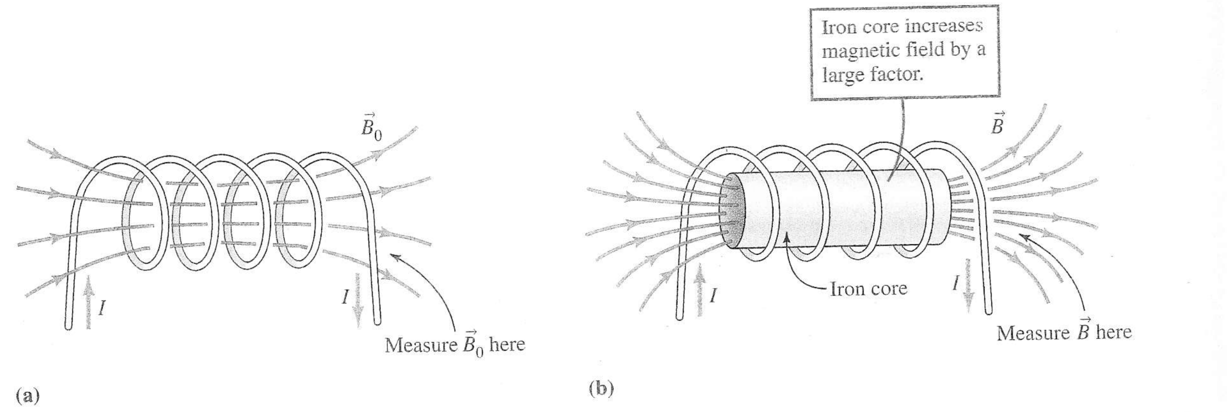
The Magnetic Properties of Bulk Matter

Experiment:



(a) A solenoid that carries a current has a magnetic field.
(b) The cylindrical volume of the solenoid is filled with an iron core.

$$\vec{B} = \kappa_m \vec{B}_0$$

$$\kappa_m \equiv 1 + \chi_m$$

Example

$$\kappa_m = 1 + \chi_m$$

Diamagnetic Material $\kappa_m < 1$ $\chi_m < 0$

	χ_m
Bi	-1.7×10^{-4}
Cu	-10^{-5}
H_2O	-10^{-5}
N_2 (1 atm)	-7×10^{-9}

Paramagnetic $\kappa_m > 1$ $\chi_m > 0$

Al	$+2 \times 10^{-5}$	$\sim 300K$
O_2 (1 atm)	$+2 \times 10^{-6}$	$\sim 300K$
O_2 (liquid)	$+3.5 \cdot 10^{-3}$	$90K$

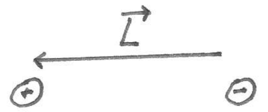
Ferromagnetic material $\chi_m \simeq 10^2 - 10^5$ $\chi_m \simeq \kappa_m$

Dielectric

parallel plate

electric dipole moment

$$\vec{p} = q\vec{l}$$



Polarization vector

$$\vec{P} = \frac{\text{Dipole Moment}}{\text{volume}}$$

polar molecule vs nonpolar molecule

polar molecule ↓ with no permanent dipole moment

nonpolar molecule ↓ with permanent dipole moment

can be polarized by external electric field

induced alignment

$$\vec{P} \propto \vec{E}$$

linear medium

$$\vec{P} = \chi \vec{E}$$

$$\kappa = 1 + \chi$$

both cases

$$\chi > 0$$

Alignment is temperature dependence $\kappa = 1 + \frac{\text{a constant}}{T}$

Magnetic Material

solenoid

magnetic dipole moment

$$\vec{\mu} = I A \hat{n}$$

Magnetization Vector

$$\vec{M} = \frac{\text{magnetic dipole moment}}{\text{volume}}$$

orbital dipole moment

spin magnetic moment

$$\vec{\mu} = -\frac{e}{m}\vec{S}$$

can be magnetized by external magnetic field

induced alignment

$$\vec{M} \propto \vec{B}$$

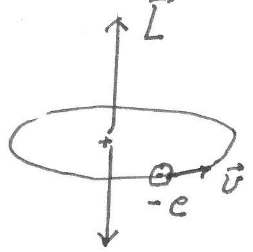
linear medium

$$\vec{M} \propto \chi_m \vec{B}$$

$$\kappa_m = 1 + \chi_m$$

χ_m can be positive or negative

Orbital angular moment ⟷ magnetic dipole moment



$$L_z = n\hbar$$

$$\vec{m} = \vec{\mu} = -\frac{e}{2m_e}\vec{L}$$

$$\vec{\mu} = -\frac{e}{m}\vec{S} \qquad S_z = \pm\frac{1}{2}\hbar$$

Alignment of permanent magnetic dipole moment

⇒ paramagnetic material

Definition of Bohr magneto

$$m_B = \frac{e}{2m_e}\hbar = 9.27\times10^{-24}\ A\cdot m^2$$

↓

characteristic of all magnetic moment on the atomic scale

· Alignment : $\chi_m > 0$

competition between

magnetic energy factor	thermal energy factor
mB	kT

Average alignment $\propto \frac{mB}{kT}$

$$\Rightarrow \vec{M} = C\frac{\mu_0\vec{H}}{T}$$

Saturation ↓ Curie's Law

· Permanent magnetic dipole moment

↓

intrinsic magnetic moments of unpaired electrons

Diamagnetism

$\chi_m < 0$

Classical point of view
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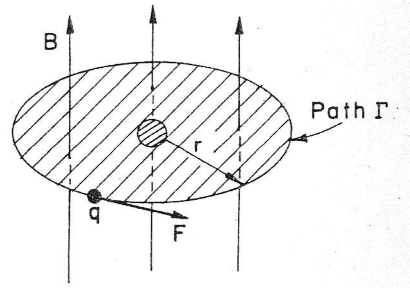
following the Feynman's "Lecture on Physics" Chapter 34



The induced electric forces on the electrons in an atom.

Faraday's law

$$E \, 2\pi r = -\frac{d}{dt}(B\pi r^2)$$

↓
average tangential electric field

$$\oint \vec{E} \cdot d\vec{l} = -\frac{d}{dt}\Phi_B$$

$$\Rightarrow \quad E = -\frac{r}{2}\frac{dB}{dt}$$

$$\tau = -q_e E r = \frac{dL}{dt}$$

$$= \frac{q_e r^2}{2}\frac{d\vec{B}}{dt}$$

integrate

$$\Delta L = \frac{q_e r^2}{2} B$$

↓
change in angular momentum due to turning on the field.

$$\Delta\mu = -\frac{q_e}{2m}\Delta L = -\frac{q_e^2 r^2}{4m} B$$

↓

relate to the Lenz's rule

↓

added moment is opposite to the magnetic field.

Remarks.

- Please check all the sign.
  Espically $q_e = -e$
  Note the final result depend on q_e^2

- Classical view point is, of course, not exactly right.
  Quantum mechanics gives the same answer.

- Provide a mechanism for diamagnetism
  ↓
  diamagnetism is present for all materials

- Usually paramagnetism (if present) is a larger effect than diamagnetism.
  However, diamagnetism will always dominate at sufficiently high temperature

Ferromagnetism

- In ferromagnetic substances, there are interactions between the magnetic moments of neighorbing atoms that are so strong

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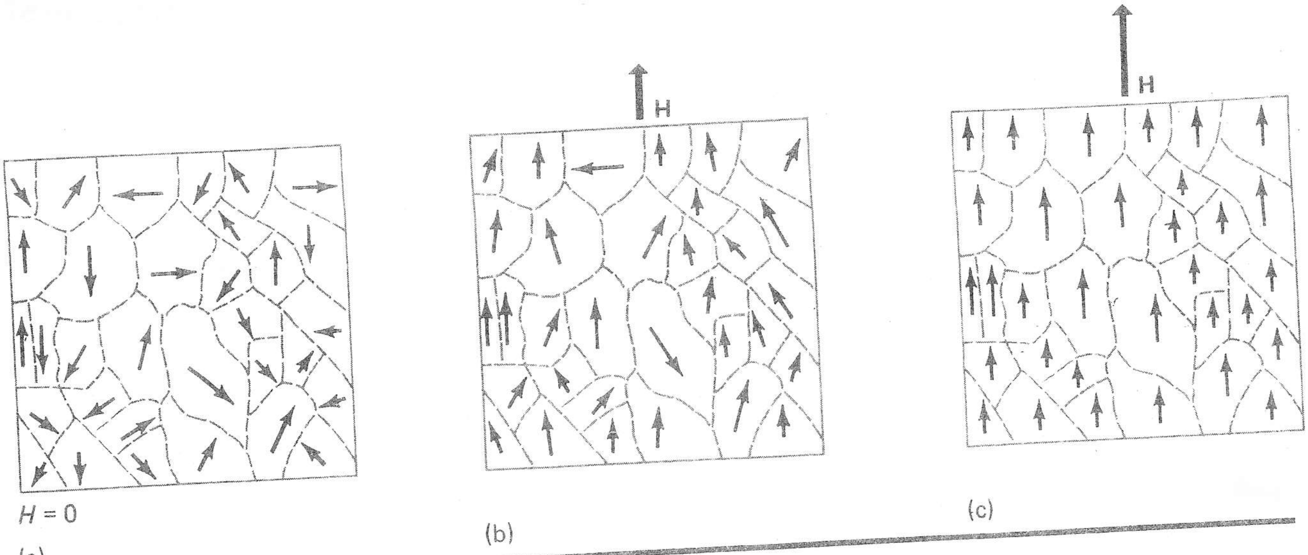
atomic moments can align themselves with little or no assistance from externally applied field

$\chi_m > 0$ and large

Domain formation

↓

in which exhibit complete magnetic alignment

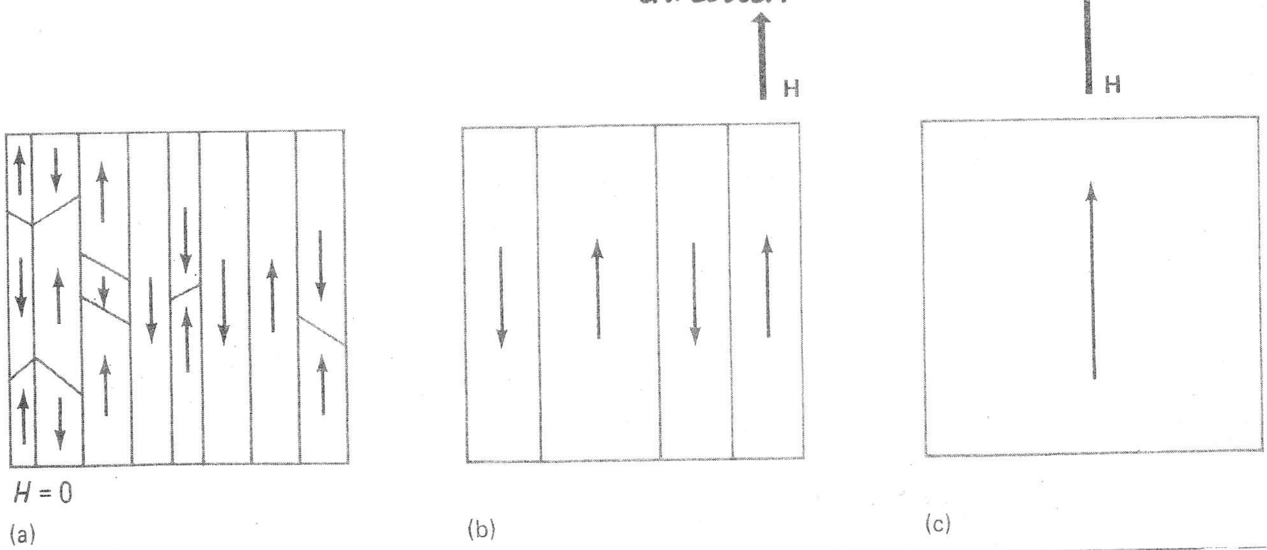


Magnetic alignment by alignment of fixed domains.

domains already alight
change the magnetic
alight of the
domain

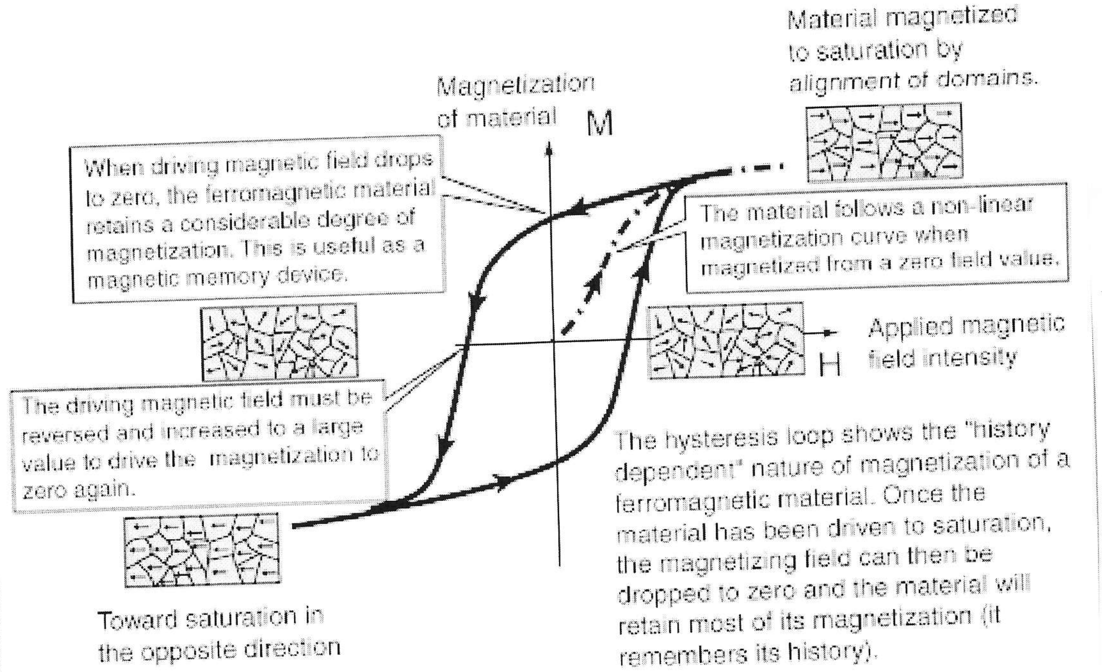
based on energy consideration.

domain aligned to the external field grows at the expense of those aligned in other direction ⇒ motion of the domain boundary



Magnetic alignment achieved by domain boundary motion.

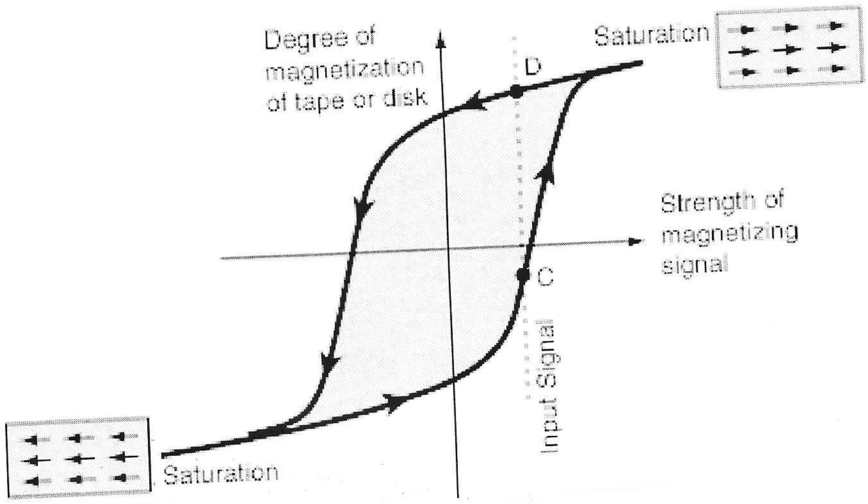
Hysteresis in magnetic materials



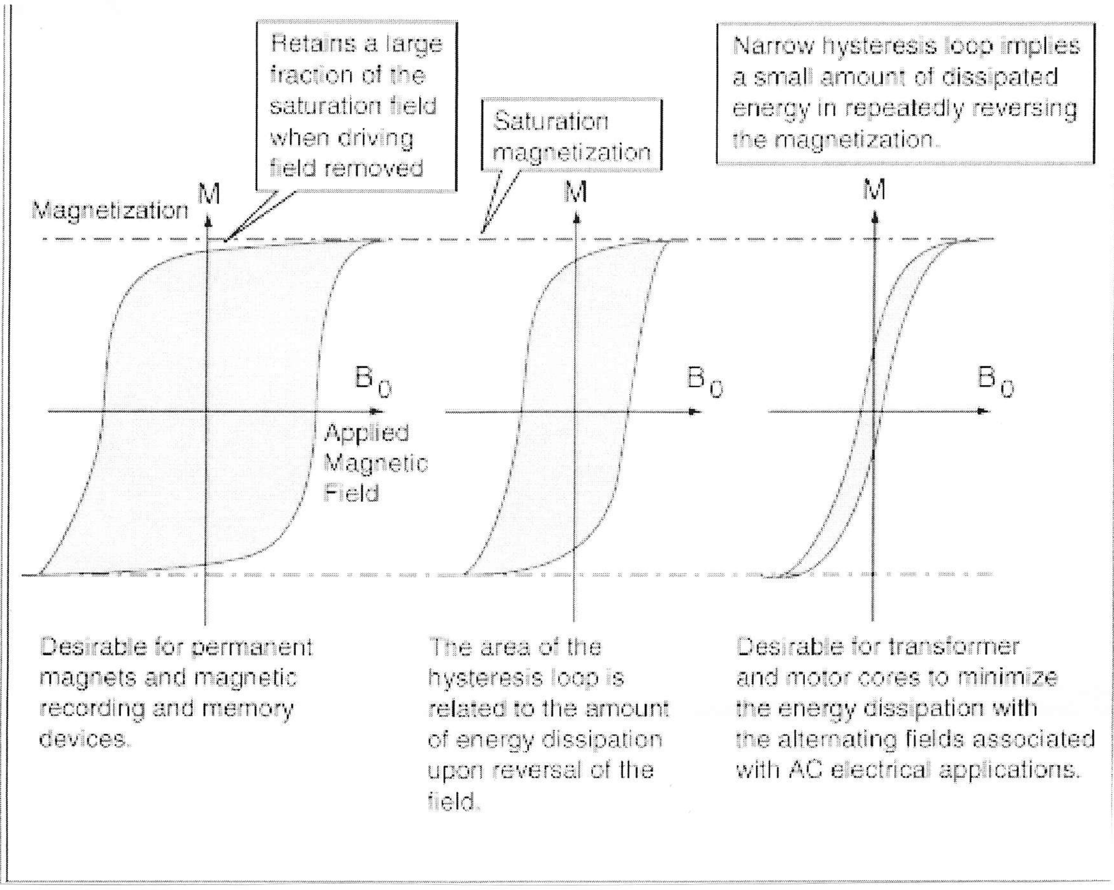
It is customary to plot the magnetization M of the sample as a function of the magnetic field strength H, since H is a measure of the externally applied field which drives the magnetization .

Hysteresis in Magnetic Recording

Because of hysteresis, an input signal at the level indicated by the dashed line could give a magnetization anywhere between C and D, depending upon the immediate previous history of the tape (i.e., the signal which preceded it). This clearly unacceptable situation is remedied by the bias signal which cycles the oxide grains around their hysteresis loops so quickly that the magnetization averages to zero when no signal is applied. The result of the bias signal is like a magnetic eddy which settles down to zero if there is no signal superimposed upon it. If there is a signal, it offsets the bias signal so that it leaves a remnant magnetization proportional to the signal offset.



Magnetic Recording

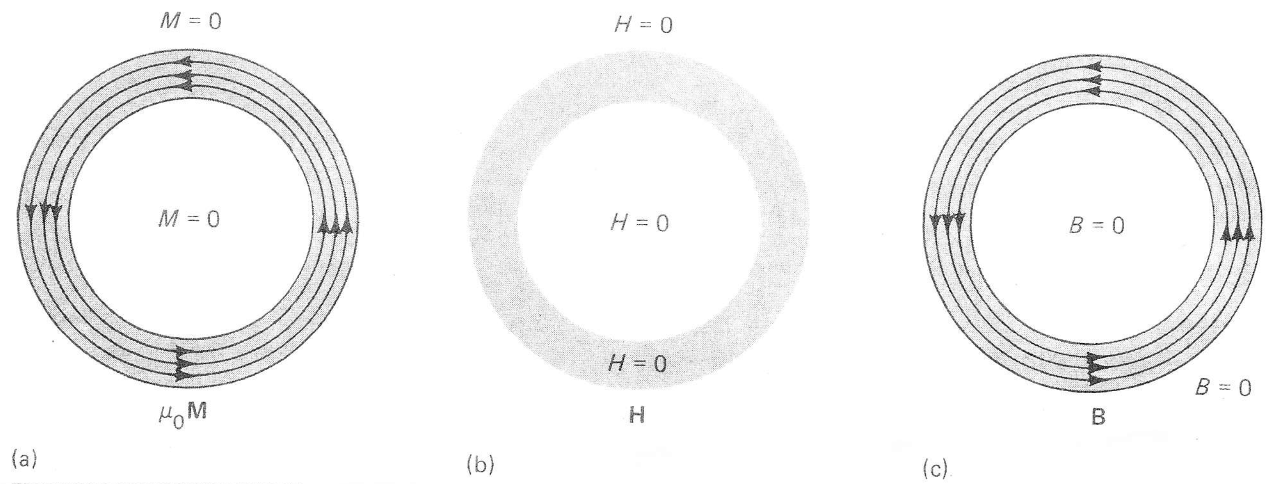

Retains a large fraction of the saturation field when driving field removed
Saturation magnetization
Narrow hysteresis loop implies a small amount of dissipated energy in repeatedly reversing the magnetization.
Magnetization M
M
M
B0
B0
B0
Applied Magnetic Field
Desirable for permanent magnets and magnetic recording and memory devices.
The area of the hysteresis loop is related to the amount of energy dissipation upon reversal of the field.
Desirable for transformer and motor cores to minimize the energy dissipation with the alternating fields associated with AC electrical applications.

$$\vec{H} = \frac{\vec{B}}{\mu_0} - \vec{M}$$

Toroidal sample

Key $\vec{H} \leftrightarrow$ free current

In this case, there is no free current



(a) Magnetization, (b) magnetic intensity, and (c) magnetic induction fields for a permanently magnetized toroidal sample.

$\vec{B}$ field is contained inside

$\vec{B}$ is continuous

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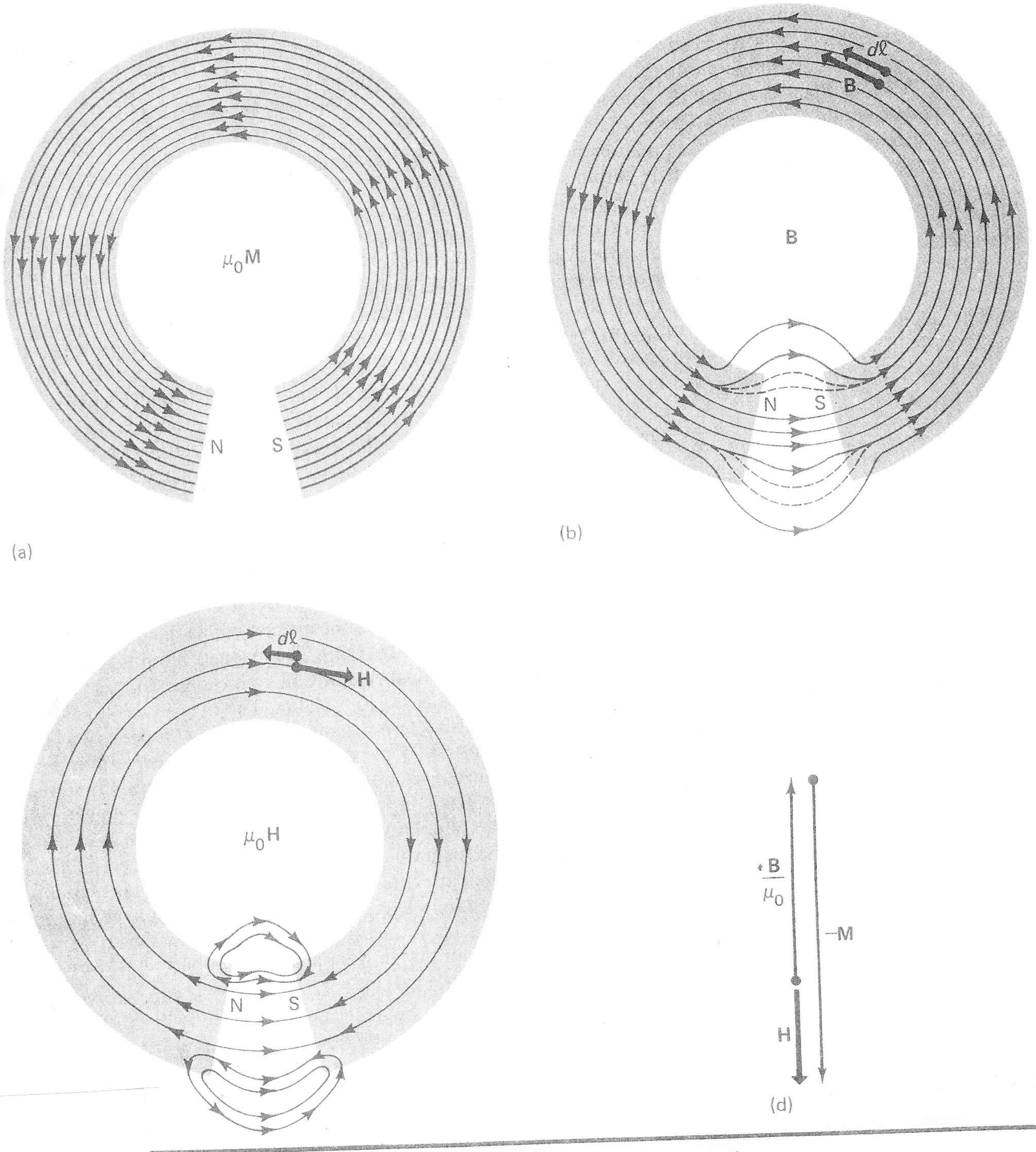
transformer

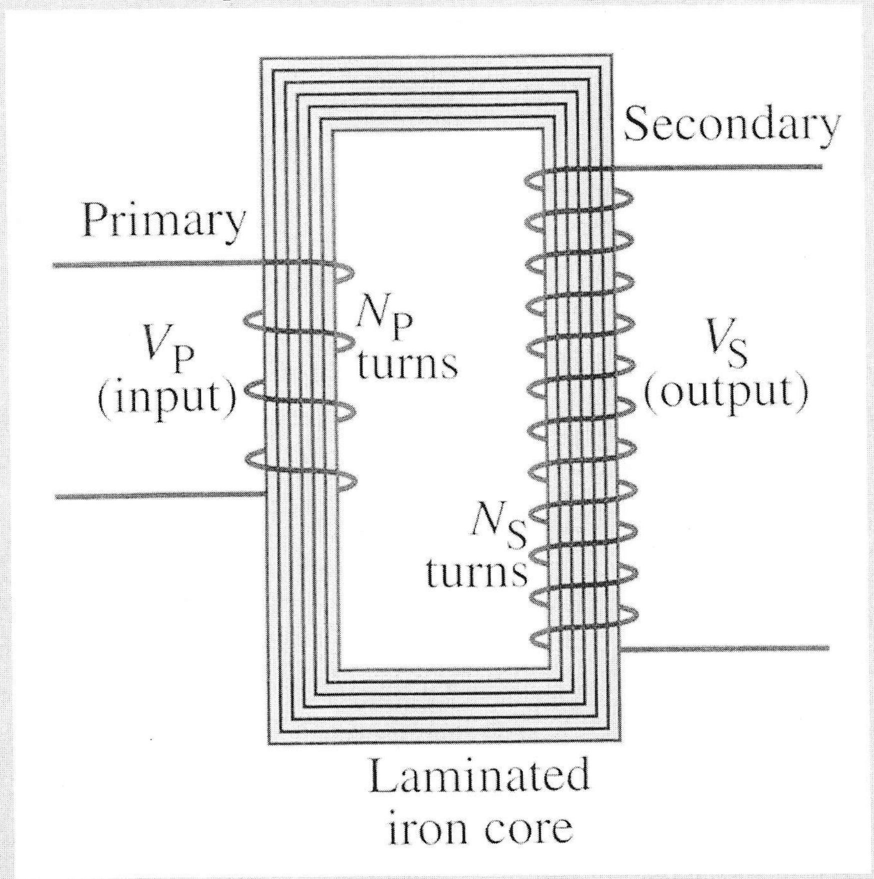
Permanent Magnet



Lines of (a) magnetization, (b) magnetic induction, and (c) magnetic intensity for a permanent magnet in the form of a toroid having a small air gap. (d) Relationship between **B**, **M**, and **H** within the magnet.

Transformer

Step-up transformer



$$\mathcal{E}_p = N_p \frac{d\Phi_B}{dt}$$

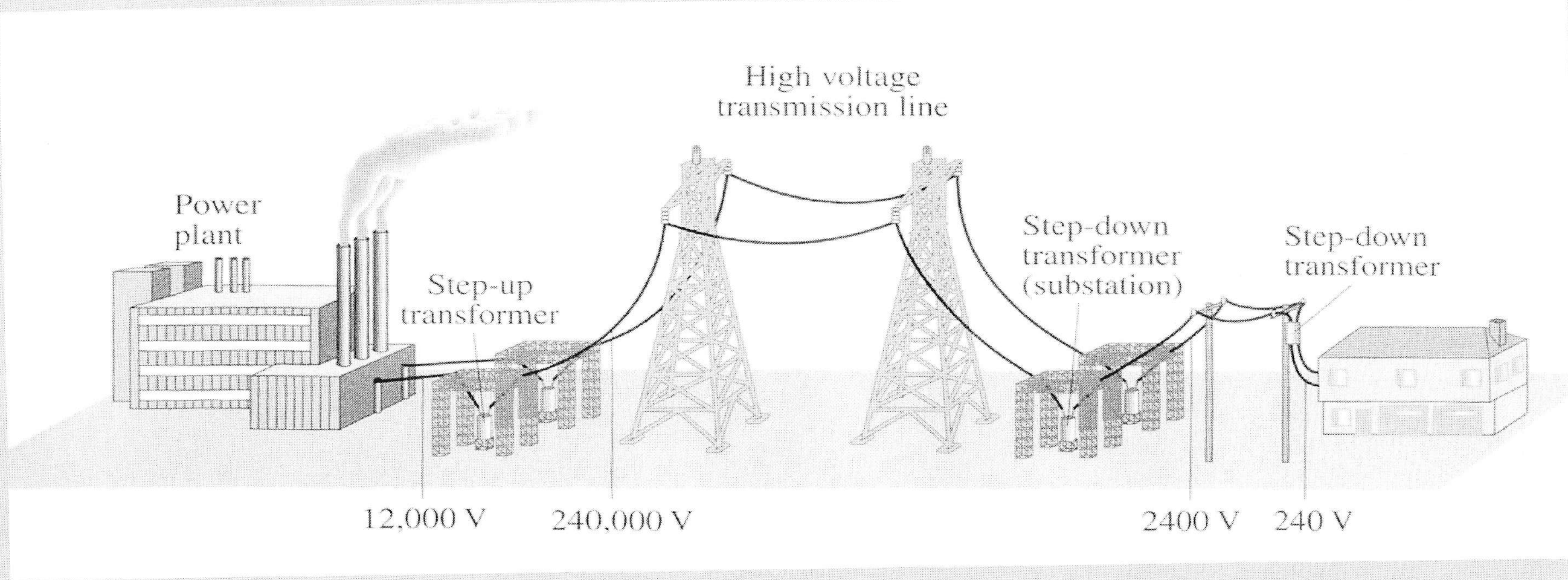
$$\mathcal{E}_s = N_s \frac{d\Phi_B}{dt}$$

$$\boxed{\frac{\mathcal{E}_s}{\mathcal{E}_p} = \frac{N_s}{N_p}}$$

$N_s > N_p$: step-up transformer

$N_s < N_p$: step-down transformer

Transmission of Electric Power



Power loss can be greatly reduced if transmitted at high voltage

Example: Transmission lines

An average of 120 kW of electric power is sent from a power plant. The transmission lines have a total resistance of 0.40 Ω. Calculate the power loss if the power is sent at (a) 240 V, and (b) 24,000 V.

(a) $$I = \frac{P}{V} = \frac{1.2 \times 10^5 W}{2.4 \times 10^2 V} = 500 A$$

$$P_L = I^2 R = (500 A)^2 (0.40 \Omega) = 100 kW$$

83% loss!!

(b) $$I = \frac{P}{V} = \frac{1.2 \times 10^5 W}{2.4 \times 10^4 V} = 5.0 A$$

$$P_L = I^2 R = (5.0 A)^2 (0.40 \Omega) = 10 W$$

0.0083% loss