Electromagnetic

Current

Loop

#### Mass

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Velocity-Dependent Forces

Magnetosphe

Magnetic

Faraday's Experiment

Magnetic Flux

Faraday's Law

Lenz's Law

# College Physics B - PHY2054C Magnetic Forces & Induction



10/02/2023

My Office Hours: Monday 1:00 - 3:00 PM 212 Keen Building



Velocity-Dependent

Faradav's Law

## Problems for this week's recitations:

5.1, 5.2, 5.5, 5.7

## **Outline**

#### Electromagnetic Forces

Current Torque on a Curren

Mass

#### Spectromet

Velocity-Dependent Forces Earth's Magnetosphere

### Magnetic

Experiment
Magnetic Flux
Faraday's Law

Lenz's Law

- 1 Electromagnetic Forces

  Magnetic Force on a C
  - Magnetic Force on a Current Torque on a Current Loop
- 2 Mass Spectrometer Velocity-Dependent Forces Earth's Magnetosphere
- 3 Magnetic Induction
  Faraday's Experiment
  Magnetic Flux
  Faraday's Law
  Electrical Generator
- 4 Lenz's Law

## Magnetic Force on a Current

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Electromagnetic

#### Magnetic Force on a Current

#### Torque on a Current Loop

Mass

Velocity-Dependent Forces Earth's

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Induction

Faraday's Experiment Magnetic Flu

Faraday's Law Electrical General

l enz's Law

# An electric current is a collection of moving charges:

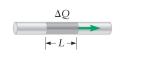
→ A force acts on a current.

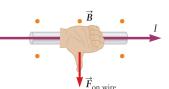
$$F_B = q v \cdot B = (\Delta Q) v \cdot B$$

Velocity of charge :  $V = \frac{L}{\Delta t}$ 

Current : 
$$I = \frac{\Delta Q}{\Delta t}$$







## Magnetic Force on a Current

Electromagnetic

#### Magnetic Force on a Current

Torque on a Current

#### Mass

Velocity-Dependent Forces

Forces Earth's Magnetosphere

## Magnetic

Faraday's Experiment Magnetic Flui

Faraday's Law

Lenz's Law

# An electric current is a collection of moving charges:

→ A force acts on a current.

$$F_B = q v \cdot B = (\Delta Q) v \cdot B$$

Velocity of charge : 
$$V = \frac{L}{\Delta t}$$

Current : 
$$I = \frac{\Delta Q}{\Delta t}$$

$$F_B = (\Delta Q) v \cdot B = (\Delta Q) \frac{L}{\Delta t} \cdot B$$

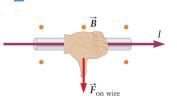
$$F_{\text{on wire}} = ILB$$

If  $\vec{B}$  is at an angle  $\theta$  with the wire:

$$F_{\text{on wire}} = ILB \sin \theta$$









#### Magnetic Force on a Current

Torque on a Curre Loop

#### Mass

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Velocity-Dependent Forces Earth's

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Faraday's Law

Lenz's Law

## **Electromagnetic Forces**



$$\vec{F} = q\vec{E} + q\vec{v} \times \vec{B}$$

- 1 Electric Force depends on the electric field.
- 2 Magnetic Force depends on the magnetic field and the particle's velocity.

## Question 1

Electromagnetic Forces

#### Magnetic Force on a Current

Mass Spectromete

Velocity-Dependent Forces Earth's

Magnetic

Faraday's
Experiment
Magnetic Flux
Faraday's Law

Electrical Generate

Lenz's Law

Two current-carrying wires are parallel as shown below; the current is the same in both wires. The current in both wires is flowing to the right. What is the effect of the magnetic force?

- A The two wires attract each other.
- B The two wires repel each other.
- C There is no effect.
- D I don't know.
  (Not for credit)





### Electromagnetic

#### Magnetic Force on a Current

Torque on a Currer Loop

Mass

Velocity-Dependent Forces

Earth's Magnetosphere

Magnetic

Faraday's Experiment Magnetic Flux

Faraday's Law Electrical Generat

Lenz's Law

## **Review Question 2**

Two current-carrying wires are parallel as shown below; the current is the same in both wires. The current in both wires is flowing to the right. At the point P in the picture, the direction of the net magnetic field is

A to the right  $\rightarrow$ 

B to the left  $\leftarrow$ 

C into the screen

D out of the screen

E The field is zero.





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Electromagnetic Forces

#### Magnetic Force on a Current

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Magnetic

Faraday's Experiment Magnetic Flu

Faraday's Law Electrical Generat

Lenz's Lav

## **Review Question 2**

Two current-carrying wires are parallel as shown below; the current is the same in both wires. The current in both wires is flowing to the right. At the point P in the picture, the direction of the net magnetic field is

- A to the right  $\rightarrow$
- B to the left  $\leftarrow$
- C into the screen
- D out of the screen
- E The field is zero.

Right-Hand Rule I



## ectro-

Electromagnetic Forces

#### Magnetic Force on a Current

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Spectromet

Velocity-Dependent Forces Earth's

Magnetosphere

Induction

Experiment Magnetic Flux Faraday's Law

Lenz's Lav

## **Review Question 3**

Two current-carrying wires are parallel as shown below; the current is the same in both wires. The current in both wires is flowing to the right. At the point P in the picture, the direction of the net magnetic field is

- A to the right  $\rightarrow$
- B to the left  $\leftarrow$
- C into the screen
- D out of the screen
- E The field is zero.



Magnetic Force on a Current

Velocity-Dependent

Faradav's Law

## **Review Question 3**

Two current-carrying wires are parallel as shown below; the current is the same in both wires. The current in both wires is flowing to the right. At the point P in the picture, the direction of the net magnetic field is

- A to the right  $\rightarrow$
- B to the left  $\leftarrow$
- C into the screen
- D out of the screen
- E The field is zero.

Right-Hand Rule I



#### Magnetic Force on a Current

Velocity-Dependent

Faradav's Law

## **Review Question 4**

Two current-carrying wires are parallel as shown below; the current is the same in both wires. The current in both wires is flowing to the right. What is the effect of the magnetic force?

- A The two wires attract each other.
- B The two wires repel each other.
- C There is no effect.
- I don't know



### Electromagnetic

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Magnetic Force on a

## Current

Mass Spectrometer

Velocity-Dependent Forces Earth's

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Induction

Faraday's Experiment

Faraday's Law

Lanz'e Law

## **Review Question 4**

Two current-carrying wires are parallel as shown below; the current is the same in both wires. The current in both wires is flowing to the right. What is the effect of the magnetic force?

- A The two wires attract each other.
- B The two wires repel each other.
- C There is no effect.
- D I don't know.



### Electromagnetic

Magnetic Force on a Current

Torque on a Current

#### Mass

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Velocity-Dependent Forces Earth's

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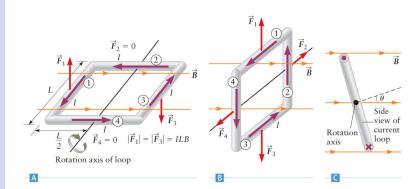
Lenz's Law

## Torque on a Current Loop

## A magnetic field can produce a torque on a current loop:

A On two sides, the current is parallel or antiparallel to the field, so the force is zero on those sides.

The forces on sides 1 and 3 are in opposite directions and produce a torque on the loop.



## Torque on a Current Loop

Electromagnetic

Magnetic Force on a Current

Torque on a Current

#### Mass

Spectromete

Velocity-Dependent Forces Earth's

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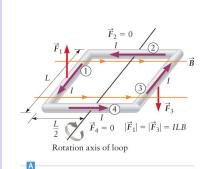
Faraday's Law

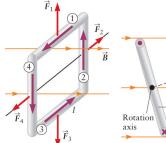
Lenz's Law

## A magnetic field can produce a torque on a current loop:

- A On two sides, the current is parallel or antiparallel to the field, so the force is zero on those sides.
- When the angle between the loop and field is  $\theta$ , the torque is:

$$ec{ au} = ec{L}/2 imes ec{F} \quad o \quad | au| = IL^2 \, B \sin heta$$





Side view of current

loop

Magnetic

Faraday's Experiment Magnetic Flux

Faraday's Law
Electrical Generate

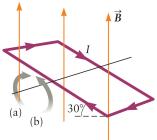
Lanz'e Law

The figure shows a current loop in a magnetic field. Is there a torque on the loop and, if so, in what direction?

A There is a torque that tends to rotate the loop in direction (a), clockwise.

B There is a torque that tends to rotate the loop in direction (b), counterclockwise.

C The torque is zero.



## Question 5

magnetic Forces

Current Torque on a Current

#### Mass

Spectromete

Velocity-Dependent Forces Earth's

Magnetic

Faraday's Experiment Magnetic Flux Faraday's Law

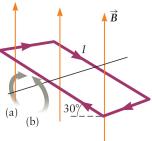
l enz's Law

The figure shows a current loop in a magnetic field. Is there a torque on the loop and, if so, in what direction?

A There is a torque that tends to rotate the loop in direction (a), clockwise.

B There is a torque that tends to rotate the loop in direction (b), counterclockwise.

C The torque is zero.



## **Outline**

Electromagnetic Forces

Current
Torque on a Currer

#### Mass Spectrometer

Velocity-Dependent Forces Earth's Magnetosphere

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Lenz's Law

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## Mass Spectrometer

Electromagnetic

Magnetic Force on a Current Torque on a Current

#### Mass Spectrometer

Velocity-Dependent Forces Earth's Magnetosphere

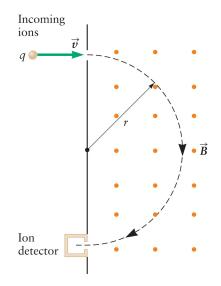
Induction
Faraday's
Experiment
Magnetic Flux
Faraday's Law
Electrical General

l enz's Law

A mass spectrometer allows for the separation of ions according to their mass or charge.

- lons enter spectrometer with some speed v.
- They pass into a region where magnetic field is perpendicular to velocity
  - → circles
- Measure v and B, then calculate q/m:

$$r = \frac{mv}{qB}$$



## **Velocity-Dependent Forces**

magnetic Forces

Current
Torque on a Curren

Mass

Velocity-Dependent Forces

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Faraday's Experiment Magnetic Flux Faraday's Law

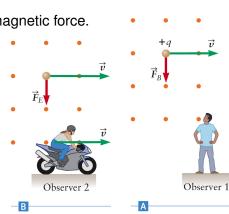
onzie Law

The magnetic force exerted on a moving charged particle is dependent on its velocity.

- Differs substantially from gravitational and electrical forces.
- Observer 1 (A) sees magnetic force.

Observer 2 (B) sees an electric force.

- Special relativity solves the dilemma.
  - → Chapter 28



Electromagnetic

Magnetic Force on a Current

Torque on a Curren

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Velocity-Dependent

Earth's Magnetosphere

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Faraday's

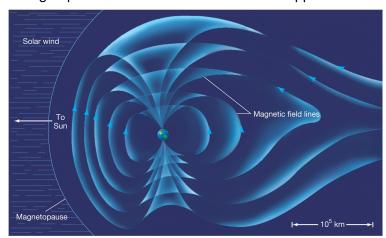
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Faraday's Law Electrical General

Lenz's Law

## Earth's Magnetosphere

The magnetosphere is the region around Earth where charged particles from the solar wind are trapped.



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Electromagnetic

Magnetic Force on Current

Torque on a Currer

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Velocity-Dependent

Earth's

Magnetosphere

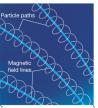
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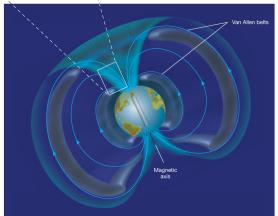
Magnetic Flux Faradav's Law

Electrical Genera

Lenz's Law



Charged particles are trapped in areas called the Van Allen Belts, where they spiral around the magnetic field lines.



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Electromagnetic

Magnetic Force on a Current

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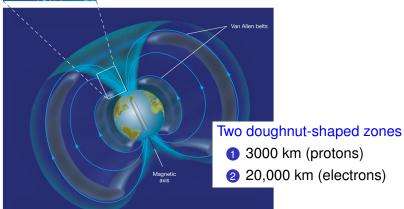
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Charged particles are trapped in areas called the Van Allen Belts, where they spiral around the magnetic field lines.



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Velocity-Dependent

Farth's Magnetosphere

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## Aurora Borealis



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## **Aurora Borealis**

Loop

Magnetic Force on a

Velocity-Dependent

Farth's

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## **Outline**

Electromagnetic Forces

Current Torque on a Curre

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## Magnetic Induction

Faraday's Experiment

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Lenz's Lav

# Connection between Electricity and Magnetism

Sources of Electric Fields Sources of Magnetic Fields

Electric Charge

Electromagnetic

Magnetic Force on Current

Torque on a Curre

Mass

Velocity-Dependent Forces

Magnetic

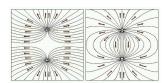
## Induction

Faraday's
Experiment
Magnetic Flux
Faraday's Law
Electrical Generate

Lenz's Law

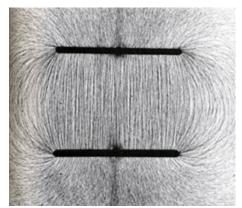
Michael Faraday (1791 - 1867)

## Static Point Charges



## **Electric Fields**

## Capacitor



Electromagnetic Forces

Torque on a Curre

Loop

Mass

Velocity-Dependent Forces

Earth's Magnetosphere

## Magnetic Induction

Faraday's Experiment Magnetic Flux Faraday's Law

Lenz's Lav

# Connection between Electricity and Magnetism

Sources of Electric Fields Sources of Magnetic Fields

Electric Charge

Moving Electric Charge

PBS | Einstein's Big Idea | Michael Faraday - Part 1

https://www.youtube.com/watch?v=TEVEBzNSwTU

Electromagnetic

Current

Torque on a Curre

#### Mass

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Velocity-Dependent Forces Earth's

## Magnetic Induction

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Lenz's Law

## Electromagnetism

Christian Oersted (1777 - 1851)



## Field around a currentcarrying wire is fairly weak





Electromagnetic

Magnetic Force on Current

Torque on a Curre

#### Mass

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## Magnetic Induction

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Lenz's Law

## Electromagnetism

A coil concentrates and strengthens the field

## Field around a currentcarrying wire is fairly weak







Electromagnetic

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Loop

Mass

Spectromete

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Magnetic

Magnetic Induction

Faraday's Experiment

Magnetic Flu

Faraday's Law Electrical Genera

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# Connection between Electricity and Magnetism

Sources of Electric Fields

Sources of Magnetic Fields

Electric Charge

Moving Electric Charge

Changing Magnetic Fields

Electromagnetic

Magnetic Force on a Current

Torque on a Curre

Mass

Velocity-Dependent Forces

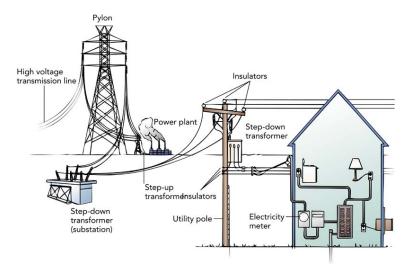
Magnetic Induction

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Faraday's Law Electrical General

Lenz's Law

Why does the power company place large electric devices on the utility poles near homes or on the ground near neighborhoods?



Electromagnetic

Magnetic Force on a Current

Loop

Mass

Velocity-Dependent Forces Earth's

## Magnetic Induction

Experiment
Magnetic Flux
Faraday's Law

Lenz'e Law

Why does the power company place large electric devices on the utility poles near homes or on the ground near neighborhoods?





Electromagnetic

Current Torque on a Curren

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Magnetic

#### Faraday's Experiment

Magnetic Flux
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Electrical Generato

Lenz's Law

## Faraday's Experiment

# Michael Faraday attempted to observe an induced electric field.

- → He did not use a light bulb.
  - A If the bar magnet is stationary, the current and the electric field are both zero.
  - B If the bar magnet was in motion, a current was observed.





## Faraday's Law:

phet.colorado.edu/sims/faradays-law/faradays-law\_en.html

Velocity-Dependent

#### Faradav's Experiment

Faradav's Law

## Another Faraday Experiment

A solenoid is positioned near a loop of wire with the light bulb. Now a current is passed through the solenoid by connecting it to a battery.

- 1 When the current through the solenoid is constant, there is no current in the wire.
- When the switch is opened or closed, the bulb does light up.



### Question 6

Electromagnetic

Magnetic Force on Current

Mass

Velocity-Dependent Forces

Magnetic

Faraday's Experiment

Magnetic Flux
Faraday's Law
Electrical Generato

Lenz's Law

What is the conclusion from Faraday's Experiment? It shows that an electric current is produced in the wire loop only when

- A the battery is directly connected to the light bulb.
- B the magnetic field at the loop is constant.
- C the magnetic field at the loop is changing.
- D No electric current is produced. A magnetic field cannot produce an electric current to power the light bulb.



### Question 6

What is the conclusion from Faraday's Experiment? It shows that an electric current is produced in the wire loop only when

- A the battery is directly connected to the light bulb.
- B the magnetic field at the loop is constant.
- C the magnetic field at the loop is changing.
- D No electric current is produced. A magnetic field cannot produce an electric current to power the light bulb.

A changing magnetic field produces an electric field.

→ It is called *induced electric field*.

The phenomenon is called electromagnetic induction.

Electromagnetic

Magnetic Force on Current Torque on a Curren

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Electromagnetic Forces

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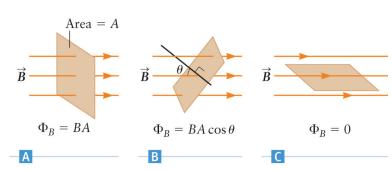
Lenz's Law

## Magnetic Flux

Faraday developed a quantitative theory of induction now called *Faraday's Law:* 

 It uses the concept of magnetic flux that is similar to the concept of electric flux:

$$\Phi_B = AB\cos\theta$$
 ( $\theta = \angle$ (normal vector, magnetic field))



# Magnetic Flux

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Magnetic Force on a

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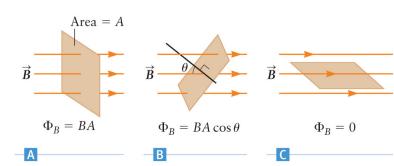
Magnetic Flux Faradav's Law

Faraday's Law Electrical Generato

Lenz's Law

Faraday developed a quantitative theory of induction now called *Faraday's Law:* 

- $\Phi_B = AB\cos\theta$
- The unit of magnetic flux is the Weber (Wb)
  - $\rightarrow$  1 Wb = 1 T · m<sup>2</sup>



## Faraday's Law



Electromagnetic Forces

Current Torque on a Curre

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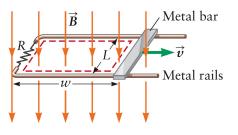
Faraday's Law indicates how to calculate the potential difference that produces the induced current:

$$|\mathcal{E}| = -\frac{\Delta \Phi_B}{\Delta t}$$

The magnitude of the induced emf equals the rate of change of the magnetic flux.

Velocity-Dependent

Faraday's Law



## Example

A magnetic field B is constant and in a direction perpendicular to the plane of the rails and the bar. Assume the bar moves at constant speed:

$$\Phi_B = BA = BwL$$

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Velocity-Dependent Forces Earth's

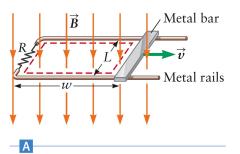
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Faraday's

Experiment Magnetic Fl

Faraday's Law

Lenz's Law



### Example

A magnetic field *B* is constant and in a direction perpendicular to the plane of the rails and the bar. Assume the bar moves at constant speed:

$$\Phi_B = BA = BwL$$

$$\frac{\Delta \Phi_B}{\Delta t} = |\mathcal{E}| = BL \frac{\Delta w}{\Delta t} = BLv$$

Electromagnetic Forces

Current Torque en a Curre

Loop

Mass

Velocity-Dependent Forces Earth's

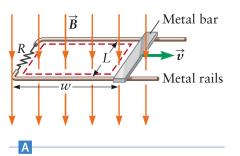
Magnetic

Faraday's Experiment

Magnetic Flux Faradav's Law

Electrical Generato

Lenz's Law



## Example

A magnetic field *B* is constant and in a direction perpendicular to the plane of the rails and the bar. Assume the bar moves at constant speed:

$$\Phi_{B} = BA = BwL$$

$$\frac{\Delta \Phi_{B}}{\Delta t} = |\mathcal{E}| = BL\frac{\Delta w}{\Delta t} = BLv$$

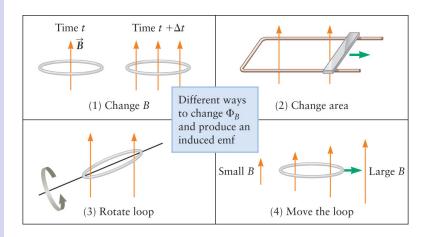
$$I = \frac{BLv}{R}$$

Velocity-Dependent

Faraday's Law



## Faraday's Law





Magnetic Force on a

Torque on a Currer

### Mass

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Induction Faraday's

Magnetic Fl

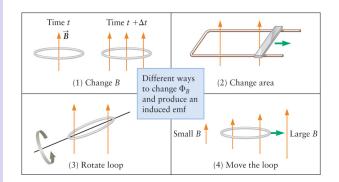
Faraday's Law

Lonzio Low

## Faraday's Law

The mechanical power put into the bar by the external agent is equal to the electrical power delivered to the resistor:

→ Energy is converted from mechanical to electrical; total energy remains the same.



### **Electrical Generator**

Electromagnetic Forces

Magnetic Force on a Current

Mass

Spectrometer
Velocity-Dependent
Forces
Earth's

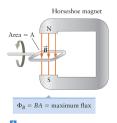
Magnetion Induction

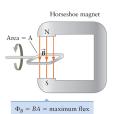
Faraday's Experiment Magnetic Flux Faraday's Law

Electrical Generator
Lenz's Law

Need to make the rate of change of the flux large enough to give a useful emf:

- Use rotational motion instead of linear motion.
- A permanent magnet produces a constant magnetic field in the region between its poles.
- The angle between the field and the plane of the loop changes as the loop rotates.
- If the shaft rotates with a constant angular velocity, the flux varies sinusoidally with time.





### Generator:

phet.colorado.edu/en/simulation/generator



### **Outline**

Electromagnetic Forces

Current Torque on a Curren

### Mass

Velocity-Dependent Forces Earth's

Magnetic Induction

Experiment
Magnetic Flux
Faraday's Law

Lenz's Law

- Electromagnetic Forces Magnetic Force on a Current Torque on a Current Loop
- 2 Mass Spectrometer Velocity-Dependent Forces Earth's Magnetosphere
- 3 Magnetic Induction
  Faraday's Experiment
  Magnetic Flux
  Faraday's Law
  Electrical Generator
- 4 Lenz's Law

### College Physics B

Electromagnetic Forces

Magnetic Force on Current

Torque on a Curre

Mass

Spectromet

Velocity-Dependent Forces

Earth's Magnetosphere

Induction

Faraday's Experiment

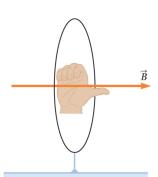
Magnetic Flux Faraday's Law

Lenz's Law

Lenz's Law gives us an easy way to determine the sign of the induced emf.

Lenz's Law states that the magnetic field produced by an induced current always opposes any changes in the magnetic flux.

### Lenz's Law



The induced emf is directed along the perimeter of the flux surface. The induced current is thus perpendicular to  $\vec{B}$ .