Lecture 15

- Electricity and Magnetism
  - Magnetism
  - Applications of magnetic forces
  - Induced voltages and induction
  - Magnetic flux and induced emf
  - Faraday’s law

http://www.physics.wayne.edu/~apetrovPHY2140/
Lightning Review

Last lecture:

1. Magnetism
   ✓ Charged particle in a magnetic field
   ✓ Ampere’s law and applications

Review Problem: A rectangular loop is placed in a uniform magnetic field with the plane of the loop parallel to the direction of the field. If a current is made to flow through the loop in the sense shown by the arrows, the field exerts on the loop:

   1. a net force.
   2. a net torque.
   3. a net force and a net torque.
   4. neither a net force nor a net torque.
19.10 Magnetic Field of a current loop

Magnetic field produced by a wire can be enhanced by having the wire in a loop.
19.11 Magnetic Field of a solenoid

- Solenoid magnet consists of a wire coil with multiple loops.
- It is often called an electromagnet.
Solenoid Magnet

- Field lines inside a solenoid magnet are parallel, uniformly spaced and close together.
- The field inside is uniform and strong.
- The field outside is non-uniform and much weaker.
- One end of the solenoid acts as a north pole, the other as a south pole.
- For a long and tightly looped solenoid, the field inside has a value:

\[ B = \mu_0 nI \]
Solenoid Magnet

\[ B = \mu_o n I \]

\[ n = \frac{N}{l} \quad : \quad \text{number of (loop) turns per unit length.} \]

\[ I \quad : \quad \text{current in the solenoid.} \]

\[ \mu_o = 4\pi \times 10^{-7} \text{Tm/} \text{A} \]
Example: Magnetic Field inside a Solenoid.

Consider a solenoid consisting of 100 turns of wire and length of 10.0 cm. Find the magnetic field inside when it carries a current of 0.500 A.

\[
N = 100 \\
l = 0.100 \text{ m} \\
I = 0.500 \text{ A} \\
\mu_o = 4\pi \times 10^{-7} \text{Tm/ A}
\]

\[
\frac{N}{l} = \frac{100 \text{ turns}}{0.10 \text{ m}} = 1000 \text{ turns/m}
\]

\[
B = \mu_0 nI = (4\pi \times 10^{-7} \text{Tm/ A}) (1000 \text{ turns/m}) (0.500 \text{ A})
\]

\[
B = 6.28 \times 10^{-4} \text{T}
\]
Comparison: *Electric Field* vs. *Magnetic Field*

<table>
<thead>
<tr>
<th></th>
<th>Electric</th>
<th>Magnetic</th>
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</thead>
<tbody>
<tr>
<td><strong>Source</strong></td>
<td>Charges</td>
<td>Moving Charges</td>
</tr>
<tr>
<td><strong>Acts on</strong></td>
<td>Charges</td>
<td>Moving Charges</td>
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<tr>
<td><strong>Force</strong></td>
<td>$F = Eq$</td>
<td>$F = q v B \sin(\theta)$</td>
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<tr>
<td><strong>Direction</strong></td>
<td>Parallel $E$</td>
<td>Perpendicular to $v, B$</td>
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<tr>
<td><strong>Field Lines</strong></td>
<td><img src="image" alt="Field Lines" /></td>
<td><img src="image" alt="Field Lines" /></td>
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<tr>
<td><strong>Opposites</strong></td>
<td>Charges Attract</td>
<td>Currents Repel</td>
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Chapter 20

Induced EMF and Induction
Introduction

- Previous chapter: electric currents produce magnetic fields (Oersted’s experiments)
- Is the opposite true: can magnetic fields create electric currents?
20.1 Induced EMF and magnetic flux

Definition of Magnetic Flux

Just like in the case of electric flux, consider a situation where the magnetic field is uniform in magnitude and direction. Place a loop in the B-field.

The flux, $\Phi$, is defined as the product of the field magnitude by the area crossed by the field lines.

$$\Phi = B_\perp A = BA \cos \theta$$

where $B_\perp$ is the component of B perpendicular to the loop, $\theta$ is the angle between B and the normal to the loop.

Units: T\cdot m^2 or Webers (Wb)

The value of magnetic flux is proportional to the total number of magnetic field lines passing through the loop.
Problem: determining a flux

A square loop 2.00m on a side is placed in a magnetic field of strength 0.300T. If the field makes an angle of 50.0° with the normal to the plane of the loop, determine the magnetic flux through the loop.
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Solution:

**Given:**

L = 2.00 m  
B = 0.300 T  
θ = 50.0°

**Find:**

Φ = ?

From what we are given, we use

\[ \Phi = BA \cos \theta = (0.300T)(2.00m)^2 \cos 50.0° \]

\[ = 0.386 \, Tm^2 \]
20.1 Induced EMF and magnetic flux

Faraday’s experiment

- Two circuits are not connected: no current?
- However, closing the switch we see that the compass’ needle moves and then goes back to its previous position.
- Nothing happens when the current in the primary coil is steady.
- But same thing happens when the switch is opened, except for the needle going in the opposite direction...

What is going on?
20.2 Faraday’s law of induction

Induced current
A current is set up in the circuit as long as there is relative motion between the magnet and the loop.
Does there have to be motion?

(induced)
Does there have to be motion?
Does there have to be motion?

(induced)
Does there have to be motion?

AC Delco
1 volt
Maybe the B-field needs to change.....
Maybe the B-field needs to change.....
Maybe the B-field needs to change.....
Faraday’s law of magnetic induction

In all of these experiments, induced EMF is caused by a change in the number of field lines through a loop. In other words, the instantaneous EMF induced in a circuit equals the rate of change of magnetic flux through the circuit.

\[ I = N \frac{\Delta \Phi}{\Delta t} \]

Lenz’s law

The number of loops matters

Lenz’s Law: The polarity of the induced emf is such that it produces a current whose magnetic field opposes the change in magnetic flux through the loop. That is, the induced current tends to maintain the original flux through the circuit.
Applications:

- Ground fault interrupter
- Electric guitar
- SIDS monitor
- Metal detector
- ...

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Example : EMF in a loop

A wire loop of radius 0.30m lies so that an external magnetic field of strength +0.30T is perpendicular to the loop. The field changes to -0.20T in 1.5s. (The plus and minus signs here refer to opposite directions through the loop.) Find the magnitude of the average induced emf in the loop during this time.
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**Given:**
- \( r = 0.30 \text{ m} \)
- \( B_i = 0.30 \text{ T} \)
- \( B_f = -0.20 \text{ T} \)
- \( \Delta t = 1.5 \text{ s} \)

**Find:**
- EMF = ?

The loop is always perpendicular to the field, so the normal to the loop is parallel to the field, so \( \cos \theta = 1 \).

The flux is then:

\[
\Phi = BA = B \pi r^2
\]

Initially the flux is:

\[
\Phi_i = (0.30 T) \pi (0.30 \text{ m})^2 = 0.085 \text{ T} \cdot \text{m}^2
\]

and after the field changes the flux is:

\[
\Phi_f = (-0.20 T) \pi (0.30 \text{ m})^2 = -0.057 \text{ T} \cdot \text{m}^2
\]

The magnitude of the average induced emf is:

\[
\text{emf} = \frac{\Delta \Phi}{\Delta t} = \frac{\Phi_f - \Phi_i}{\Delta t} = \frac{0.085 \text{ T} \cdot \text{m}^2 - (-0.057 \text{ T} \cdot \text{m}^2)}{1.5 \text{ s}} = 0.095 V
\]