C) Diamagnetic, Paramagnetic, Ferromagnetic D) Diamagnetic, Ferromagnetic, Paramagnetic **Tests:** Magnetic susceptibility — dia, para, ferromagnetic ordering **Answer:** Not in extracted key

Q.40 (CUET 2024) Magnetic moment of a bar magnet is M. If bent into a semicircle, the new magnetic moment is:

- A) $M\pi$ B) $M/2$ C) M D) $2M/\pi$ **Tests:** Magnetic moment of a bar magnet bent into a semicircle ($M' = 2M/\pi$) **Answer:** Not in extracted key

Q.41 (CUET 2024) Ferromagnetic material used in transformers should have:

- A) Low permeability & high hysteresis loss B) High permeability & low hysteresis loss C) High permeability & high hysteresis loss D) Low permeability & low hysteresis loss **Tests:** Transformer core — high μ , low hysteresis loss (soft iron) **Answer:** Not in extracted key

CUET 2023 — Actual PYQs from this chapter

Q.12 (CUET 2023) A bar of iron is placed in a uniform magnetic field parallel to the plane of paper. Field lines passing through it will look like:

- A) Straight parallel lines B) Curved lines diverging outward C) Curved lines converging inward D) Straight lines unchanged **Tests:** Magnetic field lines through diamagnetic/paramagnetic/ferromagnetic bar **Answer:** Not in extracted key

Q.16 (CUET 2023) The coercivity of a bar magnet is 140 A/m. To demagnetize it using a solenoid of length 1.6 m having 112 turns, the current required is:

- A) 9 A B) 2.25 A C) 2 A D) 1.25 A **Tests:** Coercivity and demagnetisation; solenoid field $B = \mu_0 nI$ **Answer:** Not in extracted key