1. Currents circulate in a piece of metal that is pulled through a magnetic field. What are these currents called?

A. Induced currents
B. Displacement currents
C. Faraday’s currents
D. Eddy currents
E. This topic is not covered in Chapter 34.

2. Electromagnetic induction was discovered by

A. Faraday.
B. Henry.
C. Maxwell.
D. Both Faraday and Henry.
E. All three.
3. The direction that an induced current flows in a circuit is given by

A. Faraday’s law.
B. Lenz’s law.
C. Henry’s law.
D. Hertz’s law.
E. Maxwell’s law.
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E. Maxwell’s law.
Tactics: Evaluating line integrals

\begin{enumerate}
\item If \( \vec{B} \) is everywhere perpendicular to a line, the line integral of \( \vec{B} \) is
\[ \int_{i}^{f} \vec{B} \cdot d\vec{s} = 0 \]
\item If \( \vec{B} \) is everywhere tangent to a line of length \( l \) and has the same magnitude \( B \) at every point, then
\[ \int_{i}^{f} \vec{B} \cdot d\vec{s} = Bl \]
\end{enumerate}
Ampère’s law

Whenever total current $I_{\text{through}}$ passes through an area bounded by a *closed curve*, the line integral of the magnetic field around the curve is given by Ampère’s law:

$$\oint \mathbf{B} \cdot d\mathbf{s} = \mu_0 I_{\text{through}}$$

*FIGURE 33.24 Using Ampère’s law.*
The strength of the uniform magnetic field inside a solenoid is

\[ B_{\text{solenoid}} = \frac{\mu_0 NI}{l} = \mu_0 nI \]

where \( n = N/l \) is the number of turns per unit length.
FIGURE 33.43 Magnetic force on a current-carrying wire.

There's no force on a current parallel to a magnetic field. A current perpendicular to the field experiences a force in the direction of the right-hand rule.
General Principles

Magnetic Fields

The Biot-Savart law

- A point charge, \( \mathbf{B} = \frac{\mu_0}{4\pi} \frac{q\mathbf{v} \times \mathbf{\hat{r}}}{r^2} \)

- A short current element, \( \mathbf{B} = \frac{\mu_0}{4\pi} \frac{I\Delta s \times \mathbf{\hat{r}}}{r^2} \)

To find the magnetic field of a current

- Divide the wire into many short segments.
- Find the field of each segment \( \Delta s \).
- Find \( \mathbf{B} \) by summing the fields of all \( \Delta s \), usually as an integral.

An alternative method for fields with a high degree of symmetry is Ampère’s law:

\[ \oint \mathbf{B} \cdot d\mathbf{s} = \mu_0 I_{\text{through}} \]

where \( I_{\text{through}} \) is the current through the area bounded by the integration path.
General Principles

**Magnetic Forces**

The magnetic force on a moving charge is

\[ \vec{F} = q \vec{v} \times \vec{B} \]

The force is perpendicular to \( \vec{v} \) and \( \vec{B} \).

The magnetic force on a current-carrying wire is

\[ \vec{F} = I \vec{l} \times \vec{B} \]

\( \vec{F} = 0 \) for a charge or current moving parallel to \( \vec{B} \).

The magnetic torque on a magnetic dipole is

\[ \vec{\tau} = \vec{\mu} \times \vec{B} \]
Applications

**Wire**

\[ B = \frac{\mu_0}{2\pi} \frac{I}{d} \]

**Solenoid**

\[ B = \frac{\mu_0 NI}{l} \]

**Loop**

**Flat magnet**

---

**Right-hand rule**

Point your right thumb in the direction of \( I \). Your fingers curl in the direction of \( \vec{B} \). For a dipole, \( \vec{B} \) emerges from the side that is the north pole.
Charged-particle motion

No force if $\vec{v}$ is parallel to $\vec{B}$.

Circular motion at the cyclotron frequency $f_{\text{cyc}} = \frac{qB}{2\pi m}$ if $\vec{v}$ is perpendicular to $\vec{B}$. 
Applications

Parallel wires and current loops

Parallel currents attract.
Opposite currents repel.
Faraday’s Discovery

Faraday found that there is a current in a coil of wire if and only if the magnetic field passing through the coil is changing. This is an informal statement of Faraday’s law.
Electromagnetic Induction

- If electric currents produce magnetic fields, can magnetic fields produce electric currents?
- Yes!
- Discovered independently by
  - Joseph Henry (American)
  - Michael Faraday (English)
Joseph Henry

- Lived from 1797 to 1878
- Premier American scientist after Ben Franklin
- Albany native
- Attended & then taught at Albany Academy
  - conducted experiments in his spare time!
- Invited to Princeton and stayed there
  - now endowed chair of physics department
  - Joseph Henry Laboratories
- First Secretary of the Smithsonian Institute
- One of first members of National Academy of Science
Faraday observed deflection when switched was opened and closed
d• changing B field induces current
Induced EMF

(a) Magnet moves up toward coil (\(\mathbf{B}\) in coil increasing)

(b) Magnet moves down (\(\mathbf{B}\) in coil decreasing)

(c) No movement (\(\mathbf{B}\) in coil constant)

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Faraday’s Law of Induction

- The induced emf depends on the
  - area of loop
  - how fast B field is changing
- \( \Phi_B \) = change in magnetic flux

\[
Emf = -\frac{\Delta \Phi_B}{\Delta t}
\]

where

\[
\Phi_B = B \perp A = BA \cos \theta
\]
Faraday’s Law of Induction

- If circuit contains N closely wrapped loops:

\[ Emf = -N \frac{\Delta \Phi_B}{\Delta t} \]

- Can induce emf by changing
  - B field
  - area of loop
  - loop’s orientation with respect to B field
Plug & Chug

• A 12.0-cm-diameter loop of wire is initially oriented perpendicular to a 1.5-T magnetic field. The loop is rotated so that its plane is parallel to the field direction is 0.20 s. What is the average induced emf in the loop?
Lenz’s Law

- A current produced by an induced emf moves in a direction so that its magnetic field opposes the original direction of change
- Test yourself:

(a) Pulling the loop to the right out of a magnetic field which points out of the page
(b) Shrinking a loop in a magnetic field pointing into the page
(c) N magnetic pole moving toward loop into the page
(d) N magnetic pole moving toward the loop in the plane of the page
(e) Rotating the loop by pulling the left side toward us and pushing the right side in: the magnetic field points from right to left
More practice

- What is the direction of the induced current in the circular loop due to the current in the wire?
Problem

- The rectangular loop shown is pushed into the magnetic field which points inward. In what direction is the induced current?
EMF Induced in a Moving Conductor

- Area inside loop is increasing as rod moves to right
  \[
  \Delta x = v \Delta t
  \]
  \[
  \Delta A = l \Delta x
  \]
  \[
  Emf = \frac{\Delta \Phi_B}{\Delta t} = \frac{B \Delta A}{\Delta t} = \frac{Blv\Delta t}{\Delta t}
  \]
  \[
  Emf = Blv
  \]
- A changing B field induces an electric field \((E = F/q)\)

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Electric Generators

\[ \text{Emf} = NBwAsin\omega t \]
Plug & Chug

- A simple generator is used to generate a peak output voltage of 24.0 V. The square armature consists of windings that are 6.0 cm on a side and rotates in a field of 0.420 T at a rates of 60.0 rev/s. How many loops of wire should be wound on the square armature?
Transformers

- $\Delta B/\Delta t$ in primary induces $V_S$ in secondary coil
- Works for AC only
  - DC voltages don’t have changing B field
Transformers

- Step-Up Transformer
  - $V_S > V_P$
- Step-Down Transformer
  - $V_S < V_P$
- Conservation of energy requires
  - $P_P = P_S$
  - $I_P V_P = I_S V_S$

\[
\frac{I_S}{I_P} = \frac{N_P}{N_S}
\]
Plug & Chug

A transformer has 320 turns in the primary coil and 120 in the secondary coil. What kind of transformer is this, and by what factor does it change the voltage? By what factor does it change the current?
Self-Inductance

- changing current passes through a coil
  - produces changing B flux
    - which induces an emf
- Induced emf opposes change in flux

\[ Emf = -L \frac{\Delta I}{\Delta t} \]

inductance (H)
Think-Pair-Share

- If the current in a 180-mH coil changes steadily from 25.0 A to 10.0 A in 350 ms, what is the magnitude of the induced emf?
More Practice Problems

- Magnetism: Worksheets 4 & 5