Unit 17 · Magnetic Properties of Materials

STUDY NOTES

WHAT NEB'S GRADE 12 EXAM ASKS

- **CDC's grid (2078):** Electricity and Magnetism (Units 14–19 together): 21 of 75 marks
- **The paper:** 11 MCQs × 1 · 8 short × 5 · 3 long × 8; 3 hours; 1 mark per expected point
- **MCQ (1 mark)**
  - permanent magnet: ferromagnetic
  - dip 45°: $B = \sqrt{2}B_0$
  - no horizontal component: magnetic pole
  - how a field is detected
  - ferromagnet heated: χ decreases
  - diamagnetic χ: small, negative
  - lines never intersect
  - Curie temperature
  - cause of the Earth's field
  - torque at 30°: $MB_H \sin\theta$
  - narrower loop: lower coercivity
  - which loop for which use
- **Short and long (5 or 8 marks, in parts)**
  - define μ_r, χ, retentivity, coercivity, hysteresis
  - derive $\mu_r = 1 + \chi$
  - sketch and label a hysteresis loop; retentivity, coercivity, loss on it
  - soft iron or steel from two loops; transformer core or permanent magnet; what the area means
  - dia-, para-, ferromagnetic: χ, behavior, examples
  - why ferromagnets show hysteresis (domains); why paramagnetic above the Curie temperature
  - properties of a permanent magnet's material
  - numericals: $B = \mu_0(1 + \chi)H$

Key terms

Induced magnetism: magnetism a magnetic substance gets in a field (**magnetic induction**); the field is the **magnetizing field**.

Magnetic intensity H: strength of the magnetizing field the currents or magnets apply; A/m (CGS oersted, 1 Oe ≈ 79.6 A/m).

Pole strength m: strength of each pole; A m; force $F = mB$.

Magnetic dipole moment M: $m \times 2l$ (bar magnet), IA (loop); S → N inside; A m^2.

Magnetic length $2l$: distance between the poles, about 0.85 of the bar.

Intensity of magnetization I: magnetic moment per unit volume, M/V = pole strength per unit area, m/A; A/m.

Magnetic induction B: lines of induction per unit area at right angles inside a substance; T.

Permeability μ: B/H; T m/A (H/m); $\mu_0 = 4\pi \times 10^{-7}$ T m/A.

Relative permeability μ_r: μ/μ_0; no unit.

Susceptibility χ: I/H, how easily a material is magnetized; no unit.

Curie temperature: above it a ferromagnet becomes paramagnetic.

Domain: region in which all atomic moments are lined up, magnetized to saturation.

Magnetic hysteresis: the lagging of B behind H when H is changed.

Retentivity (remanence): B left when H is brought to zero.

Coercivity: reverse H needed to bring B to zero.

Declination: angle between the geographic and magnetic meridians.

Dip (inclination) δ: angle of the Earth's total field with the horizontal.

Formulas

$H = nI$	n turns per meter **Use:** long solenoid
$B = \mu_0 H$	vacuum, air **Use:** field
$\tau = MB\sin\theta,\ \vec{\tau} = \vec{M} \times \vec{B}$	no net force **Use:** dipole in a uniform field
$I = \frac{M}{V} = \frac{m}{A}$	A/m **Use:** magnetization
$B = \mu_0(H + I)$	applied + own **Use:** induction in a material
$\mu = \frac{B}{H},\ \mu_r = \frac{\mu}{\mu_0},\ \chi = \frac{I}{H}$	χ, μ_r no unit **Use:** definitions
$\mu_r = 1 + \chi$	$\mu = \mu_0(1 + \chi)$ **Use:** relation
$\chi = \frac{C}{T}$	C Curie constant, T in K **Use:** paramagnets (Curie's law)
$\chi = \frac{C}{T - T_C}$	above T_C **Use:** Curie–Weiss law
$B_H = B\cos\delta,\ B_V = B\sin\delta$	δ dip **Use:** Earth's field
$B = \sqrt{B_H^2 + B_V^2},\ \tan\delta = \frac{B_V}{B_H}$	total field, dip **Use:** Earth's field

History

- **magnet** from **Magnesia** (Greece or Asia Minor), where **magnetite** (Fe_3O_4, **lodestone**) was found; Greeks knew it by about 600 BC
- Lucretius (*De Rerum Natura*): a lodestone holds a chain of iron rings
- Peregrinus (1269): named the poles; a broken magnet → two magnets
- Gilbert (1600): the Earth is a great magnet
- Oersted (1820): a current makes a magnetic field; then Ampère, Biot, Savart

B, H and the dipole

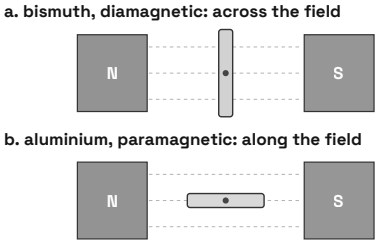
- H: what is **applied**; B: the result in the material; in a solenoid $H = nI$
- dipole in a uniform field: forces mB on N, mB on S, opposite, $2l \sin\theta$ apart → couple
  $\tau = m \times 2l \times B \sin\theta = MB \sin\theta$; no net force
- e.g. 2 A m^2 at 30°, $B_H = 0.4 \times 10^{-4}$ T → $\tau = 0.4 \times 10^{-4}$ N m
- soft iron in a field: S where the field enters, N where it leaves; gathers the lines into itself (high μ)

Derivation of $\mu_r = 1 + \chi$

1. $B = \mu_0(H + I)$
2. $I = \chi H \rightarrow B = \mu_0 H(1 + \chi)$
3. $\div H$: $\mu = \mu_0(1 + \chi)$
4. $\div \mu_0$: $\mu_r = 1 + \chi$

- e.g. $H = 1000$ A/m, $\chi = 1272$ →
  $B = 4\pi \times 10^{-7} \times 1273 \times 1000 = 1.6$ T

Three kinds of substance

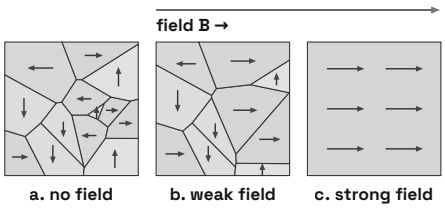


Rods between the poles of a strong magnet: a. diamagnetic settles at right angles to the field; b. paramagnetic along it.

	Diamagnetic	Paramagnetic	Ferromagnetic
in a magnet's field	weakly repelled	weakly attracted	strongly attracted
magnetized	against H	along H	strongly along H
hung rod	across the field	along the field	along, quickly
moves	strong → weak field	weak → strong field	to strong field
χ	small, **negative** (about -10^{-5})	small, **positive** (10^{-5} to 10^{-3})	large, positive
μ_r	slightly < 1	slightly > 1	$\gg 1$ (hundreds to thousands)
χ and temperature	**independent**	$\chi = C/T$ (Curie)	falls; paramagnetic above T_C
hysteresis	no	no	yes
examples	Cu, Zn, Bi, Sb, Hg, Ag, Au, water	Al, Pt, Na, K, Mg, O_2	Fe, Co, Ni, Gd, steel

- diamagnetism: in **every** atom; an applied field changes the electrons' motion, which opposes the field (as Lenz's law); alone when all electrons are paired
- **superconductor**: perfect diamagnet, $\chi = -1$, $\mu_r = 0$ (Meissner effect)
- paramagnetic liquid in a U-tube: rises in the limb between the poles
- Curie's law (Pierre Curie, 1895): hotter → atoms jiggle more → harder to line up

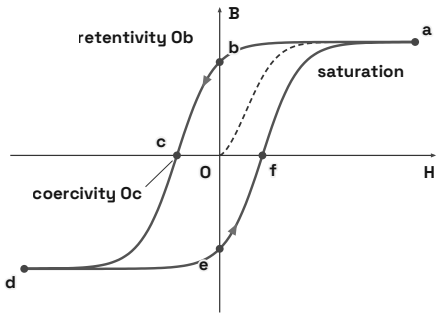
Domain theory



Domains: a. no field, pointing every way; b. weak field, domains along it grow; c. strong field, all turned: saturated.

- iron, cobalt, nickel: neighboring atomic magnets line up by themselves (**exchange interaction**)
- **domains**: 0.01–0.1 mm across, trillions of atoms each, each magnetized to saturation
- no field: domains point every way → cancel → not a magnet
- weak field: walls move, domains along the field **grow**
- strong field: the rest **turn** → **saturation**
- heated to the **Curie temperature**: lining up breaks down → paramagnetic
- walls catch on impurities and flaws → don't all go back → magnetism **remains** → hysteresis (para- and diamagnets have no domains: no hysteresis)

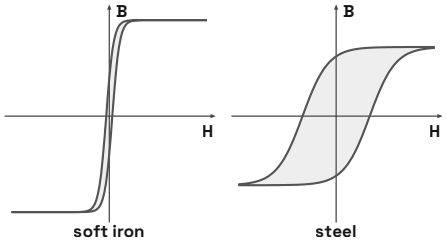
Hysteresis



Hysteresis loop: B rises to saturation at a; Ob retentivity at H = 0; Oc coercivity; saturation the other way at d; back through e, f to a.

1. H up from 0: B along Oa (slow, fast, slow)
2. saturation at a: all domains along the field
3. H down to 0: $B = \text{Ob} \neq 0$: **retentivity**
4. H reversed: $B = 0$ at $H = -\text{Oc}$: **coercivity**
5. on to saturation at d; back through e, f to a: the loop **abcdefa**

- **hysteresis loss**: energy lost as heat per unit volume per cycle = **area of the loop** ($\oint H\,dB$); domain walls jumping past flaws

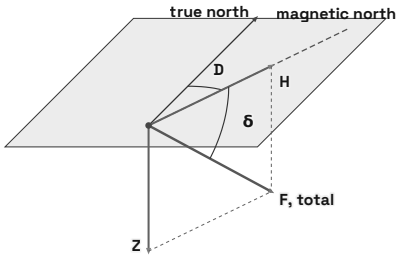


Soft iron: tall, narrow loop, small area. Steel: shorter, wide loop, large area.

	Soft iron	Steel
loop	tall, narrow, small area	shorter, wide, large area
permeability	high	lower
coercivity	low	**high**
hysteresis loss	small	large (doesn't matter for a magnet never cycled)
use	transformer, motor and generator cores, electromagnets	permanent magnets

- permanent magnet: ferromagnetic, **high coercivity** above all, high retentivity, high Curie temperature (cobalt, chromium, tungsten steel; alnico)
- soft iron keeps much B in a closed ring, but a tiny reverse field or a knock removes it
- narrower loop ↔ lower coercivity; aluminium: no loop (paramagnetic)

The Earth's field



Elements of the Earth's field: total field F at dip δ below the horizontal; H its horizontal part B_H in the magnetic meridian, Z the vertical part B_V; declination D between true and magnetic north.

- like a huge bar magnet at the center, tilted about 10°; magnetic **S pole** near the geographic North Pole
- not a magnet inside (core far above iron's Curie temperature): currents in the molten **outer core** (2,900 km down), the **geodynamo**; poles wander
- dip 0° at the magnetic equator, 90° at the magnetic poles (no B_H there)
- B_H turns an ordinary compass; dip needle shows δ
- dip 45°: $B = B_H / \cos 45° = \sqrt{2} B_0$

COMMON MISTAKES

✗ diamagnetic χ depends on temperature
✓ that is **paramagnetic** (Curie's law); diamagnetic χ doesn't.

✗ sodium is diamagnetic
✓ sodium is **paramagnetic**.

✗ chromium is ferromagnetic
✓ chromium is **antiferromagnetic**, not a ferromagnet.

✗ H is lines of force per unit area
✓ that measures B; H is the applied field (nI).

✗ best permanent magnet: highest retentivity
✓ **highest coercivity** above all.

✗ soft iron for magnets, steel for cores
✓ soft iron for **cores**, steel for **magnets**.

✗ $\mu_r = \chi - 1$
✓ $\mu_r = 1 + \chi$.

✗ the Earth has a magnet inside
✓ currents in the molten outer core.