Chapter 34. Electromagnetic Induction

Electromagnetic induction is the scientific principle that underlies many modern technologies, from the generation of electricity to communications and data storage.

**Chapter Goal:** To understand and apply electromagnetic induction.
Chapter 34. Electromagnetic Induction

Topics:
• Induced Currents
• Motional emf
• Magnetic Flux
• Lenz’s Law
• Faraday’s Law
• Induced Fields
Chapter 34. Reading Quizzes
Electromagnetic induction was discovered by

A. Faraday.
B. Henry.
C. Maxwell.
D. Both Faraday and Henry.
E. All three.
Electromagnetic induction was discovered by

A. Faraday.
B. Henry.
C. Maxwell.
D. Both Faraday and Henry.
E. All three.

Correct answer: D. Both Faraday and Henry.
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.
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.
Chapter 34. Basic Content and Examples
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.*
**FIGURE 34.3** Two different ways to generate an emf.

(a) Magnetic forces separate the charges and cause a potential difference between the ends. This is a motional emf.

\[ \Delta V = v t B \]

Electric field inside the moving conductor
There are a number of ways a magnetic field can be used to generate an electric current.

It is the changing field that produces the current.
An emf can be induced by changing the area of a coil in a constant magnetic field.

In each example, both an emf and a current are induced because the coil is part of a complete circuit. If the circuit were open, there would be no induced current, but there would be an induced emf.

The phenomena of producing an induced emf with the aid of a magnetic field is called *electromagnetic induction.*
Each charge within the conductor is moving and experiences a magnetic force

\[ F = qvB \]

The separated charges on the ends of the conductor give rise to an induced emf, called a \textit{motional emf}.
Motional emf when $v$, $B$, and $L$ are mutually perpendicular

$$E = vBL$$
Motional emf

The motional emf of a conductor of length $l$ moving with velocity $v$ perpendicular to a magnetic field $B$ is

$$\mathcal{E} = vlB$$
EXAMPLE 34.1 Measuring the earth’s magnetic field

QUESTION:

It is known that the earth’s magnetic field over northern Canada points straight down. The crew of a Boeing 747 aircraft flying at 260 m/s over northern Canada finds a 0.95 V potential difference between the wing tips. The wing span of a Boeing 747 is 65 m. What is the magnetic field strength there?
EXAMPLE 34.1 Measuring the earth’s magnetic field

**MODEL** The wing is a conductor moving through a magnetic field, so there is a motional emf.
EXAMPLE 34.1 Measuring the earth’s magnetic field

**SOLVE** The magnetic field is perpendicular to the velocity, so we can use Equation 34.3 to find

\[
B = \frac{\mathcal{E}}{vL} = \frac{0.95 \text{ V}}{(260 \text{ m/s})(65 \text{ m})} = 5.6 \times 10^{-5} \text{ T}
\]
Magnetic flux can be defined in terms of an area vector

The magnetic flux through the loop is
\[ \Phi_m = \vec{A} \cdot \vec{B}. \]

The angle \( \theta \) between \( \vec{A} \) and \( \vec{B} \) is the angle at which the loop has been tilted.
Magnetic Flux

\[ \Phi_m = A_{\text{eff}}B = AB \cos \theta \]

The magnetic flux measures the amount of magnetic field passing through a loop of area \(A\) if the loop is tilted at an angle \(\theta\) from the field, \(B\). As a dot-product, the equation becomes:

\[ \Phi_m = \vec{A} \cdot \vec{B} \]
There is an induced current in a closed, conducting loop if and only if the magnetic flux through the loop is changing. The direction of the induced current is such that the induced magnetic field opposes the change in the flux.
FIGURE 34.20 The induced current is ccw.

2. The loop needs to generate an upward-pointing magnetic field to oppose the change in flux.

1. The flux through the loop increases downward as the magnet approaches.

3. By the right-hand rule, a ccw current is needed to induce an upward-pointing magnetic field.
FIGURE 34.21 Pulling the magnet away induces a cw current.

(a)

The bar magnet is moving away from the loop.
The Emf Produced by a Moving Copper Ring.

There is a constant magnetic field directed into the page in the shaded region. The field is zero outside the shaded region. A copper ring slides through the region.

For each of the five positions, determine whether an induced current exists and, if so, find its direction.
Tactics: Using Lenz’s Law

TACTICS BOX 34.1 Using Lenz’s law

1. **Determine the direction of the applied magnetic field.** The field must pass through the loop.
2. **Determine how the flux is changing.** Is it increasing, decreasing, or staying the same?
3. **Determine the direction of an induced magnetic field that will oppose the change in the flux.**
   - Increasing flux: the induced magnetic field points opposite the applied magnetic field.
   - Decreasing flux: the induced magnetic field points in the same direction as the applied magnetic field.
   - Steady flux: there is no induced magnetic field.
4. **Determine the direction of the induced current.** Use the right-hand rule to determine the current direction in the loop that generates the induced magnetic field you found in step 3.

Exercises 10–14

Copyright © 2008 Pearson Education, Inc., publishing as Pearson Addison-Wesley.
Faraday’s Law

An emf is induced in a conducting loop if the magnetic flux through the loop changes. The magnitude of the emf is

$$\mathcal{E} = \left| \frac{d\Phi_m}{dt} \right|$$

and the direction of the emf is such as to drive an induced current in the direction given by Lenz’s law.
## Problem-Solving Strategy: Electromagnetic Induction

<table>
<thead>
<tr>
<th>PROBLEM-SOLVING STRATEGY 34.1</th>
<th>Electromagnetic induction</th>
</tr>
</thead>
</table>

**MODEL**  Make simplifying assumptions about wires and magnetic fields.

**VISUALIZE**  Draw a picture or a circuit diagram. Use Lenz’s law to determine the direction of the induced current.

**SOLVE**  The mathematical representation is based on Faraday’s law

\[ \mathcal{E} = \left| \frac{d\Phi_m}{dt} \right| \]

For an \( N \)-turn coil, multiply by \( N \). The size of the induced current is \( I = \mathcal{E}/R \).

**ASSESS**  Check that your result has the correct units, is reasonable, and answers the question.
Electromagnetic Waves

**Figure 34.35** Maxwell hypothesized the existence of induced magnetic fields.

A changing magnetic field creates an induced electric field.

A changing electric field creates an induced magnetic field.

**Figure 34.36** A self-sustaining electromagnetic wave.

Direction of propagation at speed $v_{em\ wave}$.
A transformer is a device for increasing or decreasing an ac voltage.

\[ E_s = -N_s \frac{\Delta \Phi}{\Delta t} \]

\[ E_p = -N_p \frac{\Delta \Phi}{\Delta t} \]

\[ \frac{E_s}{E_p} = \frac{N_s}{N_p} \]
A transformer that steps up the voltage simultaneously steps down the current, and a transformer that steps down the voltage steps up the current.
Chapter 34. Summary Slides
General Principles

Faraday’s Law

MODEL Make simplifying assumptions.

VISUALIZE Use Lenz’s law to determine the direction of the induced current.

SOLVE The induced emf is

\[ \mathcal{E} = \left| \frac{d\Phi_m}{dt} \right| \]

Multiply by \( N \) for an \( N \)-turn coil.
The size of the induced current is \( I = \mathcal{E}/R \).

ASSESS Is the result reasonable?
General Principles

Lenz’s Law

There is an induced current in a closed conducting loop if and only if the magnetic flux through the loop is changing. The direction of the induced current is such that the induced magnetic field opposes the change in the flux.
General Principles

Magnetic flux

Magnetic flux measures the amount of magnetic field passing through a surface.

\[ \Phi_m = \vec{A} \cdot \vec{B} = AB \cos \theta \]
Important Concepts

Three ways to change the flux

1. A loop moves into or out of a magnetic field.

2. The loop changes area or rotates.

3. The magnetic field through the loop increases or decreases.
Important Concepts

Two ways to create an induced current

1. A **motional emf** due to magnetic forces on moving charge carriers.

2. An induced electric field due to a changing magnetic field.
Chapter 34. Questions
Is there an induced current in this circuit? If so, what is its direction?

A. No
B. Yes, clockwise
C. Yes, counterclockwise
Is there an induced current in this circuit? If so, what is its direction?

A. No
B. Yes, clockwise
C. Yes, counterclockwise
A square loop of copper wire is pulled through a region of magnetic field. Rank in order, from strongest to weakest, the pulling forces $F_a$, $F_b$, $F_c$ and $F_d$ that must be applied to keep the loop moving at constant speed.

A. $F_b = F_d > F_a = F_c$
B. $F_c > F_b = F_d > F_a$
C. $F_c > F_d > F_b > F_a$
D. $F_d > F_b > F_a = F_c$
E. $F_d > F_c > F_b > F_a$
A square loop of copper wire is pulled through a region of magnetic field. Rank in order, from strongest to weakest, the pulling forces $F_a, F_b, F_c$ and $F_d$ that must be applied to keep the loop moving at constant speed.

A. $F_b = F_d > F_a = F_c$
B. $F_c > F_b = F_d > F_a$
C. $F_c > F_d > F_b > F_a$
D. $F_d > F_b > F_a = F_c$
E. $F_d > F_c > F_b > F_a$
A current-carrying wire is pulled away from a conducting loop in the direction shown. As the wire is moving, is there a cw current around the loop, a ccw current or no current?

A. There is no current around the loop.
B. There is a clockwise current around the loop.
C. There is a counterclockwise current around the loop.
A current-carrying wire is pulled away from a conducting loop in the direction shown. As the wire is moving, is there a cw current around the loop, a ccw current or no current?

A. There is no current around the loop.

B. There is a clockwise current around the loop.

C. There is a counterclockwise current around the loop.