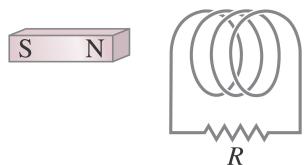


## Chapter 29

### Electromagnetic Induction and Faraday's Law


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#### Units of Chapter 29

- 29.1 Induced EMF
- 29.2 Faraday's Law of Induction; Lenz's Law: 1 - 8
- 29.3 EMF Induced in a Moving Conductor: 9, 10
- 29.4 Electric Generators: 11
- 29.5 Counter EMF and Torque; Eddy Currents: 12, 13
- 29.6 Transformers and Transmission of Power: 14, 15
- 29.7 A Changing Magnetic Flux Produces an Electric Field
- 29.8 Applications of Induction: Sound Systems, Computer Memory, Seismograph

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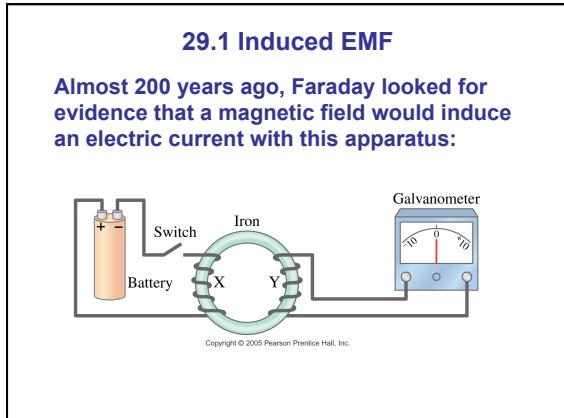
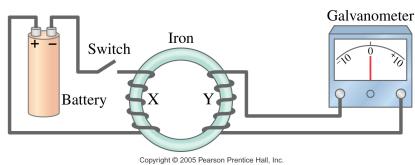
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#### 29.1 Induced EMF

Almost 200 years ago, Faraday looked for evidence that a magnetic field would induce an electric current with this apparatus:




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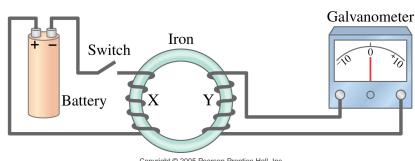
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## 29.1 Induced EMF

He found no evidence when the current was steady, but did see a current induced when the switch was turned on or off.



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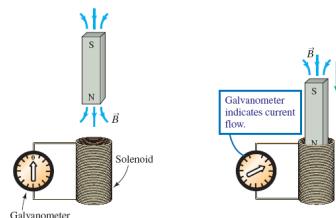
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## 29-1 Induced EMF

- Faraday wanted to know if magnetic fields would create electric fields
- Steady fields did not
- But changing fields did!




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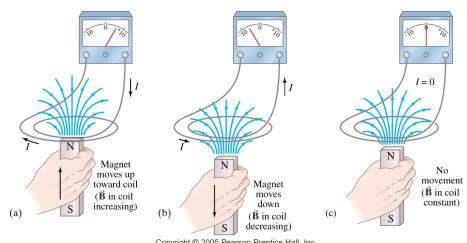
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## 29.1 Induced EMF

Determine how the magnetic flux changes in the following examples:



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## 29.1 Induced EMF

Therefore, a changing magnetic field induces an emf.

Faraday's experiment used a magnetic field that was changing because the current producing it was changing; the previous graphic shows a magnetic field that is changing because the magnet is moving.

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## 29.2 Faraday's Law of Induction; Lenz's Law

The induced emf in a wire loop is proportional to the rate of change of magnetic flux through the loop.

**Magnetic flux:**  $\Phi_B = B_{\perp}A = BA \cos \theta$

**Unit of magnetic flux:** weber, Wb.

1 Wb = 1 T·m<sup>2</sup>

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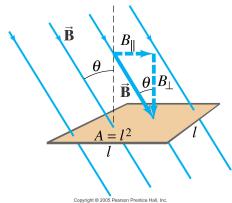
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## 29.2 Faraday's Law of Induction; Lenz's Law

This drawing shows the variables in the flux equation:




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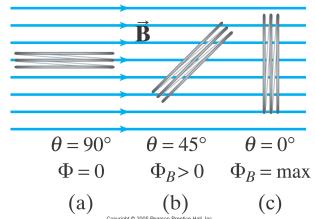
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## 29.2 Faraday's Law of Induction; Lenz's Law

The magnetic flux is analogous to the electric flux – it is proportional to the total number of lines passing through the loop.



## 29.2 Faraday's Law of Induction; Lenz's Law

**Faraday's law of induction:**

$$\mathcal{E} = -\frac{\Delta \Phi_B}{\Delta t} \quad [1 \text{ loop}] \quad (29-2a)$$

$$\mathcal{E} = -N \frac{\Delta \Phi_B}{\Delta t} \quad [N \text{ loops}] \quad (29-2b)$$

The minus sign gives the direction of the induced emf

## 29-2 Faraday's Law of Induction; Lenz's Law

- A changing magnetic flux through a loop induces a current around the loop

- **Faraday's law of induction:**

$$\mathcal{E} = \oint \vec{E} \cdot d\vec{s} = -\frac{d\Phi_B}{dt}$$

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## 29.2 Faraday's Law of Induction; Lenz's Law

A current produced by an induced emf moves in a direction so that the magnetic field it produces tends to restore the changed field.

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## 29.2 Faraday's Law of Induction; Lenz's Law

Lenz's Law:

An induced emf gives rise to a current whose magnetic field opposes the original change in magnetic flux (in a closed circuit)

It is also valid for an open circuit: An induced emf is always in the direction that opposes the original change in flux that caused it .

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## 29-2 Faraday's Law of Induction; Lenz's Law

The direction of the induced current is given by Lenz's law:

The induced current is in a direction such that the magnetic field it creates tends to oppose the change that created it

If it were in the other direction, energy would not be conserved

A current produced by an induced emf moves in a direction so that the magnetic field it produces tends to restore the changed field.

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## 29-2 Faraday's Law of Induction; Lenz's Law

There are many ways to change the magnetic flux through a surface:

- Move the magnet
- Turning current on or off in one loop induces current in another
- Move the loop
- Change the shape (and the area) of the loop

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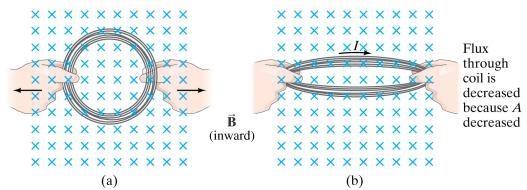
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## 29.2 Faraday's Law of Induction; Lenz's Law

Magnetic flux will change if the area of the loop changes:



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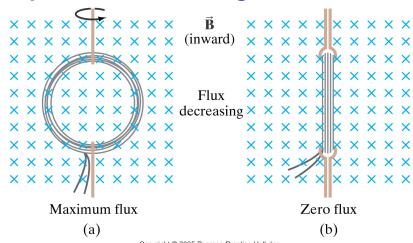
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## 29.2 Faraday's Law of Induction; Lenz's Law

Magnetic flux will change if the angle between the loop and the field changes:




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## 29.2 Faraday's Law of Induction; Lenz's Law

### Problem Solving: Lenz's Law

1. Determine whether the magnetic flux is increasing, decreasing, or unchanged.
2. The magnetic field due to the induced current points in the opposite direction to the original field if the flux is increasing; in the same direction if it is decreasing; and is zero if the flux is not changing.
3. Use the right-hand rule to determine the direction of the current.
4. Remember that the external field and the field due to the induced current are different.

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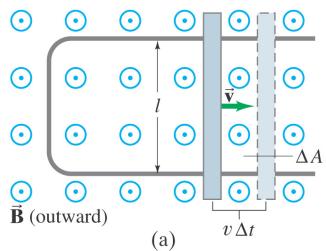
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## 29.3 EMF Induced in a Moving Conductor

This image shows another way the magnetic flux can change:




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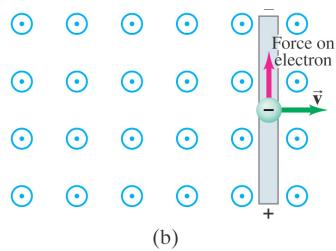
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## 29.3 EMF Induced in a Moving Conductor

The induced current is in a direction that tends to slow the moving bar – it will take an external force to keep it moving.




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### 29.3 EMF Induced in a Moving Conductor

The induced emf has magnitude

$$\mathcal{E} = \frac{\Delta\Phi_B}{\Delta t} = \frac{B \Delta A}{\Delta t} = \frac{Blv \Delta t}{\Delta t} = Blv \quad (29-3)$$

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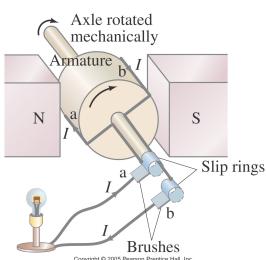


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### 29.4 Electric Generators

A generator is the opposite of a motor – it transforms mechanical energy into electrical energy. This is an ac generator:

The axle is rotated by an external force such as falling water or steam. The brushes are in constant electrical contact with the slip rings.




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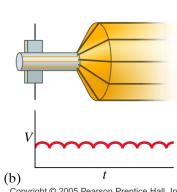
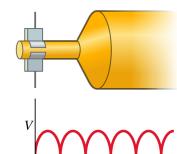
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### 29.4 Electric Generators

A dc generator is similar, except that it has a split-ring commutator instead of slip rings.




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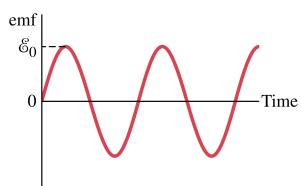


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## 29.4 Electric Generators

A sinusoidal emf is induced in the rotating loop ( $N$  is the number of turns, and  $A$  the area of the loop):

$$\mathcal{E} = NB\omega A \sin \omega t \quad (29-4)$$

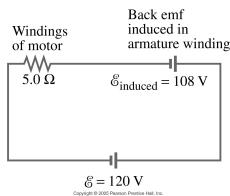


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## 29.5 Counter EMF and Torque; Eddy Currents

An electric motor turns because there is a torque on it due to the current. We would expect the motor to accelerate unless there is some sort of drag torque.

**That drag torque exists, and is due to the induced emf, called a back emf or counter emf.**



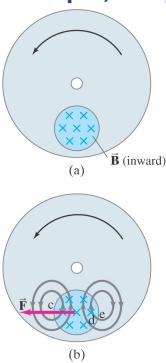
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## 29.5 Back EMF and Counter Torque; Eddy Currents

A similar effect occurs in a generator – if it is connected to a circuit, current will flow in it, and will produce a counter torque. This means the external applied torque must increase to keep the generator turning.

## 29.5 Back EMF and Counter Torque; Eddy Currents

Induced currents can flow in bulk material as well as through wires. These are called eddy currents, and can dramatically slow a conductor moving into or out of a magnetic field.



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## 29.6 Transformers and Transmission of Power

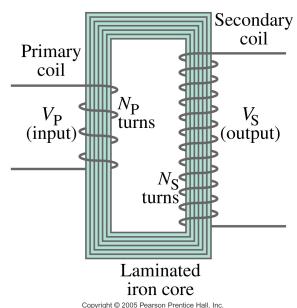
A transformer consists of two coils, either interwoven or linked by an iron core. A changing emf in one induces an emf in the other.

The ratio of the emfs is equal to the ratio of the number of turns in each coil:

$$\frac{V_S}{V_P} = \frac{N_S}{N_P} \quad (29-5)$$

## 29.6 Transformers and Transmission of Power

This is a step-up transformer – the emf in the secondary coil is larger than the emf in the primary:



## 29.6 Transformers and Transmission of Power

Energy must be conserved; therefore, in the absence of losses, the ratio of the currents must be the inverse of the ratio of turns:

$$\frac{I_S}{I_P} = \frac{N_P}{N_S} \quad (29-6)$$

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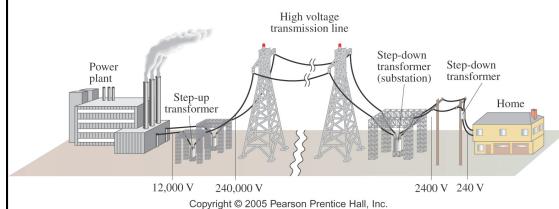
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## 29.6 Transformers and Transmission of Power

Transformers work only if the current is changing; this is one reason why electricity is transmitted as ac.




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## 29.7 Changing Magnetic Flux Produces an Electric Field

$$\mathcal{E} = \oint \vec{E} \cdot d\vec{s} = -\frac{d\Phi_B}{dt}$$

A changing magnetic flux induces an electric field; this is a generalization of Faraday's law. The electric field will exist regardless of whether there are any conductors around.

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### 29.7 Changing Magnetic Flux Produces an Electric Field

- Although static electric fields are **conservative fields**, when the electric field produced by a changing magnetic field is a **nonconservative field**.

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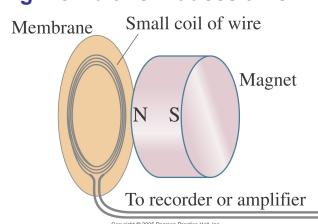
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### 29.8 Applications of Induction: Sound Systems, Computer Memory, Seismograph

This microphone works by induction; the vibrating membrane induces an emf in the coil




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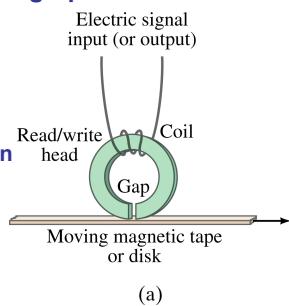
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### 29.8 Applications of Induction: Sound Systems, Computer Memory, Seismograph

Differently magnetized areas on an audio tape or disk induce signals in the read/write heads.




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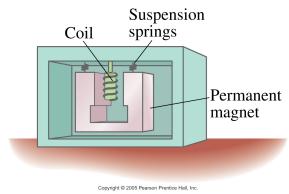
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### 29.8 Applications of Induction: Sound Systems, Computer Memory, Seismograph

A seismograph has a fixed coil and a magnet hung on a spring (or vice versa), and records the current induced when the earth shakes.


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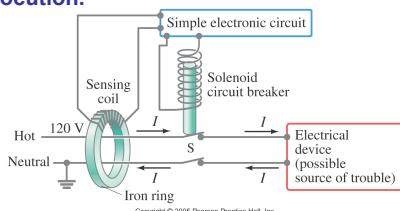
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### 29.8 Applications of Induction: Sound Systems, Computer Memory, Seismograph

A ground fault circuit interrupter (GFCI) will interrupt the current to a circuit that has shorted out in a very short time, preventing electrocution.




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### Summary of Chapter 29

- Magnetic flux:

$$\Phi_B = B_{\perp}A = BA \cos \theta$$

- Changing magnetic flux induces emf:

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

- Induced emf produces current that opposes original flux change

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**Summary of Chapter 29**

- Changing magnetic field produces an electric field
- Electric generator changes mechanical energy to electrical energy; electric motor does the opposite
- Transformer uses induction to change voltage:

$$\frac{V_S}{V_P} = \frac{N_S}{N_P}$$

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