Announcements

This week:

• Lecture Wednesday April 3:
  • Review of Chapters 25-28

• Homework 7 due Thursday April 4:
  • Chapter 28

• Recitation on Friday April 5
  • Quiz on HW 7 and Lectures 15+16
  • Review for Exam 2 on Monday, April 8

Second mid-term exam

• Monday, April 8, 2019 in lecture: 5:15-6:10 pm
• 12 multiple choice questions from Chapters 25-28, inclusive
  All exams are closed-book, no calculators or other electronic devices allowed.
Chapter 28 Summary

- Calculating magnetic fields
  - Single moving charged particle
  - Current-carrying wire bent into a circle

- Forces between current carrying wires
  - Attract: parallel
  - Repel: anti-parallel

- Ampere’s Law & calculating B fields
  - Current-carrying wire
    \[ B(r)_{\text{line}} = \frac{\mu_0 I}{2\pi r} \]
  - Other examples page 946
  - Solenoid (inside)
    \[ B_{\text{solenoid}} = \mu_0 nI \]
  - Toroid (inside)
    \[ B_{\text{toroid}} = \frac{NI}{2\pi r} \]

- Magnetic materials
  - Bohr magneton – \( \mu_B = \frac{e\hbar}{2m} \)
    size of magnetic moment of electron in (Bohr) atom
  - Ferromagnetism \((B>>B_0)\), paramagnetism \((B>B_0)\), diamagnetism \((B<B_0)\)
Chap 29: Electromagnetic Induction

Monday April 1, 2019
Chapter 29: Electromagnetic induction

- How a change in magnetic flux through a loop induces an emf in the loop (Faraday’s law).
- How to determine the direction of an induced emf (Lenz’s Law).
- How a changing magnetic flux generates a circulating electric field.
Induction demo: what we were observing

- When move magnet toward coil
  - Current in the coil, only while magnet is moving.
- When move magnet away from coil
  - Current in the coil, only while magnet is moving.

- Induced current
- Induced emf required to cause this current
Given: surface with magnetic field going through it

\[ d\Phi_B = \vec{B} \cdot d\vec{A} \]

Magnetic flux through a surface area element
Direction of area vector = outside of the surface
\[ \Phi_B = BA \cos \theta = \vec{B} \cdot \vec{A} \]

I clicker question

Which statement is TRUE about magnetic flux?

A. Flux of (a) = BA; Flux of (b) = Zero
B. Flux of (a) = Zero; Flux of (b) = BA
C. Flux of (b) = BA; Flux of (c) = Zero
D. Flux of (b) = Zero; Flux of (c) = BA \cos \theta
E. Magnetic flux through a surface is always zero
Faraday’s law of induction

- When the magnetic flux through a single closed loop changes with time
  - Induced emf that can drive a current around the loop

\[ \mathcal{E} = -\frac{d\Phi_B}{dt} \]

- Units are OK:
  - Flux unit: Weber (Wb) = T-m^2
  - EMF measured in Volt = Wb/s

- If have a coil with N turns:

\[ \mathcal{E} = -N \frac{d\Phi_B}{dt} \]
Faraday’s law of induction

- When the magnetic flux through a single closed loop changes with time
  - Induced emf that can drive a current around the loop

\[ \mathcal{E} = -\frac{d\Phi_B}{dt} \]

- Change in magnetic flux:
  - Change in magnetic field
  - Change in area
  - Change in angle between \( B \) and \( A \)
  - Any combination of these

\[ \Phi_B = \vec{B} \cdot \vec{A} = BA \cos \phi \]
The Lorentz force is given by
\[ F = q(v \times B) \]

Why change in magnetic flux?

Current carrying wire => B field

Now add a square loop of wire

Can induce a current/EMF in the loop if wire is moving

\[
B(r)_{\text{line}} = \frac{\mu_0 I}{2\pi r}
\]
Why change in magnetic flux?

Current carrying wire => B field

Now add a square loop of wire

Can induce a current/EMF in the loop if wire is moving

(a) Loop moving to the left
   ➢ Magnetic field increases

(b) Wire moving to the right
   ➢ Magnetic field increases

(a) and (b): EMF should be the same; only relative motion

\[ B(r)_{\text{line}} = \frac{\mu_0 I}{2\pi r} \]
Why change in magnetic flux?

Current carrying wire => B field

Now add a square loop of wire

Can induce a current/EMF in the loop if wire is moving

(b) Wire moving to the right
   ➢ Magnetic field increases

(c) Increase current in wire vs time
   ➢ Magnetic field increases

(b) and (c): Loop can’t tell if wire is approaching OR if current in wire is increasing

\[ B(r)_{\text{line}} = \frac{\mu_0 I}{2\pi r} \]
Why change in magnetic flux?

Current carrying wire => B field

Now add a square loop of wire

Can induce a current/EMF in the loop if wire is moving

(c) Increase current in wire vs time
   - Magnetic field increases

(d) Increase size of loop vs time
   - Magnetic field increases

\[ B(r)_{\text{line}} = \frac{\mu_0 I}{2\pi r} \]
Why change in magnetic flux?

(a) Loop moving to the left
(b) Wire moving to the right
(c) Increase current in wire vs time
(d) Increase size of loop vs time

Common change: Change in magnetic flux

\[ B(r)_{\text{line}} = \frac{\mu_0 I}{2\pi r} \]
Faraday’s Law

\[ \mathcal{E} = -\frac{d\Phi_B}{dt} \]

Change in magnetic flux through a surface induces an EMF/current

Change in magnetic flux vs time:
- Change in magnetic field
- Change in area/shape of the loop
- Change in angle between B and dA
- Any combination of these

\[ \mathcal{E} = -\frac{d}{dt} \int_{\text{surface}} \vec{B} \cdot d\vec{A} \]
The flux of the magnetic field in the wire loop varies with time as shown in the Figure. Which dependence(s) of $\Phi_B$ vs time correspond(s) to the largest magnitude of the induced current?

A. 1
B. 2 & 3
C. 5
D. 4 & 5
E. 2
Faraday’s Law

\[ \mathcal{E} = -\frac{d}{dt} \Phi_m = -\frac{d}{dt} \int_{\text{surface}} \vec{B} \cdot d\vec{A} \]

Initially: Current carrying loop

- gives rise to \( B \) field
- \( \Phi_m > 0 \)
Faraday’s Law

\[ \mathcal{E} = -\frac{d}{dt} \Phi_m \]

Increase current in loop at constant rate
- \( \Phi_m \) increases or \( \frac{d}{dt} \Phi_m > 0 \)
- Induces EMF
- Induces current in opposite direction

\[ \mathcal{E} = -\frac{d}{dt} \int_B \cdot d\vec{A} \]

\[ d\vec{\ell} \]
\[ d\vec{A} \]
Faraday’s Law

\[ \mathcal{E} = -\frac{d}{dt} \Phi_m \]

Increase current in loop at constant rate
- \( \Phi_m \) increases or \( \frac{d}{dt} \Phi_m > 0 \)

- Induces EMF
- Induces current in opposite direction
- Induces B in opposite direction

\[ \mathcal{E} = -\frac{d}{dt} \int_{\text{surface}} \vec{B} \cdot d\vec{A} \]
Faraday’s Law

\[ \mathcal{E} = -\frac{d}{dt} \Phi_m \]

- Increase current in loop at constant rate
  - \( \Phi_m \) increases or \( \frac{d}{dt} \Phi_m > 0 \)
  - \( \Phi_m \) increases or \( \frac{d}{dt} \Phi_m > 0 \)
- Induces EMF
- Induces current in opposite direction
- Induces B in opposite direction

\[ \mathcal{E} = -\frac{d}{dt} \int \mathbf{B} \cdot d\mathbf{A} \]

**Equation:**

\[ \mathcal{E} = -\frac{d}{dt} \Phi_m \]

**Diagram:**

- \( B_{\text{induced}} \)
- \( d\mathbf{\ell} \)
- \( d\mathbf{A} \)
- \( \Phi_m \)
- \( \frac{d}{dt} \Phi_m \)
- \( \frac{d}{dt} \Phi_m \)
Direction of induced EMF/current: Lenz’s Law

An induced current has a direction such that the magnetic field due to the induced current **opposes the change** in the magnetic flux that induces the current.

\[ E = -\frac{d}{dt} \Phi_m = -\frac{d}{dt} \int_{\text{surface}} \vec{B} \cdot d\vec{A} \]
Direction of induced EMF/current: Lenz’s Law

An induced current has a direction such that the magnetic field due to the induced current **opposes the change** in the magnetic flux that induces the current.

\[ B(r)_{\text{line}} = \frac{\mu_0 I}{2\pi r} \quad \mathcal{E} = -\frac{d\Phi_B}{dt} \]

(a) Loop moving to the left
B increases as r decreases

(b) Wire moving to the right
B increases as r decreases

(c) Change current in wire vs time
B increases as current increases

(d) Changing size of loop vs time
Flux increases as area increases
Lenz’s Law: Better way to state induced current direction

Initially:
- Conducting loop in uniform B field

If B is increasing:
- Change in \( \Phi_m \): 
  \[
  - \frac{d}{dt} \Phi_m = - \frac{d}{dt} \int_B \mathbf{B} \cdot d\mathbf{A} = \mathcal{E}
  \]

- Induces current/EMF
- Induces B in opposite direction

\( \Phi \) Change in \( \mathbf{B} \) (increasing)
Lenz’s Law: Better way to state induced current direction

Initially:
- Conducting loop in uniform B field

If B is increasing:
- Change in $\Phi_m$ 
  $$-\frac{d}{dt}\Phi_m = -\frac{d}{dt} \int \vec{B} \cdot d\vec{A} = \mathcal{E}$$
  - Change in $\vec{B}$
  - (increasing)

- Induces current/EMF
- Induces B in opposite direction
- Induced current/EMF clockwise

Lenz’s Law:
Induced current has direction such that the magnetic field due to the induced current opposes the change in the magnetic flux that induces the current.
Induction demo: what we were observing

- When move magnet toward coil
  - Current in the coil, only while magnet is moving.
  - Increasing $B$ down $\Rightarrow B_{\text{induced}}$ up
  - Induced current counter clockwise
**Induction demo: what we were observing**

- When move magnet up from coil
  - Current in the coil, **only while magnet is moving**.
  - Decreasing B down $\Rightarrow B_{\text{induced}}$ down
  - Induced current clockwise

![Diagram of magnetic fields and induced current](image-url)
A circular loop of wire is placed next to a long straight wire. The current $I$ in the long straight wire is increasing. What current does this induce in the circular loop?

A. a clockwise current
B. a counterclockwise current
C. zero current
D. not enough information given to decide
Faraday’s Law

\[ \mathcal{E} = -\frac{d}{dt} \Phi_m = -\frac{d}{dt} \int_{\text{surface}} \vec{B} \cdot d\vec{A} \]

Induced EMF in a closed loop = - time rate of change of magnetic flux through the loop.

Lenz’s Law

Induced current has direction such that the magnetic field due to the induced current opposes the change in the magnetic flux that induces the current.
Chap 29b: Motional EMF

Wednesday, April 10, 2019