Physics 132: Lecture 21
Elements of Physics II

Agenda for Today

- Forces on currents
  - Currents are moving charges
  - Torque on current loop
  - Torque on rotated loop
- Currents create B-fields
  - Adding magnetic fields
  - Force between wires
Review RHR

- Flat RHR
  - Direction of force charge/current moving in B field?

- Curly RHR #1
  - Direction of B-field from loop of wire?

- Curly RHR #2
  - Direction of B-field from wire? CCW
So far

- Moving charges create B-fields (cause magnets)
  - Atomic level: electrons cause magnetism
  - Current in a wire

- B-fields exert forces on moving charges
  - Current carrying wire feels a force

- Now: change in B-field causes moving charges!!!

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Faraday’s Discovery of 1831

- When a bar magnet is pushed into a coil of wire, it causes a momentary deflection of the current-meter needle.

- A quick withdrawal of the magnet deflects the needle in the other direction.

- Holding the magnet inside the coil has no effect.
Motional EMF

Charge carriers in the wire experience an upward force of magnitude $F_B = qvB$. Being free to move, positive charges flow upward (or, if you prefer, negative charges flow downward).
Motional EMF

The charge separation creates an electric field in the conductor. $\vec{E}$ increases as more charge flows.
Motional EMF

The charge flow continues until the downward electric force $\vec{F}_E$ is large enough to balance the upward magnetic force $\vec{F}_B$. Then the net force on a charge is zero and the current ceases.
Motional EMF

- The magnetic force on the charge carriers in a moving conductor creates an electric field of strength $E = vB$ inside the conductor.
- For a conductor of length $l$, the motional emf perpendicular to the magnetic field is: $\mathcal{E} = vlB$
Give it a try:

A metal bar moves through a magnetic field. The induced charges on the bar are

A. 
B. 
C. 
D. 
E.
Induced Current

- If we slide a conducting wire along a U-shaped conducting rail, we can complete a circuit and drive an electric current.

- If the total resistance of the circuit is $R$, the *induced current* is given by Ohm’s law as:

$$ I = \frac{\mathcal{E}}{R} = \frac{vlB}{R} $$
Induced Current

- To keep the wire moving at a constant speed $v$, we must apply a pulling force $F_{\text{pull}} = \nu l^2 B^2 / R$.

- This pulling force does work at a rate:

$$P_{\text{input}} = F_{\text{pull}} \nu = \frac{\nu l^2 B^2}{R}$$

- All of this power is dissipated by the resistance of the circuit.
Induced Current

1. The magnetic force on the charge carriers is down, so the induced current flows clockwise.

2. The magnetic force on the current-carrying wire is to the right.

- The figure shows a conducting wire sliding to the left.
- In this case, a *pushing* force is needed to keep the wire moving at constant speed.
- Once again, this input power is dissipated in the electric circuit.
- A device that converts mechanical energy to electric energy is called a **generator**.
Give it a try:

An induced current flows clockwise as the metal bar is pushed to the right. The magnetic field points

A. Up.
B. Down.
C. Into the screen.
D. Out of the screen.
E. To the right.
The Basic Definition of Flux

- Imagine holding a rectangular wire loop of area $A = ab$ in front of a fan.
- The volume of air flowing through the loop each second depends on the angle between the loop and the direction of flow.
- No air goes through the same loop if it lies parallel to the flow.
- The flow is *maximum* through a loop that is perpendicular to the airflow.
- This occurs because the effective area is greatest at this angle.
- The effective angle (as seen facing the fan) is:

$$A_{\text{eff}} = ab \cos \theta = A \cos \theta$$
The Basic Definition of Flux

Imagine holding a rectangular loop of wire in front of a fan. Start with the loop face-on to the direction of airflow, then tilt the loop as shown until it is horizontal.
The Basic Definition of Flux

- Loop seen from the side
  \[ \theta = 0^\circ \]
  - \[ A_{\text{eff}} = ab \]

- Loop seen facing the fan
  - \[ \theta = 90^\circ \]
  - \[ A_{\text{eff}} = 0 \]
  - \[ A_{\text{eff}} = ab \cos \theta \]
  - These lengths are the same.
Magnetic Flux Through a Loop

- **θ = 0°**
  - Loop perpendicular to field.
  - Maximum number of arrows pass through.

- **θ ≠ 0°**
  - Loop rotated through angle θ.
  - Fewer arrows pass through.

- **θ = 90°**
  - Loop rotated 90°.
  - No arrows pass through.

These lengths are the same.
The Area Vector

- Let’s define an area vector $\mathbf{A} = A\mathbf{n}$ to be a vector in the direction of, perpendicular to the surface, with a magnitude $A$ equal to the area of the surface.
- Vector $\mathbf{A}$ has units of m$^2$.

![Diagram showing a loop of area A with a normal vector A perpendicular to the loop. The area vector is perpendicular to the loop. Its magnitude is the area of the loop.]
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.

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.

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

The SI unit of magnetic flux is the weber:

$$1 \text{ weber} = 1 \text{ Wb} = 1 \text{ T m}^2$$
Give it a try:

Which loop has the larger magnetic flux through it?

A. Loop A.
B. Loop B. **(Correct Answer)**
C. The fluxes are the same.
D. Not enough information to tell.

This field is twice as strong.

This square is twice as wide.
**Lenz’s Law**

A bar magnet pushed into a loop increases the flux through the loop.

Which direction is the induced current?

**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.
Lenz’s Law

- Pushing the bar magnet into the loop causes the magnetic flux to increase in the downward direction.
- To oppose the change in flux, which is what Lenz’s law requires, the loop itself needs to generate an upward-pointing magnetic field.
- The induced current ceases as soon as the magnet stops moving.
Lenz’s Law

- Pushing the bar magnet away from the loop causes the magnetic flux to decrease in the downward direction.
- To oppose this decrease, a clockwise current is induced.
Give it a try:
The bar magnet is pushed toward the center of a wire loop. Which is true?

A. There is a clockwise induced current in the loop.
B. There is a counterclockwise induced current in the loop.
C. There is no induced current in the loop.
Give it a try:

An induced current flows clockwise as the metal bar is pushed to the right. The magnetic field points

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