Chapter 6 Static Magnetic Fields

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6-1 Introduction

- Electric charges at rest: $$\nabla \cdot \mathbf{D} = \rho,$$ $$\nabla \times \mathbf{E} = 0.$$
  - Constitutive relation: $\mathbf{D} = \epsilon \mathbf{E},$
  - Electric force $\mathbf{F}_e$: $\boxed{\mathbf{F}_e = q\mathbf{E} \qquad \text{(N).}}$
- Electric charges in motion:
  - Magnetic force $\mathbf{F}_m$: $\boxed{\mathbf{F}_m = q\mathbf{u} \times \mathbf{B} \qquad \text{(N),}}$

The force was found in experiments!
Defined as **B**: magnetic flux density (Wb/m^2 = Tesla)

- Lorentz's force equation: $\boxed{\mathbf{F} = q(\mathbf{E} + \mathbf{u} \times \mathbf{B}) \qquad \text{(N),}}$

6-2 Fundamental Postulates of Magnetostatics in Free Space

- Two postulates for **B** in free space: $\boxed{\nabla \cdot \mathbf{B} = 0,}$

$$\boxed{\nabla \times \mathbf{B} = \mu_0 \mathbf{J}.}$$

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$$\boxed{\nabla \cdot \mathbf{E} = \frac{\rho}{\epsilon_0}}$$

$$\boxed{\nabla \times \mathbf{E} = 0.}$$

$\mu_0 = 4\times10^{7}$ (H/m), permeability of free space

J: current density

Permeability is the measure of the ability of a material to support the formation of a magnetic field within itself. Hence, it is the degree of **magnetization** that a material obtains in response to an applied magnetic field.

$\nabla\cdot(\nabla\times\mathbf{B})=0$

$$\Downarrow$$

$$\nabla \cdot \mathbf{J} = 0,$$

No Magnetic Charge

- Comparison of divergence **E** and **B**:

$$\nabla \cdot \mathbf{E} = \rho/\epsilon_0 \qquad\qquad \nabla \cdot \mathbf{B} = 0,$$

➔ No magnetic charge

The Law of Conservation of Magnetic Flux

- The integral form of **E**: $\boxed{\oint_S \mathbf{E} \cdot d\mathbf{s} = \frac{Q}{\epsilon_0},}$

  ***Q* is the source** of the total outward electric flux through any closed surface.

- The integral form of **B**: $\boxed{\oint_S \mathbf{B} \cdot d\mathbf{s} = 0,}$

  The total outward magnetic flux through any closed surface is zero.

  - **No magnetic flow sources**
  - The magnetic flux lines always close upon themselves

The Law of Conservation of Magnetic Flux

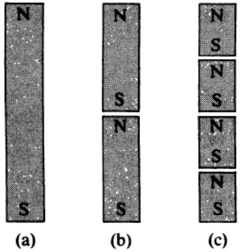
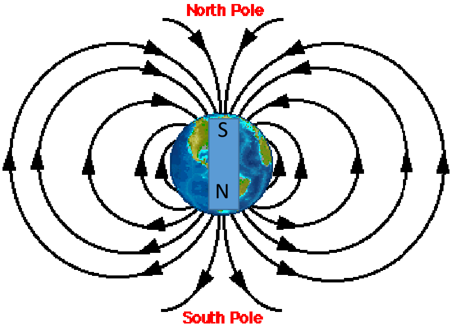


FIGURE 6–1
Successive division of a bar magnet.

The magnetic flux lines follow closed paths from one end of a magnet to the other end outside the magnet and then continue inside the magnet back to the first end.

The Earth’s Magnetic Field



Ampere's Circuital Law

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J}.$$

$$\Downarrow$$

$$\int_S (\nabla \times \mathbf{B}) \cdot d\mathbf{s} = \mu_0 \int_S \mathbf{J} \cdot d\mathbf{s}$$

$$\Downarrow$$

$$\boxed{\oint_C \mathbf{B} \cdot d\boldsymbol{\ell} = \mu_0 I,}$$

C: the contour bounding the surface S

I: the total current through S

Chap.3

$$\boxed{\nabla \cdot \mathbf{E} = \frac{\rho}{\epsilon_0}}$$

Gauss's law

Ampere's circuital law: the circulation of the magnetic flux density in free space around any closed path is equal to μ_0 times the total current flowing through the surface bounded by the path.

A Summary

Postulates of Magnetostatics in Free Space	
Differential Form	Integral Form
$\nabla \cdot \mathbf{B} = 0$	$\oint_S \mathbf{B} \cdot d\mathbf{s} = 0$
$\nabla \times \mathbf{B} = \mu_0 \mathbf{J}$	$\oint_C \mathbf{B} \cdot d\boldsymbol{\ell} = \mu_0 I$

6-3 Vector Magnetic Potential

Chap.3

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

B is solenoidal
By null identity

$$\boxed{\mathbf{B} = \nabla \times \mathbf{A} \qquad \text{(T)}.}$$

where **A**: **vector** magnetic potential (Wb/m)

$$\nabla \times \mathbf{E} = 0$$

$$\boxed{\mathbf{E} = -\nabla V}$$

In magnetostatics: **J** ➔ **A** ➔ **B**
In electrostatics: ρ ➔ V ➔ **E**

$\nabla \cdot A = ?$

- To specify a vector, we should specify its curl and divergence.
  We have $\boxed{\mathbf{B} = \nabla \times \mathbf{A} \qquad (\mathrm{T}).}$ How to choose $\nabla \cdot \mathbf{A}$?

$$\boxed{\nabla \times \mathbf{B} = \mu_0 \mathbf{J}}$$

$$\boxed{\mathbf{B} = \nabla \times \mathbf{A}}$$

$$\nabla \times \nabla \times \mathbf{A} = \mu_0 \mathbf{J}.$$

Vector identity:

$$\nabla \times \nabla \times \mathbf{A} = \nabla(\nabla \cdot \mathbf{A}) - \nabla^2 \mathbf{A}$$

$$\underline{\nabla^2 \mathbf{A} = \nabla(\nabla \cdot \mathbf{A}) - \nabla \times \nabla \times \mathbf{A}.}$$

Definition of Laplacian of **A**

- In Cartesian: $\nabla^2 \mathbf{A} = \mathbf{a}_x \nabla^2 A_x + \mathbf{a}_y \nabla^2 A_y + \mathbf{a}_z \nabla^2 A_z.$
  (Similar to Laplacian of *V*)

- In other coordinates: should use the definition of Laplacian of **A**

$$\nabla(\nabla \cdot \mathbf{A}) - \nabla^2 \mathbf{A} = \mu_0 \mathbf{J}.$$

$$\nabla(\nabla \cdot \mathbf{A}) - \nabla^2 \mathbf{A} = \mu_0 \mathbf{J}.$$

To simplify the equation, we choose

$$\boxed{\nabla \cdot \mathbf{A} = 0,}$$

Vector's Poisson's equation

$$\boxed{\nabla^2 \mathbf{A} = -\mu_0 \mathbf{J}.}$$

In Cartesian coordinate:

$$\nabla^2 A_x = -\mu_0 J_x,$$
$$\nabla^2 A_y = -\mu_0 J_y,$$
$$\nabla^2 A_z = -\mu_0 J_z.$$

By comparison

Solution:

$$A_x = \frac{\mu_0}{4\pi} \int_{V'} \frac{J_x}{R} dv'.$$

Combine 3 components

$$\boxed{\mathbf{A} = \frac{\mu_0}{4\pi} \int_{V'} \frac{\mathbf{J}}{R} dv' \qquad \text{(Wb/m).}}$$

Analogy in electrostatics:

Scalar's Poisson's equation

$$\nabla^2 V = -\frac{\rho}{\epsilon_0}$$

Solution:

$$V = \frac{1}{4\pi\epsilon_0} \int_{V'} \frac{\rho}{R} dv'.$$

Review the Analogy

$$\mathbf{A} = \frac{\mu_0}{4\pi} \int_{V'} \frac{\mathbf{J}}{R}\, dv' \qquad \text{(Wb/m)}.$$

In magnetostatics: **J** ➔ **A** ➔ **B**

In electrostatics: ρ ➔ V ➔ **E**

$$V = \frac{1}{4\pi\epsilon_0} \int_{V'} \frac{\rho}{R}\, dv'.$$

Relation of Magnetic Flux Φ and Magnetic Vector Potential A

$$\Phi = \int_S \mathbf{B} \cdot d\mathbf{s}.$$

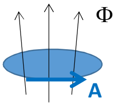
Magnetic flux

Magnetic flux density

$$\boxed{\mathbf{B} = \nabla \times \mathbf{A}}$$

$$\Phi = \int_S (\nabla \times \mathbf{A}) \cdot d\mathbf{s} = \oint_C \mathbf{A} \cdot d\boldsymbol{\ell} \qquad \text{(Wb)}.$$

Physical significance of **A**: line integral of **A** around any closed path = the total Φ passing through the area enclosed by the path

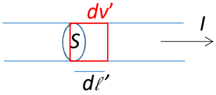


6-4 The Biot-Savart Law and Applications

- The magnetic field due to a current-carrying circuit.
- For a thin wire with cross-sectional area S ($dv'=Sd\ell'=\mathbf{S} \bullet \mathbf{d\ell'}$), we have

$$\mathbf{J}\,dv' = JS\,d\boldsymbol{\ell}' = I\,d\boldsymbol{\ell}',$$

J: (A/m^2)
$JS = I$



$$\boxed{\mathbf{A} = \frac{\mu_0}{4\pi}\int_{V'} \frac{\mathbf{J}}{R}\,dv' \qquad \text{(Wb/m).}}$$

$$\boxed{\mathbf{A} = \frac{\mu_0 I}{4\pi}\oint_{C'} \frac{d\boldsymbol{\ell}'}{R} \qquad \text{(Wb/m),}}$$

C' is closed because current must flow in a closed path.

$$\boxed{\mathbf{B} = \nabla \times \mathbf{A}}$$

$$\boxed{\mathbf{A} = \frac{\mu_0 I}{4\pi} \oint_{C'} \frac{d\boldsymbol{\ell}'}{R} \qquad \text{(Wb/m)},}$$

$$\mathbf{B} = \nabla \times \mathbf{A} = \nabla \times \left[\frac{\mu_0 I}{4\pi} \oint_{C'} \frac{d\boldsymbol{\ell}'}{R} \right]$$

$$= \frac{\mu_0 I}{4\pi} \oint_{C'} \nabla \times \left(\frac{d\boldsymbol{\ell}'}{R} \right).$$

unprimed curl: to the field coordinate
primed integration: to the source coordinate

$$\nabla \times (f\mathbf{G}) = f\nabla \times \mathbf{G} + (\nabla f) \times \mathbf{G}.$$

with $f = 1/R$ and $\mathbf{G} = d\boldsymbol{\ell}'$,

$$\mathbf{B} = \frac{\mu_0 I}{4\pi} \oint_{C'} \left[\frac{1}{R} \nabla \times d\boldsymbol{\ell}' + \left(\nabla \frac{1}{R} \right) \times d\boldsymbol{\ell}' \right].$$

(1) (2)

$$\mathbf{B} = \frac{\mu_0 I}{4\pi} \oint_{C'} \underbrace{\left[\frac{1}{R} \nabla \times d\boldsymbol{\ell}' + \left(\nabla \frac{1}{R} \right) \times d\boldsymbol{\ell}' \right]}_{(1) \qquad\qquad (2)}.$$

For term (1): primed and unprimed coordinates are independent ➔ 0

For term (2):

$$\frac{1}{R} = [(x - x')^2 + (y - y')^2 + (z - z')^2]^{-1/2};$$

R is from source to field

$$\begin{aligned} \nabla\left(\frac{1}{R}\right) &= \mathbf{a}_x \frac{\partial}{\partial x}\left(\frac{1}{R}\right) + \mathbf{a}_y \frac{\partial}{\partial y}\left(\frac{1}{R}\right) + \mathbf{a}_z \frac{\partial}{\partial z}\left(\frac{1}{R}\right) \\ &= -\frac{\mathbf{a}_x(x - x') + \mathbf{a}_y(y - y') + \mathbf{a}_z(z - z')}{[(x - x')^2 + (y - y')^2 + (z - z')^2]^{3/2}} \\ &= -\frac{\mathbf{R}}{R^3} = -\mathbf{a}_R \frac{1}{R^2}, \end{aligned}$$

Quotient rule and chain rule

$\mathbf{a}_R$: unit vector from source to field

$$\mathbf{B} = \frac{\mu_0 I}{4\pi} \oint_{C'} \left[\frac{1}{R} \cancel{\nabla \times d\boldsymbol{\ell}'} + \underline{\left(\nabla \frac{1}{R} \right)} \times d\boldsymbol{\ell}' \right].$$

$$\nabla\left(\frac{1}{R}\right) = -\mathbf{a}_R \frac{1}{R^2},$$

$$\boxed{\mathbf{B} = \frac{\mu_0 I}{4\pi} \oint_{C'} \frac{d\boldsymbol{\ell}' \times \mathbf{a}_R}{R^2} \quad \text{(T)}.}$$

Biot-Savart law: **B** due to a current element $Id\ell'$

Comparison with Ampere's circuital law: $\boxed{\oint_C \mathbf{B} \cdot d\boldsymbol{\ell} = \mu_0 I,}$

Because **B** does not have to be constant along *C*, **Biot-Savart law is more general** to determine B than Ampere's circuital law (although the former is more difficult in calculation).

EXAMPLE 6–4 A direct current I flows in a straight wire of length $2L$. Find the magnetic flux density $\mathbf{B}$ at a point located at a distance r from the wire in the bisecting plane: (a) by determining the vector magnetic potential $\mathbf{A}$ first, and (b) by applying Biot-Savart law.

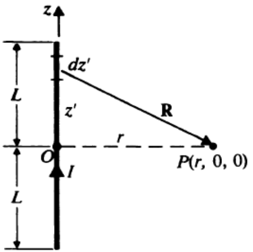


FIGURE 6–5
A current-carrying straight wire (Example 6–4).

6-5 The Magnetic Dipole

- Example 6-7:

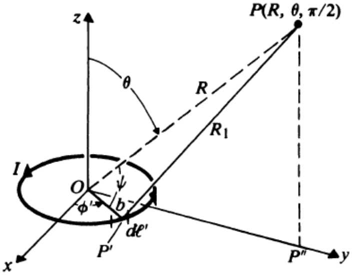


FIGURE 6–8
A small circular loop carrying current I (Example 6–7).

$$\mathbf{A} = \mathbf{a}_\phi \frac{\mu_0 I b^2}{4R^2} \sin\theta.$$

$$\mathbf{B} = \frac{\mu_0 I b^2}{4R^3}(\mathbf{a}_R\, 2\cos\theta + \mathbf{a}_\theta \sin\theta),$$

EXAMPLE 6–7 Find the magnetic flux density at a distant point of a small circular loop of radius b that carries current I (a ***magnetic dipole***).

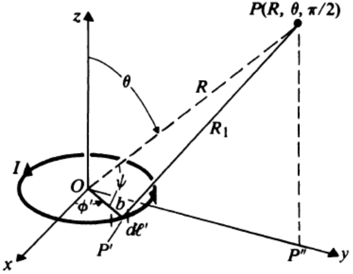
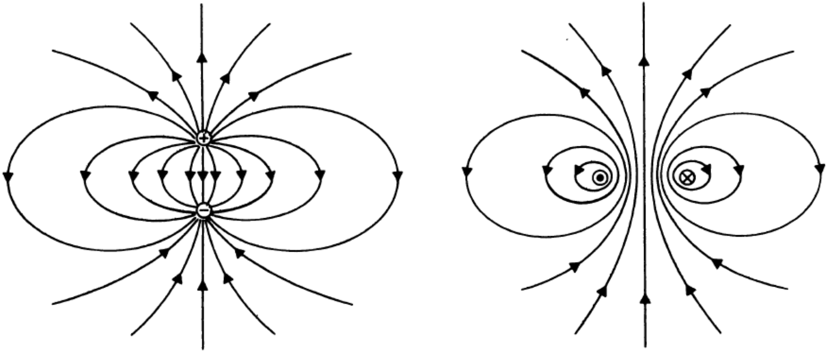


FIGURE 6–8
A small circular loop carrying current I (Example 6–7).

$$\mathbf{E} = \frac{p}{4\pi\epsilon_0 R^3}(\mathbf{a}_R 2\cos\theta + \mathbf{a}_\theta \sin\theta).$$

$$\mathbf{B} = \frac{\mu_0 I b^2}{4R^3}(\mathbf{a}_R\, 2\cos\theta + \mathbf{a}_\theta \sin\theta),$$



(a) Electric dipole. (b) Magnetic dipole.

FIGURE 6–9
Electric field lines of an electric dipole and magnetic flux lines of a magnetic dipole.

- Difference: **E** terminated on the charges; **B** continuous
- Fields (**E** and **B**) are similar at far fields

$$\boxed{\mathbf{A} = \mathbf{a}_\phi \frac{\mu_0 I b^2}{4R^2} \sin\theta.}$$

$$\mathbf{A} = \mathbf{a}_\phi \frac{\mu_0 (I\pi b^2)}{4\pi R^2} \sin\theta$$

$$\boxed{\mathbf{a}_z \times \mathbf{a}_R = \mathbf{a}_\phi \sin\theta}$$

$$\boxed{\mathbf{A} = \frac{\mu_0 \mathbf{m} \times \mathbf{a}_R}{4\pi R^2} \qquad (\mathrm{Wb/m}),}$$

where $\mathbf{m} = \mathbf{a}_z I\pi b^2 = \mathbf{a}_z IS = \mathbf{a}_z m \qquad (\mathrm{A \cdot m^2})$

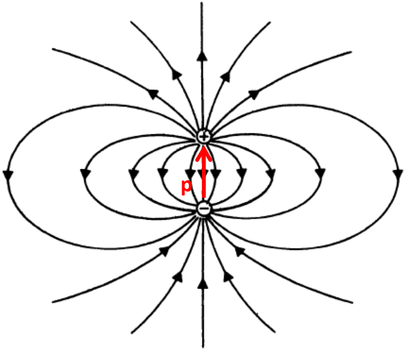
Defined as **magnetic dipole moment**

$$\boxed{\mathbf{B} = \frac{\mu_0 I b^2}{4R^3} (\mathbf{a}_R\, 2\cos\theta + \mathbf{a}_\theta \sin\theta),}$$

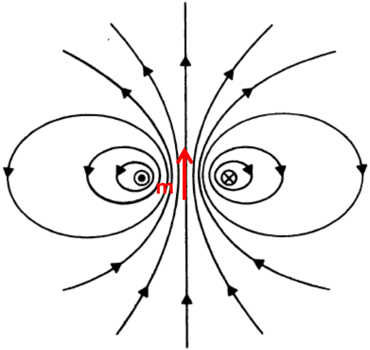
$$\boxed{\mathbf{B} = \frac{\mu_0 m}{4\pi R^3} (\mathbf{a}_R\, 2\cos\theta + \mathbf{a}_\theta \sin\theta) \qquad (\mathrm{T}).}$$

$\boxed{\mathbf{p=qd}}$

Electric dipole moment



(a) Electric dipole.



(b) Magnetic dipole.

Electric dipole moment **p**

Magnetic dipole moment **m**

p -> **m**

$1/\varepsilon_0$ -> μ_0

• -> ×

Right-hand rule: **m** along thumb and **direction of current** along fingers

$$V = \frac{\mathbf{p} \cdot \mathbf{a}_R}{4\pi\epsilon_0 R^2} \quad \text{(V)},$$

$$\mathbf{A} = \frac{\mu_0 \mathbf{m} \times \mathbf{a}_R}{4\pi R^2} \quad \text{(Wb/m)},$$

We call a small current-carrying loop a **magnetic dipole**

6-5.1 Scalar Magnetic Potential

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J}.$$

$\Downarrow$ **For a region J = 0**

$$\nabla \times \mathbf{B} = 0.$$

$\Downarrow$ By null identity

$$\mathbf{B} = -\mu_0 \nabla V_m,$$

V_m: scalar magnetic potential

$$\boxed{\mathbf{E} = -\nabla V}$$

Analogy

V_m	V
$\mathbf{B}/\mu_0$	$\mathbf{E}$

Analogous to electric potential

$$\boxed{\mathbf{E} = -\nabla V}$$

$$\mathbf{B} = -\mu_0 \nabla V_m,$$

$$V_2 - V_1 = -\int_{P_1}^{P_2} \mathbf{E} \cdot d\ell \qquad \text{(V)}.$$

$$V_{m2} - V_{m1} = -\int_{P_1}^{P_2} \frac{1}{\mu_0} \mathbf{B} \cdot d\ell.$$

E

B/μ_0

$k = 1/(4\pi\varepsilon_0)$

$k = (\mu_0/(4\pi))\ /\mu_0$

$$V = \frac{1}{4\pi\epsilon_0} \int_{V'} \frac{\rho}{R}\, dv' \qquad \text{(V)}.$$

$$V_m = \frac{1}{4\pi} \int_{V'} \frac{\rho_m}{R}\, dv' \qquad \text{(A)}.$$

No μ_0 in V_m

If there ***were*** magnetic charges

Fictitious magnetic charges:

1. A mathematical (not physical) model
2. Helpful in discussion of magnetostatics from electrostatics

Magnetic Source

- Macroscopic (traditional) view: magnetic pole (a magnetic dipole)

Fictitious magnetic charges

$$\mathbf{m} = q_m\mathbf{d} = \mathbf{a}_n IS.$$

- Microscopic view: circulating atomic current

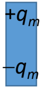
Potential due to a dipole

Electric dipole

$\boxed{\text{See 3-5.1}}$

$$V = \frac{\mathbf{p} \cdot \mathbf{a}_R}{4\pi\epsilon_0 R^2} \qquad \text{(V)},$$

Magnetic dipole



$$V_m = \frac{\mathbf{m} \cdot \mathbf{a}_R}{4\pi R^2} \qquad \text{(A)}.$$

$\boxed{\text{No } \mu_0 \text{ in } V_m}$

$$\boxed{\mathbf{B} = -\mu_0 \nabla V_m,}$$

$$\boxed{\mathbf{B} = \frac{\mu_0 m}{4\pi R^3}(\mathbf{a}_R\, 2\cos\theta + \mathbf{a}_\theta \sin\theta) \qquad \text{(T)}.}$$

Same as in Example 6-7

Electric potential

$$V = \frac{\mathbf{p} \cdot \mathbf{a}_R}{4\pi\epsilon_0 R^2} \qquad \text{(V)},$$

$$\nabla \times \mathbf{E} = 0.$$

J = 0

Fictitious magnetic charge and magnetic scalar potential

$$V_m = \frac{\mathbf{m} \cdot \mathbf{a}_R}{4\pi R^2} \qquad \text{(A)}.$$

$$\nabla \times \mathbf{B} = 0.$$

V_m holds at any points **with no currents**

B is conservative

J ≠ 0

Circulating current and magnetic vector potential

$$\mathbf{A} = \frac{\mu_0 \mathbf{m} \times \mathbf{a}_R}{4\pi R^2} \qquad \text{(Wb/m)},$$

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J}.$$

B is nonconservative

6-6 Magnetization and Equivalent Current Densities

- Microscopic viewpoint: orbiting electrons ➔ atomic currents ➔ magnetic dipoles **m**
- Without external **B**: random orientation of magnetic dipoles ➔ no net magnetic dipole moment, $\sum \mathbf{m} = 0$
- With external **B**: alignment of magnetic dipoles ➔ induced magnetic dipole moment $\mathbf{m} \neq 0$

Let $\mathbf{m}_k$: magnetic dipole moment of an atom

Define magnetization vector **M**

n: number density

$n\Delta v = N$: total #

$$\mathbf{M} = \lim_{\Delta v \to 0} \frac{\sum_{k=1}^{n\,\Delta v} \mathbf{m}_k}{\Delta v} \qquad \text{(A/m)},$$

M: density of total magnetic dipoles

$$d\mathbf{m} = \mathbf{M}\,dv'$$

$$\boxed{\mathbf{A} = \frac{\mu_0 \mathbf{m} \times \mathbf{a}_R}{4\pi R^2} \qquad \text{(Wb/m)},}$$

$$\boxed{d\mathbf{m} = \mathbf{M}\,dv'}$$

$$d\mathbf{A} = \frac{\mu_0 \mathbf{M} \times \mathbf{a}_R}{4\pi R^2}\,dv'.$$

Recall polarization vector **P**

$$V = \frac{\mathbf{p} \cdot \mathbf{a}_R}{4\pi\epsilon_0 R^2} \qquad \text{(V)},$$

$$\nabla'\left(\frac{1}{R}\right) = \frac{\mathbf{a}_R}{R^2}.$$ **R**: source to field

$$dA = \frac{\mu_0}{4\pi} \mathbf{M} \times \nabla'\left(\frac{1}{R}\right) dv'.$$

$$\mathbf{A} = \int_{V'} d\mathbf{A} = \frac{\mu_0}{4\pi} \int_{V'} \mathbf{M} \times \nabla'\left(\frac{1}{R}\right) dv',$$

By using the vector identity

$$\mathbf{M} \times \nabla'\left(\frac{1}{R}\right) = \frac{1}{R} \nabla' \times \mathbf{M} - \nabla' \times \left(\frac{\mathbf{M}}{R}\right)$$

$$\mathbf{A} = \frac{\mu_0}{4\pi} \int_{V'} \frac{\nabla' \times \mathbf{M}}{R} dv' - \underline{\frac{\mu_0}{4\pi} \int_{V'} \nabla' \times \left(\frac{\mathbf{M}}{R}\right) dv'}.$$

By using the vector identity (Prob. 6-20)

$$\int_{V'} \nabla' \times \mathbf{F}\, dv' = -\oint_{S'} \mathbf{F} \times d\mathbf{s}',$$

$$\mathbf{A} = \frac{\mu_0}{4\pi} \int_{V'} \frac{\nabla' \times \mathbf{M}}{R} dv' + \underline{\frac{\mu_0}{4\pi} \oint_{S'} \frac{\mathbf{M} \times \mathbf{a}'_n}{R} ds'},$$

See section 3-7.1

$$V = \frac{1}{4\pi\epsilon_0} \int_{V'} \mathbf{P} \cdot \nabla'\left(\frac{1}{R}\right) dv'.$$

$$\mathbf{A} = \frac{\mu_0}{4\pi}\int_{V'} \frac{\nabla' \times \mathbf{M}}{R}\, dv' + \frac{\mu_0}{4\pi}\oint_{S'} \frac{\mathbf{M} \times \mathbf{a}'_n}{R}\, ds',$$

Comparisons with

$$\boxed{\mathbf{A} = \frac{\mu_0}{4\pi}\int_{V'} \frac{\mathbf{J}}{R}\, dv'}$$

$$\boxed{\mathbf{J}_m = \nabla \times \mathbf{M} \qquad (\mathrm{A/m^2})}$$

$$\boxed{\mathbf{J}_{ms} = \mathbf{M} \times \mathbf{a}_n \qquad (\mathrm{A/m}).}$$

Prime is omitted for simplicity

For a given **M**

➔Find equivalent **magnetization current densities** $\mathbf{J}_m$ and $\mathbf{J}_{ms}$

➔**A**

➔**B** = ∇×**A**

See section 3-7.1

$$\boxed{\rho_p = -\nabla \cdot \mathbf{P}.}$$

$$\boxed{\rho_{ps} = \mathbf{P} \cdot \mathbf{a}_n}$$

Magnetization **M**

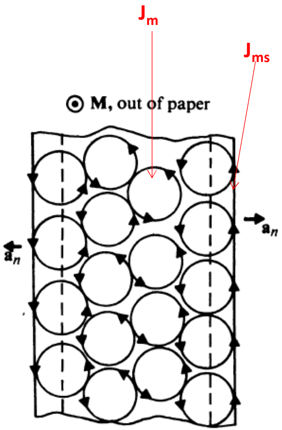


FIGURE 6–10
A cross section of a magnetized material.

Polarization **P**

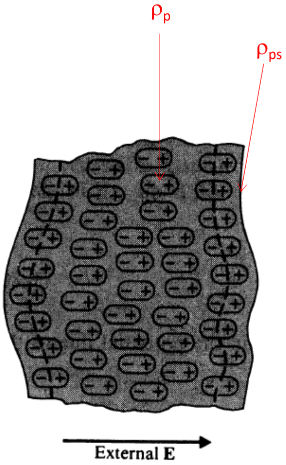
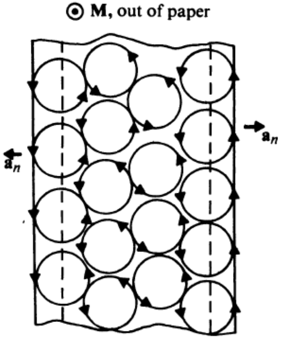


FIGURE 3–20
A cross section of a polarized dielectric medium.



$$\boxed{\mathbf{J}_m = \nabla \times \mathbf{M} \qquad (\text{A/m}^2)}$$

$$\boxed{\mathbf{J}_{ms} = \mathbf{M} \times \mathbf{a}_n \qquad (\text{A/m}).}$$

- Check directions of $\mathbf{J}_{ms}$
- If **M** is uniform inside ➔ currents inside cancel each other ➔ $\mathbf{J}_m = 0$ (i.e., $\nabla\times$(constant) = 0)

6-6.1 Equivalent Magnetization Charge Densities

- In a **current-free** region, we may define V_m
- **B** can be found by $\mathbf{B} = -\mu_0 \nabla V_m,$

$$\boxed{V_m = \frac{\mathbf{m} \cdot \mathbf{a}_R}{4\pi R^2} \qquad \text{(A)}.}$$

$$\Downarrow \qquad \boxed{d\mathbf{m} = \mathbf{M}\, dv'}$$

$$dV_m = \frac{\mathbf{M} \cdot \mathbf{a}_R}{4\pi R^2}\, dv'$$

$$\Downarrow$$

integration

$$V_m = \frac{1}{4\pi} \int_{V'} \frac{\mathbf{M} \cdot \mathbf{a}_R}{R^2} \, dv'.$$

$$V = \frac{1}{4\pi\epsilon_0} \int_{V'} \frac{\mathbf{P} \cdot \mathbf{a}_R}{R^2} \, dv',$$

Following similar steps as in section 3-7.1

$$V_m = \frac{1}{4\pi} \oint_{S'} \frac{\mathbf{M} \cdot \mathbf{a}'_n}{R} \, ds' + \frac{1}{4\pi} \int_{V'} \frac{-(\nabla' \cdot \mathbf{M})}{R} \, dv',$$

$$\boxed{\rho_{ms} = \mathbf{M} \cdot \mathbf{a}_n \qquad (\mathrm{A/m})}$$

$$\boxed{\rho_m = -\nabla \cdot \mathbf{M} \qquad (\mathrm{A/m^2}).}$$

$$V = \frac{1}{4\pi\epsilon_0} \oint_{S'} \frac{\mathbf{P} \cdot \mathbf{a}'_n}{R} \, ds' + \frac{1}{4\pi\epsilon_0} \int_{V'} \frac{(-\nabla' \cdot \mathbf{P})}{R} \, dv',$$

$$\boxed{\rho_{ps} = \mathbf{P} \cdot \mathbf{a}_n}$$

$$\boxed{\rho_p = -\nabla \cdot \mathbf{P}.}$$

- A **polarized dielectric** may be replaced by an equivalent ρ_p and ρ_{ps}

Polarization charge density

$$\boxed{\rho_{ps} = \mathbf{P} \cdot \mathbf{a}_n}$$

$$\boxed{\rho_p = -\nabla \cdot \mathbf{P}.}$$

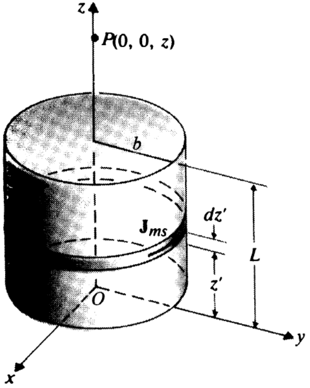
- A **magnetized body** may be replaced by an equivalent ρ_m and ρ_{ms}

Magnetization charge density

$$\boxed{\rho_{ms} = \mathbf{M} \cdot \mathbf{a}_n \qquad (\text{A/m})}$$

$$\boxed{\rho_m = -\nabla \cdot \mathbf{M} \qquad (\text{A/m}^2).}$$

EXAMPLE 6–8 Determine the magnetic flux density on the axis of a uniformly magnetized circular cylinder of a magnetic material. The cylinder has a radius b, length L, and axial magnetization $\mathbf{M} = \mathbf{a}_z M_0$.



Question: **B** on z axis?

Methods:

(1) Calculate J_m and J_{ms}

(2) **B** due to J

FIGURE 6–11

A uniformly magnetized circular cylinder (Example 6–8).

6-7 Magnetic Field Intensity and Relative Permeability

- Review: External $\mathbf{E}_{ext}$ applied to a dielectric material → induced dipole moments inside the dielectric material (and thus, $\mathbf{E}_{induced}$)

→ **E** inside the dielectric $\mathbf{E}_{total} = \mathbf{E}_{ext} + \mathbf{E}_{induced}$

→ $$\boxed{\nabla \cdot \mathbf{E} = \frac{1}{\epsilon_0}(\rho + \rho_p).}$$

Magnetic Side

- External $\mathbf{B}_{ext}$ applied to a **magnetic** material → induced dipole moments inside the **magnetic** material (and thus, $\mathbf{B}_{induced}$)

➡ **B** inside the magnetic $\mathbf{B}_{total} = \mathbf{B}_{ext} + \mathbf{B}_{induced}$

➡ $$\frac{1}{\mu_0}\nabla \times \mathbf{B} = \mathbf{J} + \mathbf{J}_m = \mathbf{J} + \nabla \times \mathbf{M}$$

$$\nabla \times \left(\frac{\mathbf{B}}{\mu_0} - \mathbf{M}\right) = \mathbf{J}.$$

Defined as **H**: magnetic field intensity

$$\boxed{\mathbf{H} = \frac{\mathbf{B}}{\mu_0} - \mathbf{M} \qquad \text{(A/m).}}$$

$$\nabla \times \left(\frac{\mathbf{B}}{\mu_0} - \mathbf{M} \right) = \mathbf{J}.$$

$$\boxed{\mathbf{H} = \frac{\mathbf{B}}{\mu_0} - \mathbf{M} \qquad (\mathrm{A/m}).}$$

$$\Downarrow$$

$$\boxed{\nabla \times \mathbf{H} = \mathbf{J} \qquad (\mathrm{A/m^2}),}$$

J: volume density of **free** current

$$\nabla \cdot (\epsilon_0 \mathbf{E} + \mathbf{P}) = \rho.$$

$$\boxed{\mathbf{D} = \epsilon_0 \mathbf{E} + \mathbf{P} \qquad (\mathrm{C/m^2}).}$$

$$\Downarrow$$

$$\boxed{\nabla \cdot \mathbf{D} = \rho \qquad (\mathrm{C/m^3}),}$$

ρ: volume density of **free** charges

$$\boxed{\nabla \times \mathbf{H} = \mathbf{J} \qquad (\text{A/m}^2),}$$

integration

$$\int_S (\nabla \times \mathbf{H}) \cdot d\mathbf{s} = \int_S \mathbf{J} \cdot d\mathbf{s}$$

Stoke's theorem

$$\boxed{\oint_C \mathbf{H} \cdot d\boldsymbol{\ell} = I \qquad (\text{A}),}$$

C: the contour bounding the surface S

Another form of Ampere's circuital law: the circulation of the magnetic field intensity around any closed path is equal to the free current flowing through the surface bounded by the path.

$$\boxed{\nabla \cdot \mathbf{D} = \rho \qquad (\text{C/m}^3),}$$

$$\int_V \nabla \cdot \mathbf{D} \, dv = \int_V \rho \, dv$$

$$\boxed{\oint_S \mathbf{D} \cdot d\mathbf{s} = Q \qquad (\text{C}).}$$

Another form of Gauss's law: …

If the magnetic properties of the medium is *linear* and *isotropic*, then

M ~ H

$$\mathbf{M} = \chi_m \mathbf{H},$$

χ_m: magnetic susceptibility

$$\boxed{\mathbf{H} = \frac{\mathbf{B}}{\mu_0} - \mathbf{M} \qquad \text{(A/m).}}$$

$$\mathbf{M} = \chi_m \mathbf{H},$$

$$\boxed{\begin{aligned} \mathbf{B} &= \mu_0(1 + \chi_m)\mathbf{H} \\ &= \mu_0 \mu_r \mathbf{H} = \mu \mathbf{H} \qquad (\text{Wb/m}^2) \end{aligned}}$$

$$\mathbf{P} = \epsilon_0 \chi_e \mathbf{E},$$

$$\boxed{\begin{aligned} \mathbf{D} &= \epsilon_0(1 + \chi_e)\mathbf{E} \\ &= \epsilon_0 \epsilon_r \mathbf{E} = \epsilon \mathbf{E} \qquad (\text{C/m}^2), \end{aligned}}$$

$$\boxed{\begin{aligned}\mathbf{B} &= \mu_0(1+\chi_m)\mathbf{H} \\ &= \mu_0\mu_r\mathbf{H} = \mu\mathbf{H} \qquad (\text{Wb/m}^2)\end{aligned}}$$

$$\boxed{\begin{aligned}\mathbf{D} &= \epsilon_0(1+\chi_e)\mathbf{E} \\ &= \epsilon_0\epsilon_r\mathbf{E} = \epsilon\mathbf{E} \qquad (\text{C/m}^2),\end{aligned}}$$

Or $$\boxed{\mathbf{H} = \frac{1}{\mu}\mathbf{B} \qquad (\text{A/m}),}$$

where $$\boxed{\mu_r = 1 + \chi_m = \frac{\mu}{\mu_0}}$$

$$\epsilon_r = 1 + \chi_e = \frac{\epsilon}{\epsilon_0}$$

μ: permeability
μ_r: relative permeability

For a simple medium (linear, isotropic, homogeneous), χ_m and μ_r are constants.

Relative permeability μ_r

- Ferromagnetic materials: iron, nickel, and cobalt. μ_r is very large (i.e., easy to be magnetized)

Analogy between electrostatics and magnetostatics

Electrostatics	Magnetostatics
$\mathbf{E}$	$\mathbf{B}$
$\mathbf{D}$	$\mathbf{H}$
ϵ	$\dfrac{1}{\mu}$
$\mathbf{P}$	$-\mathbf{M}$
ρ	$\mathbf{J}$
V	$\mathbf{A}$
$\cdot$	$\times$
$\times$	$\cdot$

6-8 Magnetic Circuits

- Magnetic circuits: transformers, generators, motors, relays, magnetic recording devices, and so on.
- Electric circuits: to find V (and **E**) and I
  Magnetic circuits: to find I (and **H**) and Φ
- Analysis of magnetic circuits: $$\nabla \cdot \mathbf{B} = 0,$$ $$\nabla \times \mathbf{H} = \mathbf{J}.$$

Magnetomotive Force (mmf)

- Analogous to electromotive force (emf)
- Not a force in Newtons, but in ampere (A)

$$\boxed{\oint_C \mathbf{H} \cdot d\boldsymbol{\ell} = I \qquad \text{(A)},}$$

For *N* turns (see Example 6-10)

$$\oint_C \mathbf{H} \cdot d\boldsymbol{\ell} = NI = \mathcal{V}_m.$$

A toroidal core with *N* turns of wires wound

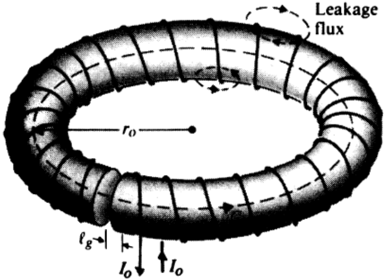


FIGURE 6–13
Coil on ferromagnetic toroid with air gap (Example 6–10).

In the ferromagnetic core

$$\mathbf{B}_f = \mathbf{a}_\phi \frac{\mu_0 \mu N I_o}{\mu_0(2\pi r_o - \ell_g) + \mu \ell_g}.$$

$$\mathbf{H}_f = \mathbf{a}_\phi \frac{\mu_0 N I_o}{\mu_0(2\pi r_o - \ell_g) + \mu \ell_g}.$$

In the air gap

$$\mathbf{H}_g = \mathbf{a}_\phi \frac{\mu N I_o}{\mu_0(2\pi r_o - \ell_g) + \mu \ell_g}.$$

EXAMPLE 6–10 Assume that N turns of wire are wound around a toroidal core of a ferromagnetic material with permeability μ. The core has a mean radius r_o, a circular cross section of radius a ($a \ll r_o$), and a narrow air gap of length ℓ_g, as shown in Fig. 6–13. A steady current I_o flows in the wire. Determine (a) the magnetic flux density, $\mathbf{B}_f$, in the ferromagnetic core; (b) the magnetic field intensity, $\mathbf{H}_f$, in the core; and (c) the magnetic field intensity, $\mathbf{H}_g$, in the air gap.

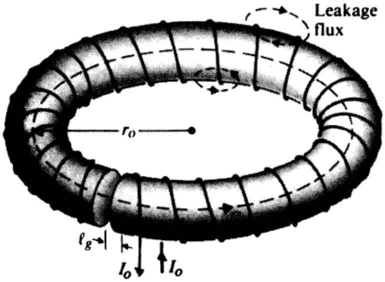
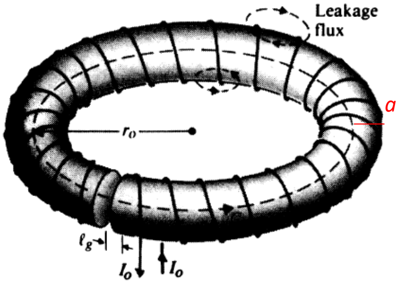


FIGURE 6–13
Coil on ferromagnetic toroid with air gap (Example 6–10).



a: radius of the coil
S: cross section of the toroid core

FIGURE 6–13
Coil on ferromagnetic toroid with air gap (Example 6–10).

If $a \ll r_0$, **B** ~ constant,

$$\Phi \cong BS,$$

$$\boxed{\mathbf{B}_f = \mathbf{a}_\phi \frac{\mu_0 \mu N I_o}{\mu_0(2\pi r_o - \ell_g) + \mu \ell_g}.}$$

$$\Phi = \frac{N I_o}{(2\pi r_o - \ell_g)/\mu S + \ell_g/\mu_0 S}.$$

$$\Phi = \frac{NI_o}{(2\pi r_o - \ell_g)/\mu S + \ell_g/\mu_0 S}.$$

$$\Phi = \frac{\mathscr{V}_m}{\mathscr{R}_f + \mathscr{R}_g},$$

where $$\mathscr{R}_f = \frac{2\pi r_o - \ell_g}{\mu S} = \frac{\ell_f}{\mu S}, \qquad \mathscr{R}_g = \frac{\ell_g}{\mu_0 S}.$$

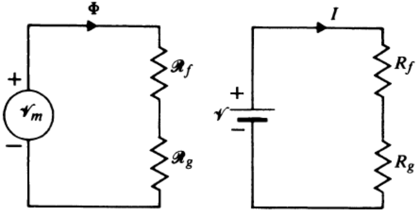
$$\ell_f = 2\pi r_o - \ell_g$$

ℓ_f: length of the ferromagnetic core

R_f: reluctance of the ferromagnetic core (H^{-1})
R_g: reluctance of the air gap

Ohm's law: $I = V/R$ Resistance $R = \ell/(\sigma S)$

Analogous to Electric Circuit



(a) Magnetic circuit. (b) Electric circuit.

FIGURE 6–14
Equivalent magnetic circuit and analogous electric circuit for toroidal coil with air gap in Fig. 6–13.

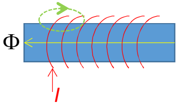
$$\Phi = \frac{\mathscr{V}_m}{\mathscr{R}_f + \mathscr{R}_g}, \qquad I = \frac{\mathscr{V}}{R_f + R_g}.$$

Magnetic Circuits	Electric Circuits
mmf, $\mathscr{V}_m$ $(=NI)$	emf, $\mathscr{V}$
magnetic flux, Φ	electric current, I
reluctance, $\mathscr{R}$	resistance, R
permeability, μ	conductivity, σ

Difficulty in Analysis of Magnetic Circuits

- 1. Very difficult to account for leakage fluxes

Magnetic circuits



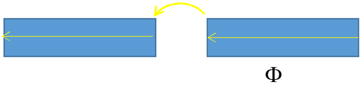
Leakage fluxes Φ outside $\neq 0$
due to $\mu_0 \neq 0$ (in air)

Electric circuits

Current I outside = 0
because of $\sigma = 0$ (in air)

- 2. Difficult to account for fringing effect (at the air gap)

Magnetic circuits



- 3. *B* and *H* have a nonlinear relationship
  - *B*(*H*) or μ is not a constant

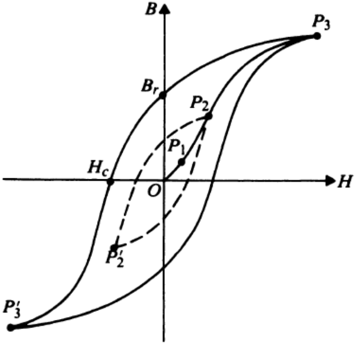


FIGURE 6–17
Hysteresis loops in the *B–H* plane for ferromagnetic material.

KVL and KCL in Magnetic Circuits

See Chap. 5

$$\Phi = \frac{\mathscr{V}_m}{\mathscr{R}_f + \mathscr{R}_g}, \quad \Rightarrow \quad \boxed{\sum_j N_j I_j = \sum_k \mathscr{R}_k \Phi_k.}$$

$$I = \frac{\mathscr{V}}{R_f + R_g}.$$

KVL: around a closed path in a magnetic circuit the algebraic sum of ampere-terns is equal to the algebraic sum of the products of the reluctances and fluxes

$$\nabla \cdot \mathbf{B} = 0 \quad \Rightarrow \quad \boxed{\sum_j \Phi_j = 0,}$$

$$\nabla \cdot \mathbf{J} = 0.$$

KCL: the algebraic sum of all the magnetic fluxes flowing out of a junction in a magnetic circuit is zero

6-9 Behavior of Magnetic Materials

$$\boxed{\mathbf{M} = \chi_m \mathbf{H},}$$

$$\boxed{\mu_r = 1 + \chi_m = \frac{\mu}{\mu_0}}$$

χ_m: magnetic susceptibility
μ_r: relative permeability

Diamagnetic, if $\mu_r \lesssim 1$ (χ_m is a very small negative number).
Paramagnetic, if $\mu_r \gtrsim 1$ (χ_m is a very small positive number).
Ferromagnetic, if $\mu_r \gg 1$ (χ_m is a large positive number).

$\mathbf{B}/\mu_0 = \mathbf{H}+\mathbf{M}$

$\varepsilon_0\mathbf{E} = \mathbf{D}-\mathbf{P}$

1. Diamagnetic

- Without external magnetic field ➔ no net magnetic dipole moments, **m** = 0
- With external magnetic field ➔ a net magnetic dipole moment (induced magnetization **M**), **m** $\neq$ 0
- **M** opposes $\mathbf{B}_{ext}$, thus reducing the **B**. That is, $\chi_m<0$ (~ -10^{-5})

$$\mathbf{M} = \chi_m \mathbf{H},$$

$$\mathbf{B}/\mu_0 = \mathbf{H}+\mathbf{M}$$

$$\varepsilon_0 \mathbf{E} = \mathbf{D}-\mathbf{P}$$

- Like **P** opposes **E**, reducing the **E** in dielectrics, **B** is reduced in diamagnetics. $\mathbf{M} = \chi_m \mathbf{H}$,

  $\mathbf{B}/\mu_0 = \mathbf{H}+\mathbf{M}$ $\varepsilon_0\mathbf{E} = \mathbf{D}-\mathbf{P}$

- No permanent magnetism: the induced magnetic moments disappears when applied field is withdrawn.
- Diamagnetic materials: bismuth, copper, lead, mercury, germanium, silver, gold, diamond
- Due to mainly orbiting electrons

2. Paramagnetic

- Without external magnetic field ➔ there is net magnetic dipole moments, **m** $\neq$ 0
- With external magnetic field ➔ a very weak induced magnetization **M** (similar to diamagnetic effect)
- **M** is in the direction of $\mathbf{B}_{ext}$, thus increasing the **B**. $\chi_m > 0$ (~ 10^{-5})

$$\mathbf{M} = \chi_m \mathbf{H},$$

$$\mathbf{B}/\mu_0 = \mathbf{H} + \mathbf{M} \qquad \varepsilon_0 \mathbf{E} = \mathbf{D} - \mathbf{P}$$

- Paramagnetic materials: aluminum, magnesium, titanium, and tungsten
- Due to mainly spinning electrons

3. Ferromagnetic

- Magnetization can be many orders of magnitude larger than that of paramagnetic substances.
- Magnetized domain:

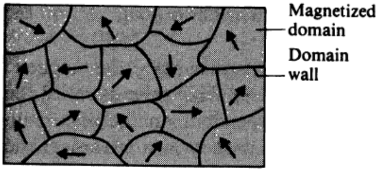


FIGURE 6–16
Domain structure of a polycrystalline ferromagnetic specimen.

- Without external magnetic field → no net magnetization (due to random orientation in the various domains)
- With external magnetic field → the domains aligned with applied magnetic field grow → **B** is increased (χ_m>0) $\mathbf{M} = \chi_m \mathbf{H}$,

$$\mathbf{B}/\mu_0 = \mathbf{H} + \mathbf{M}$$

- Due to mainly spinning electrons
- Ferromagnetic materials: cobalt, nickel, and iron

Q&A

- When a permanent magnet is placed against a steel (ferromagnetic material) refrigerator, it sticks. What is the best explanation of the physics involved?

Hysteresis for ferromagnetic materials

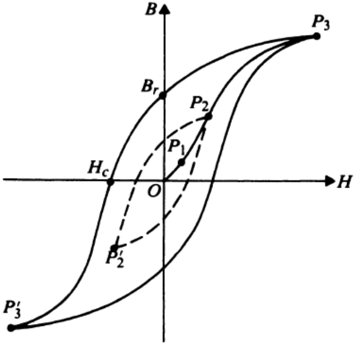


FIGURE 6–17
Hysteresis loops in the B–H plane for ferromagnetic material.

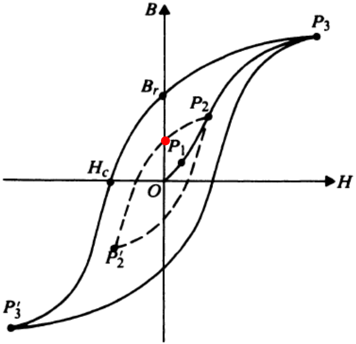


FIGURE 6–17
Hysteresis loops in the *B*–*H* plane for ferromagnetic material.

1. For weak applied fields (e.g., to P_1), magnetization are reversible.
2. For stronger applied fields (e.g., to P_2), magnetization are no longer reversible.
   - Forward: OP_1P_2
   - Backward: P_2P_2'

   Magnetization (B) lags the field (H), called **hysteresis** ("to lag" in Greek word)

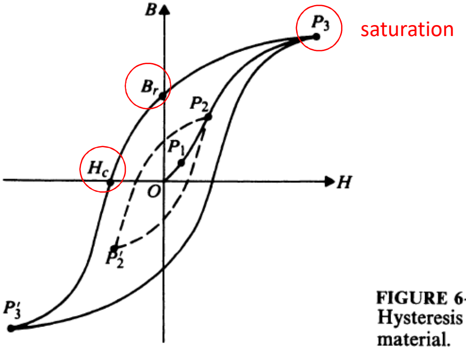


FIGURE 6–17
Hysteresis loops in the *B–H* plane for ferromagnetic material.

3. For much stronger fields (e.g., to P_3) ➔ total alignment of microscopic magnetic dipole moments with the applied field ➔ reached the saturation
   - **Permanent magnets**: If *H* is reduced to 0, *B* does not go to 0 but the value B_r (called residual or remnant *B*).
   - Coercive field intensity: to make *B* back to 0, a H_c in the opposite direction is necessary.

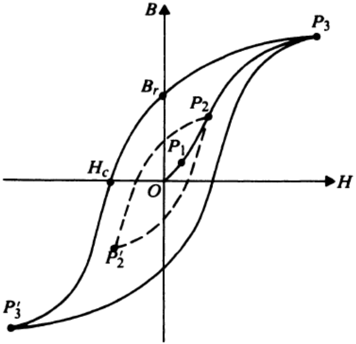


FIGURE 6–17
Hysteresis loops in the B–H plane for ferromagnetic material.

Soft materials

Q: How to have a large magnetization for a very small applied field?

A: **Tall narrow** hysteresis loops

The area of hysteresis loop = energy loss per unit volume per cycle (when the hysteresis loop is traced once per cycle)

hysteresis energy loss is the energy lost in the form of heat in overcoming the friction encountered during domain-wall motion and domain rotation.

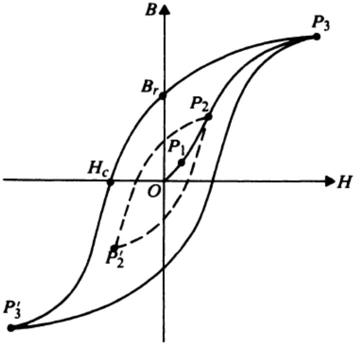


FIGURE 6–17
Hysteresis loops in the B–H plane for ferromagnetic material.

Hard materials

Q: How to have good permanent magnets?

A: **Fat** hysteresis loops (i.e., large H_c)

Temperature Effect to Ferromagnetic Material

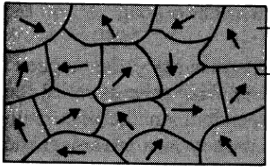
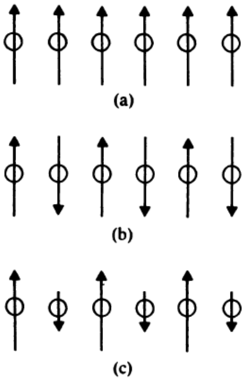


FIGURE 6–16
Domain structure of a polycrystalline ferromagnetic specimen.

- Under curie temperature T_c → well-defined magnetized domain (T_c = 770°C for iron)
- Above curie temperature → loses magnetization, reducing to paramagnetic substances

Anti-ferromagnetic and Ferri-magnetic



- (a) Ferromagnetic: parallel alignments of electron spins (in a magnetized domain)
- (b) Anti-ferromagnetic: antiparallel alignments of electron spins ➔ no net magnetic moment
- (c) Ferri-magnetic: alternating alignments of electron spins with unequal magnitudes ➔ nonzero net magnetic moment
  - Due to partial cancelation, B_{ferri} ~ 1/10 B_{ferro}

FIGURE 6–18
Schematic atomic spin structures for (a) ferromagnetic, (b) antiferromagnetic, and (c) ferrimagnetic materials.

	Diamagnetic	Paramagnetic	Ferromagnetic
μ_r	≤ 1	≥ 1	$>>1$
χ_m	Small negative	Small positive	Larger positive
M (**M** = χ_m**H**)	//−**H**	//**H**	//**H**
B in the material ($\mathbf{B}/\mu_0 = \mathbf{H}+\mathbf{M}$)	Reduced	Increased	Increased
Mainly due to	Orbiting electrons	Spinning electrons	
When $\mathbf{B}_{\mathbf{ext}}$=0	Net **m** = 0	Net m $\neq$ 0 (very weak)	Net m $\neq$ 0 (hysteresis)

6-10 Boundary Conditions for Magnetostatic Field

Magnetostatics

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

$$\boxed{B_{1n} = B_{2n} \qquad \text{(T)}.}$$

The normal component of **B** is continuous across an interface

For linear media,

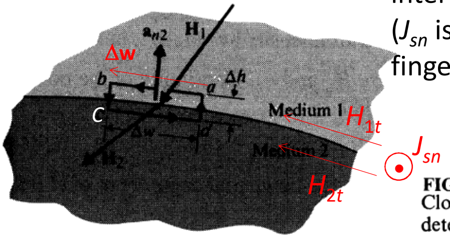
$$\mathbf{B}_1 = \mu_1 \mathbf{H}_1 \text{ and } \mathbf{B}_2 = \mu_2 \mathbf{H}_2,$$

$$\boxed{\mu_1 H_{1n} = \mu_2 H_{2n}.}$$

Electrostatics

$$\nabla \cdot \mathbf{D} = \rho$$

$$\boxed{D_{1n} - D_{2n} = \rho_s \qquad (\text{C/m}^2),}$$



J_{sn}: the surface current density on the interface **normal** to the contour C (J_{sn} is along the thumb when the fingers of right hand follow the path C)

FIGURE 6–19
Closed path about the interface of two media for determining the boundary condition of H_t.

Magnetostatics

$$\oint_C \mathbf{H} \cdot d\boldsymbol{\ell} = I.$$

Let bc = da = $\Delta h \rightarrow 0$

$$\oint_{abcda} \mathbf{H} \cdot d\boldsymbol{\ell} = \mathbf{H}_1 \cdot \Delta\mathbf{w} + \mathbf{H}_2 \cdot (-\Delta\mathbf{w}) = J_{sn}\Delta w$$

$$H_{1t} - H_{2t} = J_{sn} \qquad \text{(A/m)},$$

along the finger – opposite to the finger

Electrostatics

$$\nabla \times \mathbf{E} = 0$$

$$\boxed{E_{1t} = E_{2t} \qquad \text{(V/m)},}$$

Or $$\boxed{\mathbf{a}_{n2} \times (\mathbf{H}_1 - \mathbf{H}_2) = \mathbf{J}_s \qquad (\text{A/m}),}$$

The tangential component of the **H** field is discontinuous across an interface where a free surface current exists

- For finite σ of two media ➔ only J, no J_s ➔ H_t continuous
- If infinite σ for one medium ➔ J_s exists ➔ H_t discontinuous

Recall in Chap.5: $\boxed{J_{1n} = J_{2n} \qquad (\text{A/m}^2).}$ $\boxed{\frac{J_{1t}}{J_{2t}} = \frac{\sigma_1}{\sigma_2}.}$ (see Prob. 6-30)

Analogous Boundary-value Problems

Magnetostatics

In current-free regions, ∇x(**B**/μ)=0

$$\mathbf{B} = -\mu \nabla V_m.$$

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

And assume a constant μ

$$\nabla^2 V_m = 0.$$

Thus, the techniques (method of images and method of separation of variables) discussed in Chap. 4 for solving boundary-value problems (BVPs) can be adapted to solving analogous magnetostatic BVPs.

Electrostatics

In charge-free regions, ∇x**E**=0

Laplace's equation

$$\nabla^2 V = 0,$$

6-11 Inductances and Inductors

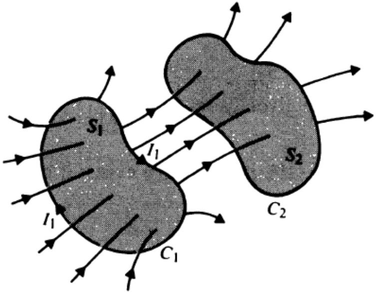


FIGURE 6–22
Two magnetically coupled loops.

I_1 ➔ Φ_1 ➔ part of Φ_1 (Φ_{12}) passes through S_2

$$\Phi_{12} = \int_{S_2} \mathbf{B}_1 \cdot d\mathbf{s}_2 \qquad \text{(Wb)}.$$

$\Phi_{12} \sim B_1$ (fixed S_2)

and from Biot-Savart law: $B \sim I$

$$\boxed{\mathbf{B} = \frac{\mu_0 I}{4\pi} \oint_{C'} \frac{d\boldsymbol{\ell}' \times \mathbf{a}_R}{R^2} \qquad \text{(T)}.}$$

$\rightarrow \Phi_{12} \sim I_1$

1 turn for C_2, mutual flux $\Phi_{12} = \underline{L_{12}} I_1,$

The proportionality constant L_{12} (called mutual inductance)

If N turns for C_2, flux linkage $\Lambda_{12} = N_2 \Phi_{12} \qquad \text{(Wb)},$

$\boxed{\Phi \cong BS,}$

$\rightarrow \Phi \sim S$ (fixed B)

Thus, the general expression: $\Lambda_{12} = L_{12} I_1 \qquad \text{(Wb)}$

$$\boxed{L_{12} = \frac{\Lambda_{12}}{I_1} \qquad \text{(H)}.}$$

The mutual inductance between two circuits is then the magnetic flux linkage with one circuit (Λ_{12}) per unit current in the other (I_1)

For linear media, μ is a constant

$$\boxed{\mathbf{B} = \frac{\mu_0 I}{4\pi} \oint_{C'} \frac{d\boldsymbol{\ell}' \times \mathbf{a}_R}{R^2} \qquad \text{(T).}}$$

$\mathbf{B} \sim I$

$$\Phi_{12} = L_{12} I_1, \Rightarrow \boxed{L_{12} = \frac{\Lambda_{12}}{I_1} \qquad \text{(H).}}$$

For linear media only

For nonlinear media, μ is a function of I

$\mathbf{B}(\mu, I)$

$$\Phi_{12}(\mu, I) \Rightarrow \boxed{L_{12} = \frac{d\Lambda_{12}}{dI_1} \qquad \text{(H).}}$$

In general

Self-inductance

$I_1 \Rightarrow \Phi_1 \Rightarrow$ part of Φ_1 (Φ_{11}) passes through S_1

If N_1 turns for C_1, flux linkage $\Lambda_{11} = N_1\Phi_{11} > N_1\Phi_{12}$.

.

.

.

Self-inductance

$$\boxed{L_{11} = \frac{\Lambda_{11}}{I_1} \quad \text{(H)},}$$

For linear media only

$$\boxed{L_{11} = \frac{d\Lambda_{11}}{dI_1} \quad \text{(H)}.}$$

In general

Inductor

- A conductor arranged in an appropriate shape (such as a conducting wire wound as a coil) to supply a certain amount of self-inductance is called an **inductor**.
- The procedure to determine self-inductance of an inductor: **From *I* to Λ**
  - 1. Choose an appropriate coordinate system
  - 2. Assume *I* in the conducting wire
  - 3. Find B from *I* by Ampere's circuital law (for the symmetric case) or Biot-Savart law (otherwise)

- 4. Find the flux linkage with each turn, Φ, from **B** $\boxed{\Phi = \int_S \mathbf{B} \cdot d\mathbf{s},}$
- 5. Find the total flux linkage Λ $\boxed{\Lambda = N\Phi}$
- 6. Find L by $L = \Lambda / I$

- The procedure to determine mutual-inductance L_{12}: slight modification

  I_1 ➔ B_1 ➔ **Φ_{12} by integrating B_1 over S_2** ➔ $\Lambda_{12} = N_2\Phi_{12}$ ➔ $L_{12} = \Lambda_{12}/I_1$

$$L_{12} = L_{21}?$$

<Proof>

$$\Phi_{12} = \int_{S_2} \mathbf{B}_1 \cdot d\mathbf{s}_2 \qquad \text{(Wb).}$$

$$\Lambda_{12} = N_2 \Phi_{12} \qquad \text{(Wb),}$$

$$L_{12} = \frac{\Lambda_{12}}{I_1} \qquad \text{(H).}$$

$$L_{12} = \frac{N_2}{I_1} \int_{S_2} \mathbf{B}_1 \cdot d\mathbf{s}_2.$$

$$\mathbf{B}_1 = \nabla \times \mathbf{A}_1$$

$$L_{12} = \frac{N_2}{I_1} \int_{S_2} (\nabla \times \mathbf{A}_1) \cdot d\mathbf{s}_2$$

$$= \frac{N_2}{I_1} \oint_{C_2} \mathbf{A}_1 \cdot d\boldsymbol{\ell}_2.$$

$$\mathbf{A}_1 = \frac{\mu_0 N_1 I_1}{4\pi} \oint_{C_1} \frac{d\boldsymbol{\ell}_1}{R}.$$

$$L_{12} = \frac{\mu_0 N_1 N_2}{4\pi} \oint_{C_1} \oint_{C_2} \frac{d\boldsymbol{\ell}_1 \cdot d\boldsymbol{\ell}_2}{R},$$

1 turn for C_1
1 turn for C_2

Neumann formula for mutual inductance

$$\boxed{L_{12} = \frac{\mu_0}{4\pi} \oint_{C_1} \oint_{C_2} \frac{d\boldsymbol{\ell}_1 \cdot d\boldsymbol{\ell}_2}{R} \quad \text{(H)},}$$

N_1 turns for C_1
N_2 turns for C_2

Mutual inductance:
- dependent on the geometrical shape and the physical arrangement of coupled circuits
- independent of currents (for linear media where μ is a constant)
- interchanging subscript 1 and 2 does not change the value ➔ $L_{12} = L_{21}$

EXAMPLE 6–15 Find the inductance per unit length of a very long solenoid with air core having n turns per unit length.

EXAMPLE 6–16 An air coaxial transmission line has a solid inner conductor of radius a and a very thin outer conductor of inner radius b. Determine the inductance per unit length of the line.

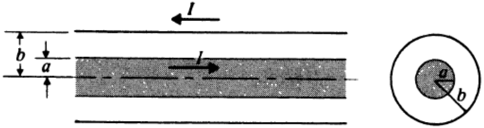


FIGURE 6–24
Two views of a coaxial transmission line (Example 6–16).

EXAMPLE 6–19 Determine the mutual inductance between a conducting triangular loop and a very long straight wire as shown in Fig. 6–27.

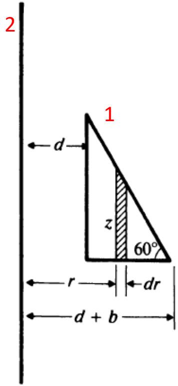


FIGURE 6–27
A conducting triangular loop and a long straight wire (Example 6–19).

6-12 Magnetic Energy

- For DC, the inductor behaves like short circuit.
- Exact AC case: retardation and radiation effects should be considered (Chaps. 7 and 8)
- Here, we consider **quasi-static conditions**: the current vary very slowly in time (low frequency, or long wavelength)

- In section 3-11, work is required to assemble a group of charges (stored electric energy)
- Here, work is required to send currents into conducting loops (stored magnetic energy)

Stored Magnetic Energy

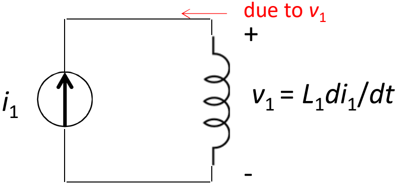
- A current generator increases the current i_1 from 0 to I_1:
- Work must be done to **overcome** this induced v_1

$$W_1 = \int v_1 i_1 \, dt = L_1 \int_0^{I_1} i_1 \, di_1 = \tfrac{1}{2} L_1 I_1^2.$$

For linear media

$$L_1 = \Phi_1 / I_1$$

$$W_1 = \tfrac{1}{2} I_1 \Phi_1,$$



Recall: in Chap.3

$$W_e = \frac{1}{2} \sum_{k=1}^{N} Q_k V_k \qquad \text{(J)},$$

Two loops C_1 and C_2 to I_1 and I_2

- Initially, $i_1 = 0$, $i_2 = 0$
- Step 1: increase i_1 from 0 to I_1

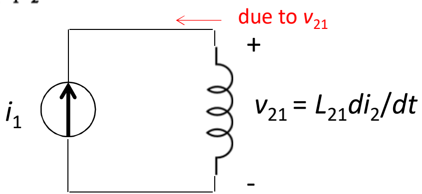
$$W_1 = \tfrac{1}{2}L_1 I_1^2.$$

- Step 2: increase i_2 from 0 to I_2
  - Work must be done to **overcome** the induced $v_{21} = L_{21}di_2/dt$ (to keep i_1 constant at I_1)

$$W_{21} = \int v_{21} I_1\,dt = L_{21} I_1 \int_0^{I_2} di_2 = L_{21} I_1 I_2.$$

  - Work in C_2

$$W_{22} = \tfrac{1}{2}L_2 I_2^2.$$



Total work required: $W_2 = \frac{1}{2}L_1 I_1^2 + L_{21} I_1 I_2 + \frac{1}{2}L_2 I_2^2$

$$= \frac{1}{2} \sum_{j=1}^{2} \sum_{k=1}^{2} L_{jk} I_j I_k.$$

Generalization to a system of *N* loops carrying currents $I_1, I_2, \ldots, I_n$:

$$\boxed{W_m = \frac{1}{2} \sum_{j=1}^{N} \sum_{k=1}^{N} L_{jk} I_j I_k \qquad \text{(J)},}$$

The stored magnetic energy for a current *I* through a single inductor with inductance *L*:

$$\boxed{W_m = \tfrac{1}{2} L I^2 \qquad \text{(J).}}$$

Alternative Derivation

Consider a kth loop of *N* magnetically coupled loops

The work done in the kth loop in time *dt*

$$dW_k = \underbrace{v_k i_k}_{\text{power}}\, dt = i_k\, d\phi_k,$$

$$\boxed{v_k = d\phi_k/dt.}$$

$d\phi_k$: change in flux ϕ_k linking with the kth loop due to the change of currents in all the coupled loops
($di \rightarrow d\phi \rightarrow v_k$)

The differential work done to the system $dW_m = \sum_{k=1}^{N} dW_k = \sum_{k=1}^{N} i_k\, d\phi_k.$

$$dW_m = \sum_{k=1}^{N} dW_k = \sum_{k=1}^{N} i_k \, d\phi_k.$$

$\boxed{i_k = \alpha I_k,}$ $\boxed{\phi_k = \alpha \Phi_k}$

I_k and Φ_k are final values (constants);
α increases from 0 to 1

The total magnetic energy $W_m = \int dW_m = \sum_{k=1}^{N} I_k \Phi_k \int_0^1 \alpha \, d\alpha$

$$\boxed{W_m = \frac{1}{2} \sum_{k=1}^{N} I_k \Phi_k \qquad \text{(J)},}$$

For linear media

$$\Phi_k = \sum_{j=1}^{N} L_{jk} I_j,$$

$$\boxed{W_m = \frac{1}{2} \sum_{j=1}^{N} \sum_{k=1}^{N} L_{jk} I_j I_k \qquad \text{(J)},}$$

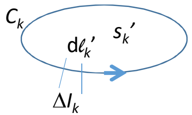
6-12.1 Magnetic Energy in Terms of Field Quantities

$$\boxed{W_m = \frac{1}{2}\sum_{k=1}^{N} I_k \Phi_k \qquad \text{(J)},}$$

$$\Phi_k = \int_{S_k} \mathbf{B}\cdot\mathbf{a}_n\, ds'_k = \oint_{C_k} \mathbf{A}\cdot d\boldsymbol{\ell}'_k,$$

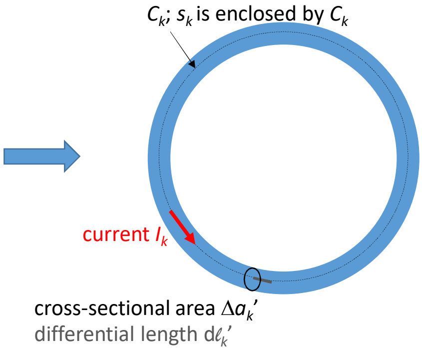
$$\boxed{\mathbf{B} = \nabla\times\mathbf{A}}$$

A single current-carrying loop



N contiguous filamentary current elements with a current ΔI_k (flowing in an infinitesimal cross-sectional area $\Delta a_k'$; $\Delta v_k' = \Delta a_k' d\ell_k'$)

Top view


C_k; s_k is enclosed by C_k
current I_k
cross-sectional area $\Delta a_k'$
differential length $d\ell_k'$

$$W_m = \frac{1}{2}\sum_{k=1}^{N} \Delta I_k \oint_{C_k} \mathbf{A}\cdot d\boldsymbol{\ell}'_k.$$

$$\Delta I_k\, d\boldsymbol{\ell}'_k = J(\Delta a'_k)\, d\boldsymbol{\ell}'_k = \mathbf{J}\,\Delta v'_k.$$

As $N \rightarrow \infty$, $\Delta v_k'$ becomes dv_k'

$$\boxed{W_m = \frac{1}{2}\int_{V'} \mathbf{A}\cdot\mathbf{J}\, dv' \qquad \text{(J)},}$$

Analogy to electric energy

$$\boxed{W_e = \frac{1}{2}\int_{V'} \rho V\, dv \qquad \text{(J)}.}$$

V': the volume of the loop or the linear medium in which **J** exists

By vector identity

$$\nabla\cdot(\mathbf{A}\times\mathbf{H}) = \mathbf{H}\cdot(\nabla\times\mathbf{A}) - \mathbf{A}\cdot(\nabla\times\mathbf{H}),$$

$$\mathbf{A}\cdot(\nabla\times\mathbf{H}) = \mathbf{H}\cdot(\nabla\times\mathbf{A}) - \nabla\cdot(\mathbf{A}\times\mathbf{H})$$

$$\mathbf{A}\cdot\mathbf{J} = \mathbf{H}\cdot\mathbf{B} - \nabla\cdot(\mathbf{A}\times\mathbf{H}).$$

$$W_m = \frac{1}{2}\int_{V'} \mathbf{H}\cdot\mathbf{B}\, dv' - \frac{1}{2}\oint_{S'} (\mathbf{A}\times\mathbf{H})\cdot\mathbf{a}_n\, ds'.$$

$$W_m = \frac{1}{2}\int_{V'} \mathbf{H}\cdot\mathbf{B}\,dv' - \frac{1}{2}\oint_{S'} (\mathbf{A}\times\mathbf{H})\cdot\mathbf{a}_n\,ds'.$$

$$\mathbf{A} = \frac{\mu_0}{4\pi}\int_{V'} \frac{\mathbf{J}}{R}\,dv' \qquad \text{(Wb/m)}.$$

$$\mathbf{B} = \frac{\mu_0 I}{4\pi}\oint_{C'} \frac{d\boldsymbol{\ell}'\times\mathbf{a}_R}{R^2} \qquad \text{(T)}.$$

$|\mathbf{A}| \sim 1/R$

$|\mathbf{H}| \sim 1/R^2$

$S' \sim R^2$

As $R \to \infty$, 2nd term $\to 0$

$$\boxed{W_m = \frac{1}{2}\int_{V'} \mathbf{H}\cdot\mathbf{B}\,dv' \qquad \text{(J)}.}$$

For linear media

$$\mathbf{H} = \mathbf{B}/\mu,$$

$$\boxed{W_m = \frac{1}{2}\int_{V'} \frac{B^2}{\mu}\,dv' \qquad \text{(J)}}$$

$$\boxed{W_m = \frac{1}{2}\int_{V'} \mu H^2\,dv' \qquad \text{(J)}.}$$

The magnetic energy density

$$W_m = \int_{V'} w_m \, dv',$$

$$w_m = \tfrac{1}{2}\mathbf{H} \cdot \mathbf{B} \qquad (\mathrm{J/m^3})$$

$$w_m = \frac{B^2}{2\mu} \qquad (\mathrm{J/m^3})$$

$$w_m = \tfrac{1}{2}\mu H^2 \qquad (\mathrm{J/m^3}).$$

L can be calculated more easily by W_m formula here than using flux linkage (Λ):

$$W_m = \tfrac{1}{2}LI^2 \qquad (\mathrm{J}). \quad \Rightarrow \quad \boxed{L = \frac{2W_m}{I^2} \qquad (\mathrm{H}).}$$

6-13 Magnetic Forces and Torques

- A magnetic force $\mathbf{F}_m$ on a moving charge q

$$\mathbf{F}_m = q\mathbf{u} \times \mathbf{B} \qquad \text{(N)}.$$

6-13.1 Hall Effect

Applied: **B** and **J**
Results: V_h

$$\boxed{\mathbf{J} = \mathbf{a}_y J_0 = Nq\mathbf{u},}$$

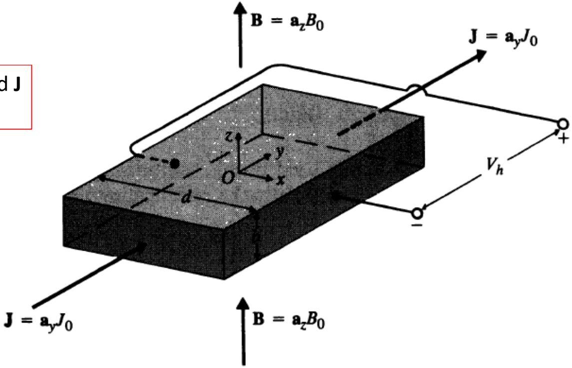
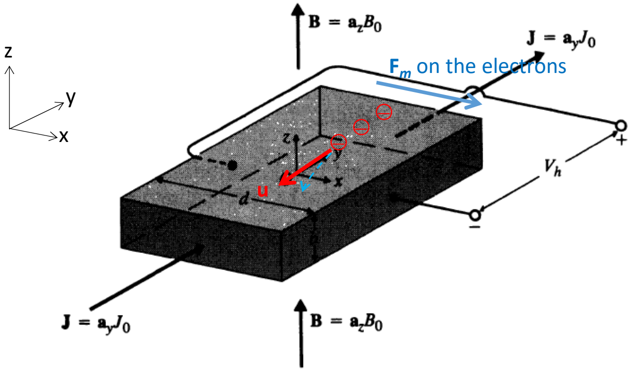


FIGURE 6–28
Illustrating the Hall effect.

From $\mathbf{F}_m = q\mathbf{u} \times \mathbf{B}$ (N). There is a force $\perp$ **u**, $\perp$ **B**

Considering a n-type semiconductor (carriers: electrons): *q* is negative



$$\boxed{\mathbf{F}_m = q\mathbf{u} \times \mathbf{B} \qquad \text{(N)}.}$$

$$\mathbf{F}_m \,//\, -(-\mathbf{a}_y)\times\mathbf{a}_z = \mathbf{a}_x$$

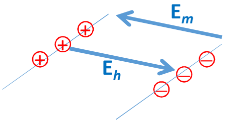
$$\mathbf{E}_m = \mathbf{F}_m/q = \mathbf{u}\times\mathbf{B}$$

$$\mathbf{E}_m \,//\, (-\mathbf{a}_y)\times\mathbf{a}_z = -\mathbf{a}_x$$

For electrons:

$$\mathbf{u} = -\mathbf{a}_y u_0$$

FIGURE 6–28
Illustrating the Hall effect.



$\mathbf{E}_m$: due to moving charge ($\mathbf{u}\times\mathbf{B}$ magnetic force)
$\mathbf{E}_h$: due to charge accumulation

In the steady state, the net force on the charge carriers is zero.

F = q($\mathbf{E}_m$+$\mathbf{E}_h$) = 0

$\mathbf{E}_m$+$\mathbf{E}_h$ = 0

$$\mathbf{E}_h + \mathbf{u} \times \mathbf{B} = 0$$

or $\mathbf{E}_h = -\mathbf{u} \times \mathbf{B}.$

$\mathbf{E}_h$: Hall field

$\boxed{\mathbf{u} = -\mathbf{a}_y u_0}$

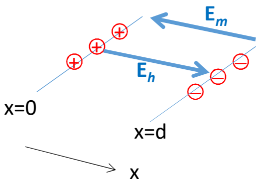
$$\mathbf{E}_h = -(-\mathbf{a}_y u_0) \times \mathbf{a}_z B_0$$
$$= \mathbf{a}_x u_0 B_0.$$

Correction: should be… $\int_d^0 \sim$

$$V_h = -\int_0^d E_h\,dx = u_0 B_0 d,$$

Hall effect can be used to measure the B field

V_h: Hall voltage



$$\boxed{\mathbf{J} = \mathbf{a}_y J_0 = Nq\mathbf{u},}$$

$$\boxed{\begin{aligned}\mathbf{E}_h &= -(-\mathbf{a}_y u_0) \times \mathbf{a}_z B_0 \\ &= \mathbf{a}_x u_0 B_0.\end{aligned}}$$

Scalars only:

E_h/JB

$= E_x/J_yB_z$

$= u_0B_0/(\rho u_0)B_0$

$= 1/\rho$

$$E_x/J_yB_z = \underline{1/Nq}$$

Hall coefficient, a characteristic of the material (ρ)

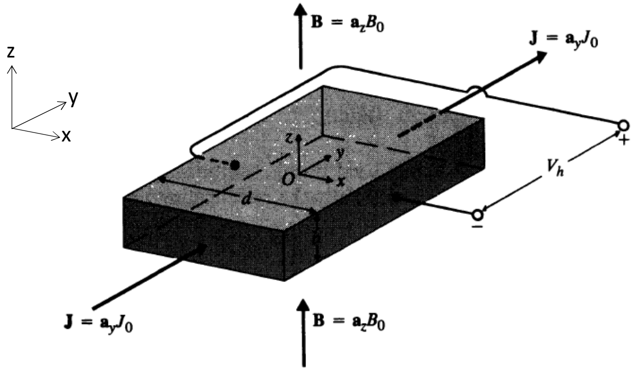


FIGURE 6–28
Illustrating the Hall effect.

- Considering a p-type semiconductor (carriers: + charges): $\mathbf{E}_{h}$ will be reversed, V_h will be in opposite polarity (see Fig. 6-28)
- Hall effect can be used to determine the sign of predominant charge carriers.

6-13.2 Forces and Torques on Current-Carrying Conductors

Magnetic force

dQ

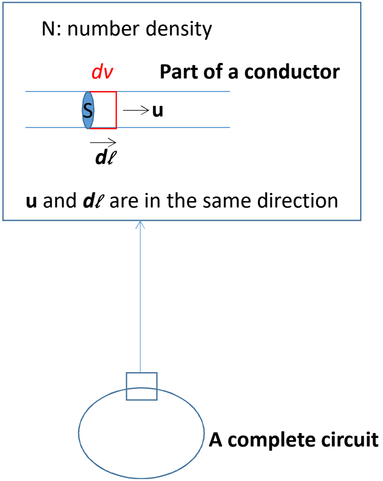
$$
\begin{aligned}
d\mathbf{F}_m &= -NeS|d\boldsymbol{\ell}|\mathbf{u} \times \mathbf{B} \\
&= -NeS|\mathbf{u}|\, d\boldsymbol{\ell} \times \mathbf{B},
\end{aligned}
$$

$= JS = I \qquad (J = -Ne|\mathbf{u}|)$

$$\boxed{d\mathbf{F}_m = I\, d\boldsymbol{\ell} \times \mathbf{B} \quad \text{(N)}.}$$

For a complete circuit

$$\boxed{\mathbf{F}_m = I \oint_C d\boldsymbol{\ell} \times \mathbf{B} \quad \text{(N)}.}$$

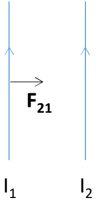


Two Circuits Carrying Currents

$$\mathbf{F}_{21} = I_1 \oint_{C_1} d\boldsymbol{\ell}_1 \times \mathbf{B}_{21},$$

Force $\mathbf{F}_{21}$ on circuit C_1

$\mathbf{B}$ from I_2 on circuit 1



Biot-Savart law (source: 2)

$$\mathbf{B}_{21} = \frac{\mu_0 I_2}{4\pi} \oint_{C_2} \frac{d\boldsymbol{\ell}_2 \times \mathbf{a}_{R_{21}}}{R_{21}^2}.$$

$\mathbf{a}_{R21}$: from 2 (source) to 1 (field)

The Ampere's law of force

$$\boxed{\mathbf{F}_{21} = \frac{\mu_0}{4\pi} I_1 I_2 \oint_{C_1} \oint_{C_2} \frac{d\boldsymbol{\ell}_1 \times (d\boldsymbol{\ell}_2 \times \mathbf{a}_{R_{21}})}{R_{21}^2} \quad \text{(N)},}$$

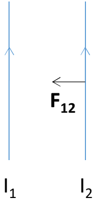
Comparison with Coulomb's law:

$$\mathbf{F}_{12} = \mathbf{a}_R \frac{q_1 q_2}{4\pi\epsilon_0 R^2}$$

$$\boxed{\mathbf{F}_{21} = \frac{\mu_0}{4\pi} I_1 I_2 \oint_{C_1} \oint_{C_2} \frac{d\boldsymbol{\ell}_1 \times (d\boldsymbol{\ell}_2 \times \mathbf{a}_{R_{21}})}{R_{21}^2} \quad \text{(N)},}$$

Interchanging subscript 1 and 2

$$\mathbf{F}_{12} = \frac{\mu_0}{4\pi} I_2 I_1 \oint_{C_2} \oint_{C_1} \frac{d\boldsymbol{\ell}_2 \times (d\boldsymbol{\ell}_1 \times \mathbf{a}_{R_{12}})}{R_{12}^2}.$$



<Proof> Newton's third law in this case

First, $d\boldsymbol{\ell}_2 \times (d\boldsymbol{\ell}_1 \times \mathbf{a}_{R_{12}}) \neq -d\boldsymbol{\ell}_1 \times (d\boldsymbol{\ell}_2 \times \mathbf{a}_{R_{21}})$,

So we need to check if $F_{12} = -F_{21}$!?

Expand the left side by back-cab rule:

$$\frac{d\boldsymbol{\ell}_1 \times (d\boldsymbol{\ell}_2 \times \mathbf{a}_{R_{21}})}{R_{21}^2} = \frac{d\boldsymbol{\ell}_2 (d\boldsymbol{\ell}_1 \cdot \mathbf{a}_{R_{21}})}{R_{21}^2} - \frac{\mathbf{a}_{R_{21}} (d\boldsymbol{\ell}_1 \cdot d\boldsymbol{\ell}_2)}{R_{21}^2}.$$

$$\frac{d\boldsymbol{\ell}_1 \times (d\boldsymbol{\ell}_2 \times \mathbf{a}_{R_{21}})}{R_{21}^2} = \underline{\frac{d\boldsymbol{\ell}_2(d\boldsymbol{\ell}_1 \cdot \mathbf{a}_{R_{21}})}{R_{21}^2}} - \frac{\mathbf{a}_{R_{21}}(d\boldsymbol{\ell}_1 \cdot d\boldsymbol{\ell}_2)}{R_{21}^2}.$$

Double closed line integration

$$\boxed{\boldsymbol{\nabla}_1(1/R_{21}) = -\mathbf{a}_{R_{21}}/R_{21}^2.}$$

$$\begin{aligned}\oint_{C_1}\oint_{C_2} \frac{d\boldsymbol{\ell}_2(d\boldsymbol{\ell}_1 \cdot \mathbf{a}_{R_{21}})}{R_{21}^2} &= \oint_{C_2} d\boldsymbol{\ell}_2 \oint_{C_1} \frac{d\boldsymbol{\ell}_1 \cdot \mathbf{a}_{R_{21}}}{R_{21}^2} \\ &= \oint_{C_2} d\boldsymbol{\ell}_2 \oint_{C_1} d\boldsymbol{\ell}_1 \cdot \left(-\boldsymbol{\nabla}_1 \frac{1}{R_{21}}\right) \\ &= -\oint_{C_2} d\boldsymbol{\ell}_2 \underbrace{\oint_{C_1} d\left(\frac{1}{R_{21}}\right)}_{=0} = 0.\end{aligned}$$

Thus,

$$\boxed{\mathbf{F}_{21} = \frac{\mu_0}{4\pi} I_1 I_2 \oint_{C_1}\oint_{C_2} \frac{d\boldsymbol{\ell}_1 \times (d\boldsymbol{\ell}_2 \times \mathbf{a}_{R_{21}})}{R_{21}^2}}$$

$$\mathbf{F}_{21} = -\frac{\mu_0}{4\pi} I_1 I_2 \oint_{C_1}\oint_{C_2} \frac{\mathbf{a}_{R_{21}}(d\boldsymbol{\ell}_1 \cdot d\boldsymbol{\ell}_2)}{R_{21}^2},$$

Interchanging subscript 1 and 2

$$\xrightarrow[\mathbf{a}_{R_{12}} = -\mathbf{a}_{R_{21}}]{} \quad \mathbf{F}_{21} = -\mathbf{F}_{12}$$

A Circular Circuit Carrying Currents

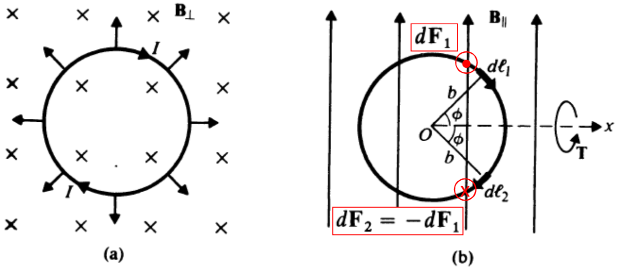
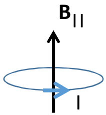
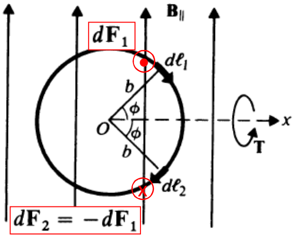


FIGURE 6–30
A circular loop in a uniform magnetic field $\mathbf{B} = \mathbf{B}_\perp + \mathbf{B}_{\parallel}$.

(a) $\mathbf{B}_\perp$ ➔ $\mathbf{F}_m$ tends to expand the loop
(b) $\mathbf{B}_{//}$ ➔ $\mathbf{F}_m$ tends to rotates the loop about *x* axis
(or, tends to align the $\mathbf{B}_I$ (due to ***I***) with $\mathbf{B}_{||}$)





The torque by d$\mathbf{F_1}$ and d$\mathbf{F_2}$

$$dF = |d\mathbf{F}_1| = |d\mathbf{F}_2|$$

$$d\ell = |d\ell_1| = |d\ell_2| = b\,d\phi.$$

Torque due to $d\ell_1$ and $d\ell_2$

arm

$$d\mathbf{T} = \mathbf{a}_x(dF)2b\sin\phi$$

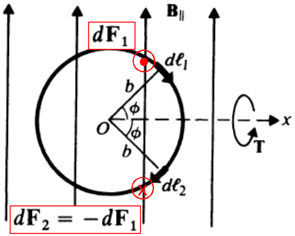
dF = $Id\ell \times B_{||}$

$$= \mathbf{a}_x(I\,d\ell\,B_{||}\sin\phi)2b\sin\phi$$

$$= \mathbf{a}_x 2Ib^2 B_{||}\sin^2\phi\,d\phi,$$

$$\mathbf{T} = \int d\mathbf{T} = \mathbf{a}_x 2Ib^2 B_{||}\int_0^{\pi}\sin^2\phi\,d\phi$$

$$= \mathbf{a}_x I(\pi b^2)B_{||}.$$



$$\mathbf{T} = \int d\mathbf{T} = \mathbf{a}_x 2Ib^2 B_{||} \int_0^{\pi} \sin^2\phi \, d\phi$$
$$= \mathbf{a}_x I(\pi b^2) B_{||}.$$

By definition of magnetic dipole moment **m**

$$\boxed{\mathbf{m} = \mathbf{a}_n I(\pi b^2) = \mathbf{a}_n IS,}$$

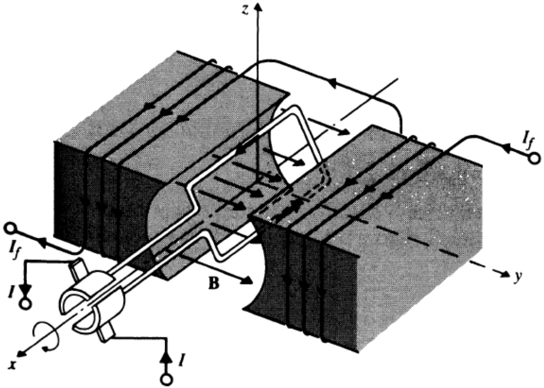
$$\mathbf{m} \times (\mathbf{B}_{\perp} + \mathbf{B}_{||}) = \mathbf{m} \times \mathbf{B}_{||}.$$

$$\boxed{\mathbf{T} = \mathbf{m} \times \mathbf{B} \qquad (\mathrm{N \cdot m}).}$$

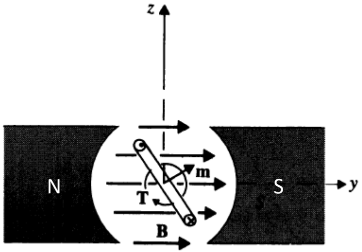
holds also for a planar loop of any shape under a uniform **B**

Microscopically, an applied $\mathbf{B}_{ext}$
➔ **T** to align magnetic dipoles **m** along $\mathbf{B}_{ext}$ in magnetic materials
➔ magnetization in the material

DC Motor



(a) Perspective view.

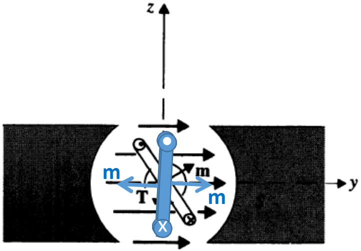


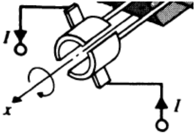
$$\mathbf{m} = \mathbf{a}_n I(\pi b^2) = \mathbf{a}_n IS,$$

$$\boxed{\mathbf{T} = \mathbf{m} \times \mathbf{B} \qquad (\mathrm{N \cdot m}).}$$

(b) Schematic view from $+x$ direction.

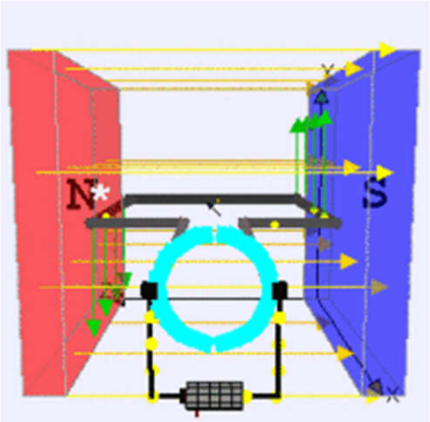
FIGURE 6–32
Illustrating the principle of operation of d-c motor.





When **m** // **B**, a split ring with brushes is used to reverse the direction of currents

➔ **T** always in the same direction (clockwise here)



Yellow: **B**
Green: force, **F**

When **m** $\perp$ **B**, |T| max
When **m** // **B**, the direction of currents reverses

6-13.4 Forces and Torques in Terms of Mutual Inductance

- All current-carrying conductors and circuits experience $\mathbf{F}_m$ when situated in a magnetic field.
- In general, determination of $\mathbf{F}_m$ is tedious by Ampere's law of force (except for special symmetrical cases).

$$\boxed{\mathbf{F}_{21} = \frac{\mu_0}{4\pi} I_1 I_2 \oint_{C_1} \oint_{C_2} \frac{d\boldsymbol{\ell}_1 \times (d\boldsymbol{\ell}_2 \times \mathbf{a}_{R_{21}})}{R_{21}^2} \quad \text{(N)},}$$

Ampere's law of force

- Alternative method: principle of virtual displacement

Case 1: System of Circuits with **Constant Flux Linkages**

Assume a virtual differential displacement $d\ell$

Assume **Constant Flux Linkages**

➔ $\Delta\Phi = 0$

➔ emf = $d\Phi/dt = 0$

The source supplies no energy to the system

The mechanical work done by the system

$\mathbf{F}_{\Phi} \cdot d\boldsymbol{\ell}$,

0 from emf → system → Mechanical work, dW

system → Stored magnetic energy, dW_m

$dW + dW_m = 0$

The mechanical work (increase) is provided by the stored magnetic energy (decrease, $dW_m<0$)

$$\mathbf{F}_{\Phi} \cdot d\boldsymbol{\ell} = -dW_m = -(\nabla W_m) \cdot d\boldsymbol{\ell},$$

$$\mathbf{F}_{\Phi} \cdot d\boldsymbol{\ell} = -dW_m = -(\nabla W_m) \cdot d\boldsymbol{\ell},$$

$$\boxed{\mathbf{F}_{\Phi} = -\nabla W_m \qquad \text{(N)}.}$$

In Cartesian coordinates,

$$(F_{\Phi})_x = -\frac{\partial W_m}{\partial x},$$

$$(F_{\Phi})_y = -\frac{\partial W_m}{\partial y},$$

$$(F_{\Phi})_z = -\frac{\partial W_m}{\partial z}.$$

For the case with a virtual rotation $d\phi$ about an axis (say z axis)

$$\boxed{(T_{\Phi})_z = -\frac{\partial W_m}{\partial \phi} \qquad (\mathrm{N \cdot m}),}$$

Case 2: System of Circuits with **Constant Currents**

Assume a virtual differential displacement $d\ell$

$d\ell \rightarrow d\Phi$

$$dW_s = \sum_k I_k \, d\Phi_k .$$

The source supplies energy to the system

dW_s from I_k → system

→ Mechanical work, dW

→ Stored magnetic energy, dW_m

$dW_s = dW + dW_m$

The mechanical work (increase) and the stored magnetic energy (increase, $dW_m>0$) are provided by dW_s

$$dW_s = dW + dW_m.$$

$$\boxed{W_m = \frac{1}{2}\sum_{k=1}^{N} I_k\Phi_k \qquad \text{(J)},}$$

$$\boxed{dW_s = \sum_k I_k\, d\Phi_k.}$$

$$dW_m = \frac{1}{2}\sum_k I_k\, d\Phi_k = \frac{1}{2}\, dW_s.$$

$$dW = \mathbf{F}_I \cdot d\ell = dW_m$$
$$= (\nabla W_m) \cdot d\ell$$

$$\boxed{\mathbf{F}_I = \nabla W_m \qquad \text{(N)},}$$

Similar to case 1 except for a sign change

For the case with a virtual rotation $d\phi$ about an axis (say z axis)

$$\boxed{(T_I)_z = \frac{\partial W_m}{\partial \phi} \qquad (\text{N}\cdot\text{m}).}$$

- Method of virtual displacement ($d\ell$) for constant currents is powerful to determine the **F** and **T** between rigid-carrying circuits.
- The magnetic energy of two circuits with currents I_1 and I_2:

$$W_m = \tfrac{1}{2}L_1 I_1^2 + L_{12} I_1 I_2 + \tfrac{1}{2} L_2 I_2^2.$$

$$\boxed{\mathbf{F}_I = \nabla W_m \qquad \text{(N)},} \qquad \boxed{(T_I)_z = \frac{\partial W_m}{\partial \phi} \qquad \text{(N·m)}.}$$

$$\boxed{\mathbf{F}_I = I_1 I_2 (\nabla L_{12}) \qquad \text{(N)}.} \qquad \boxed{(T_I)_z = I_1 I_2 \frac{\partial L_{12}}{\partial \phi} \qquad \text{(N·m)}.}$$

Given a virtual displacement $d\ell$:
L_1 and L_2 (self inductance) remain constants
L_{12} changes

EXAMPLE 6–24 Determine the force between two coaxial circular coils of radii b_1 and b_2 separated by a distance d that is much larger than the radii ($d \gg b_1, b_2$). The coils consist of N_1 and N_2 closely wound turns and carry currents I_1 and I_2, respectively.

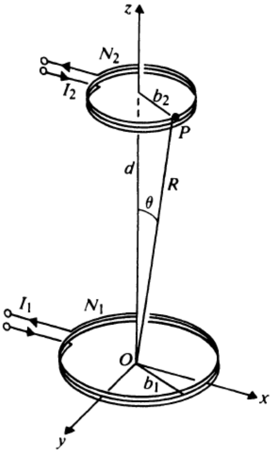


FIGURE 6–34
Coaxial current-carrying circular loops (Example 6–24).