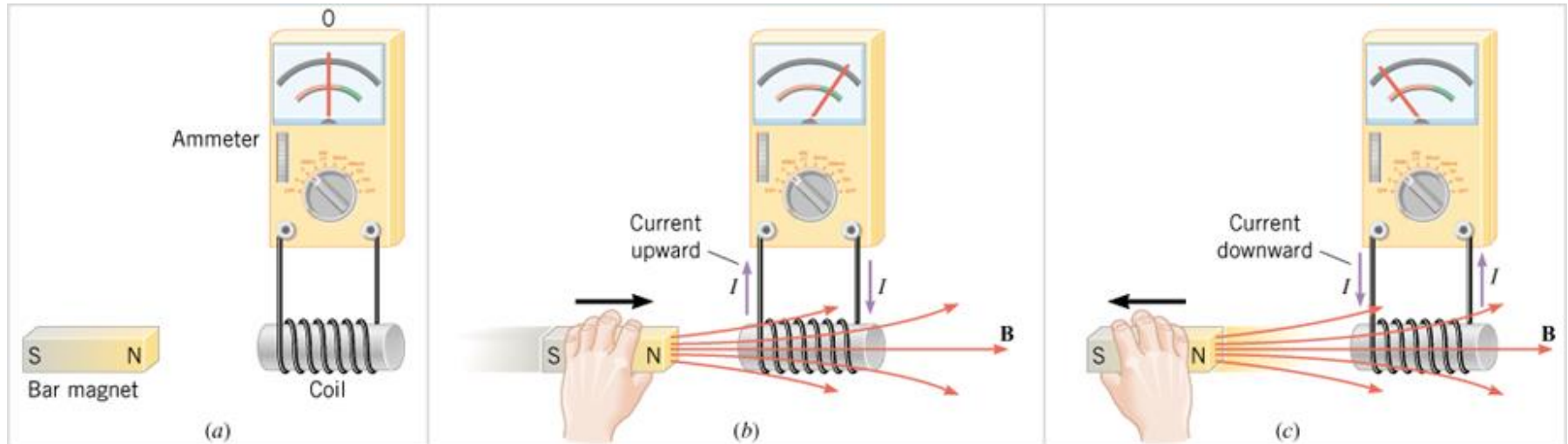


Chapter 22

Electromagnetic Induction

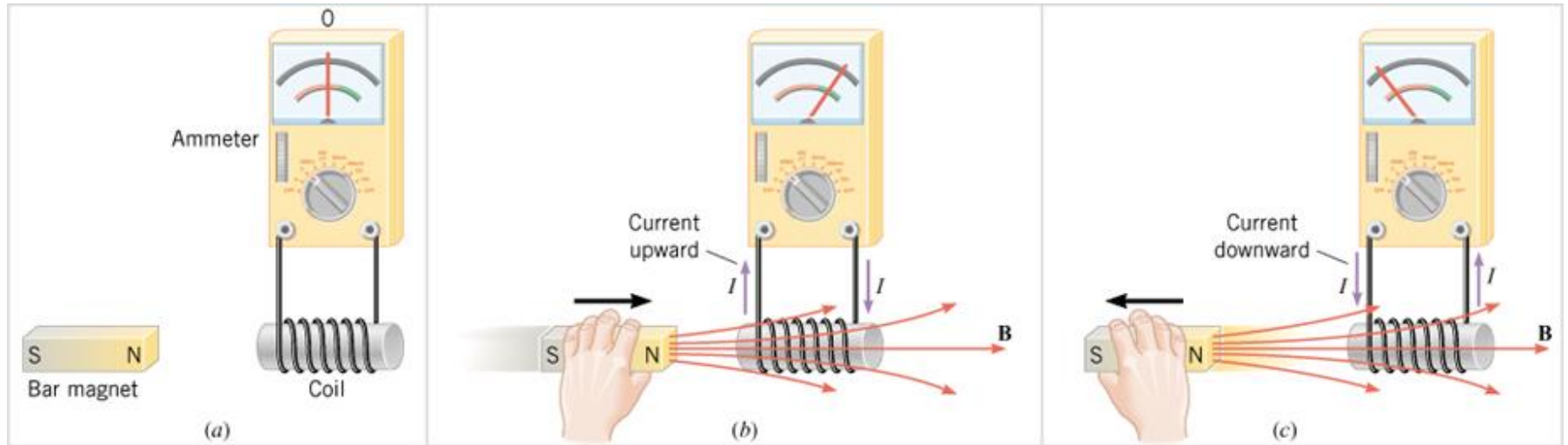
22.1 Induced Emf and Induced Current

There are a number of ways a magnetic field can be used to generate an electric current.



It is the ***changing*** field that produces the current.

22.1 Induced Emf and Induced Current

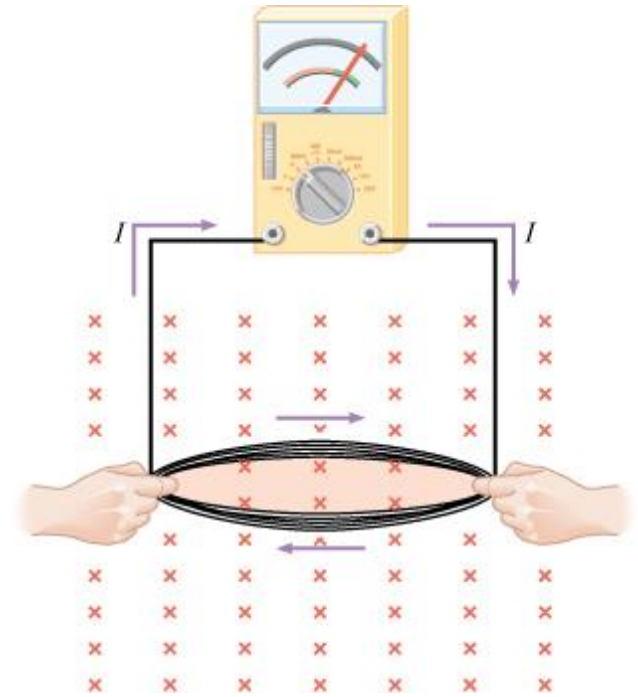


The current in the coil is called the ***induced current*** because it is brought about by a changing magnetic field.

Since a source emf is always needed to produce a current, the coil behaves as if it were a source of emf. This emf is known as the ***induced emf***.

22.1 Induced Emf and Induced Current

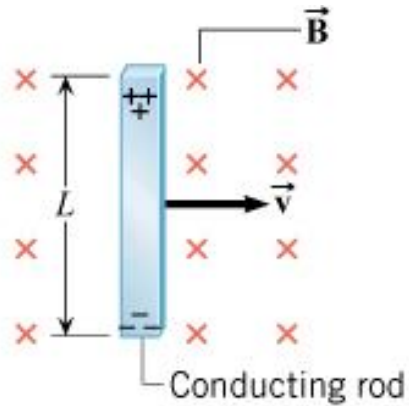
An emf can be induced by changing the area of a coil in a constant magnetic field



In each example, both an emf and a current are induced because the coil is part of a complete circuit. If the circuit were open, there would be no induced current, but there would be an induced emf.

The phenomena of producing an induced emf with the aid of a magnetic field is called ***electromagnetic induction***.

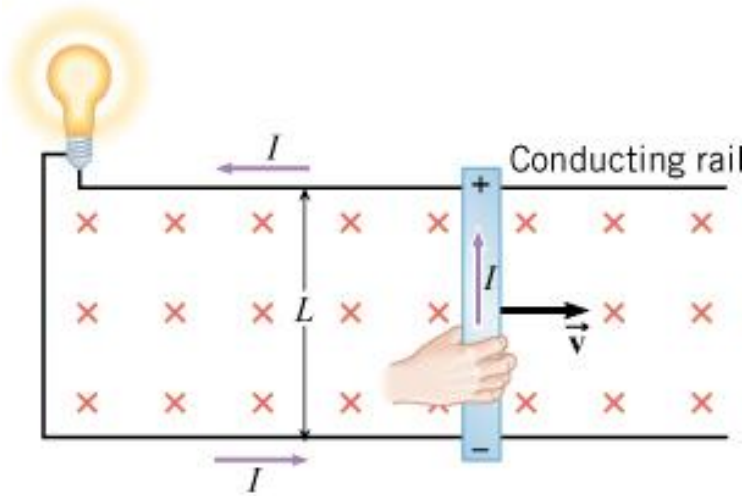
THE EMF INDUCED IN A MOVING CONDUCTOR



(a)

Each charge within the conductor is moving and experiences a magnetic force

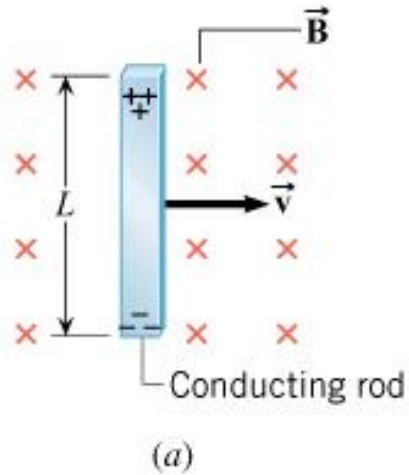
$$F = qvB$$



(b)

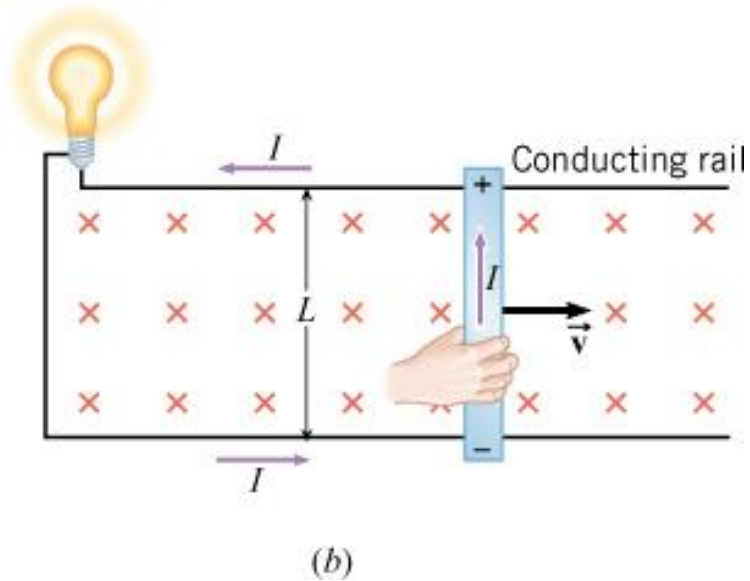
The separated charges on the ends of the conductor give rise to an induced emf, called a ***motional emf***.

22.2 Motional Emf



Motional emf when v , B , and L are mutually perpendicular

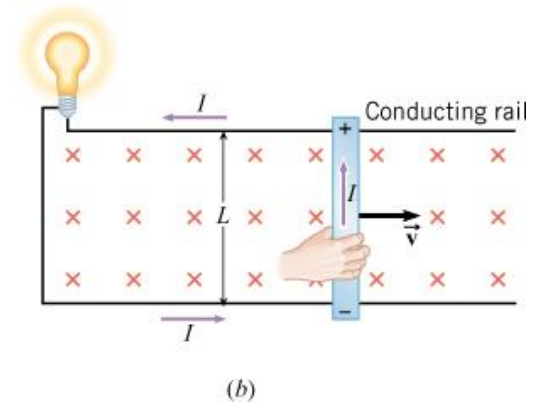
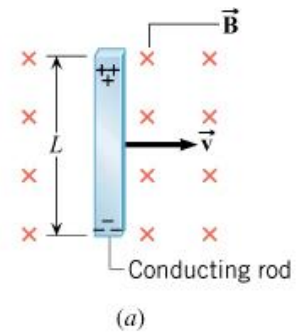
$$\mathcal{E} = vBL$$



22.2 Motional Emf

Example 1 Operating a Light Bulb with Motional Emf

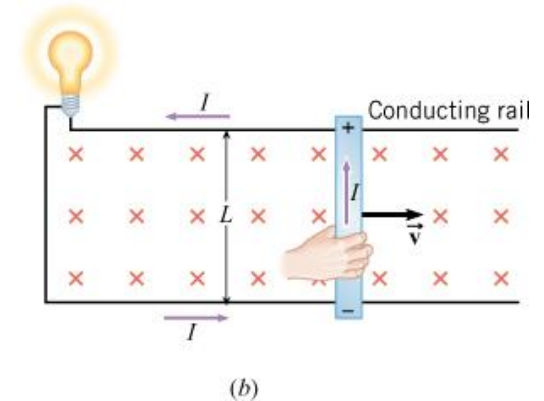
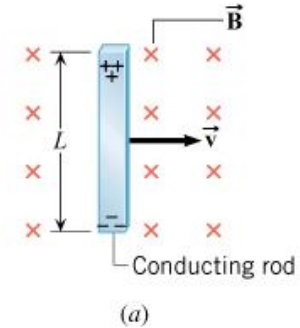
Suppose the rod is moving with a speed of 5.0 m/s perpendicular to a 0.80-T magnetic field. The rod has a length of 1.6 m and a negligible electrical resistance. The rails also have a negligible electrical resistance. The light bulb has a resistance of 96 ohms . Find (a) the emf produced by the rod and (b) the current induced in the circuit.



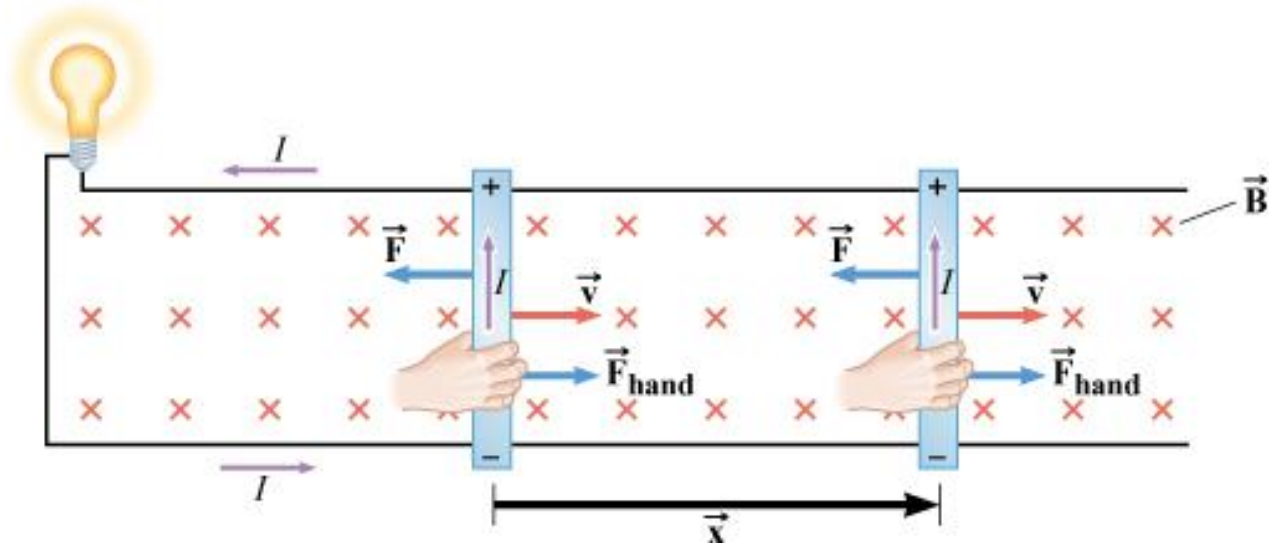
22.2 Motional Emf

(a) $\mathcal{E} = vBL = (5.0 \text{ m/s})(0.80 \text{ T})(1.6 \text{ m}) = 6.4 \text{ V}$

(b) $I = \frac{\mathcal{E}}{R} = \frac{6.4 \text{ V}}{96 \Omega} = 0.067 \text{ A}$



MOTIONAL EMF AND ELECTRICAL ENERGY

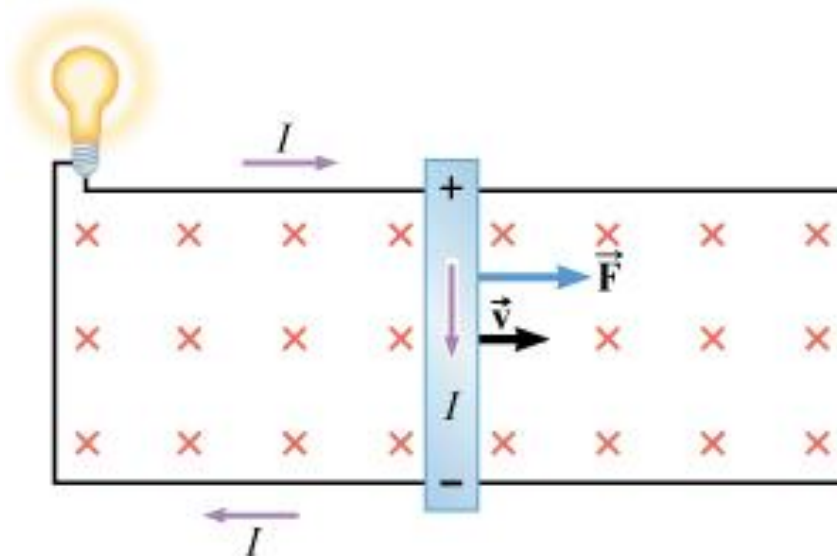


In order to keep the rod moving at constant velocity, the force the hand exerts on the rod must balance the magnetic force on the current:

$$F_{\text{hand}} = F = ILB$$

22.2 Motional Emf

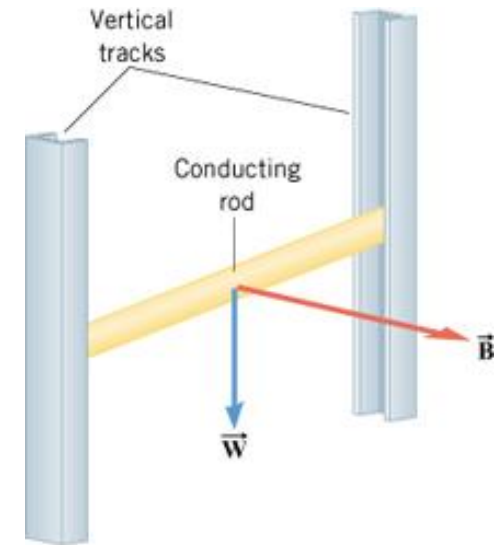
The direction of the force in this figure would violate the principle of conservation of energy.



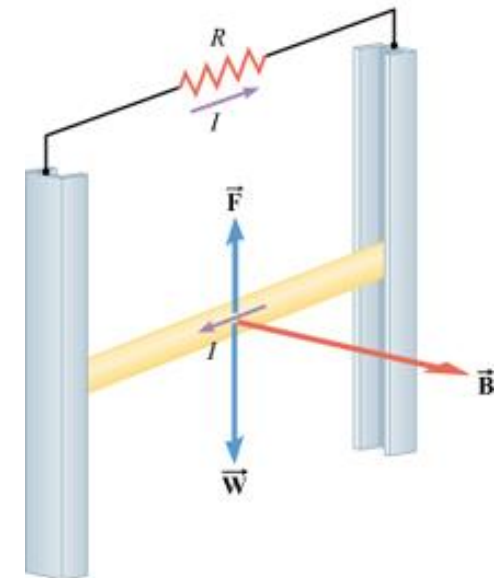
Conceptual Example 3 Conservation of Energy

A conducting rod is free to slide down between two vertical copper tracks. There is no kinetic friction between the rod and the tracks. Because the only force on the rod is its weight, it falls with an acceleration equal to the acceleration of gravity.

Suppose that a resistance connected between the tops of the tracks. (a) Does the rod now fall with the acceleration of gravity? (b) How does the principle of conservation of energy apply?

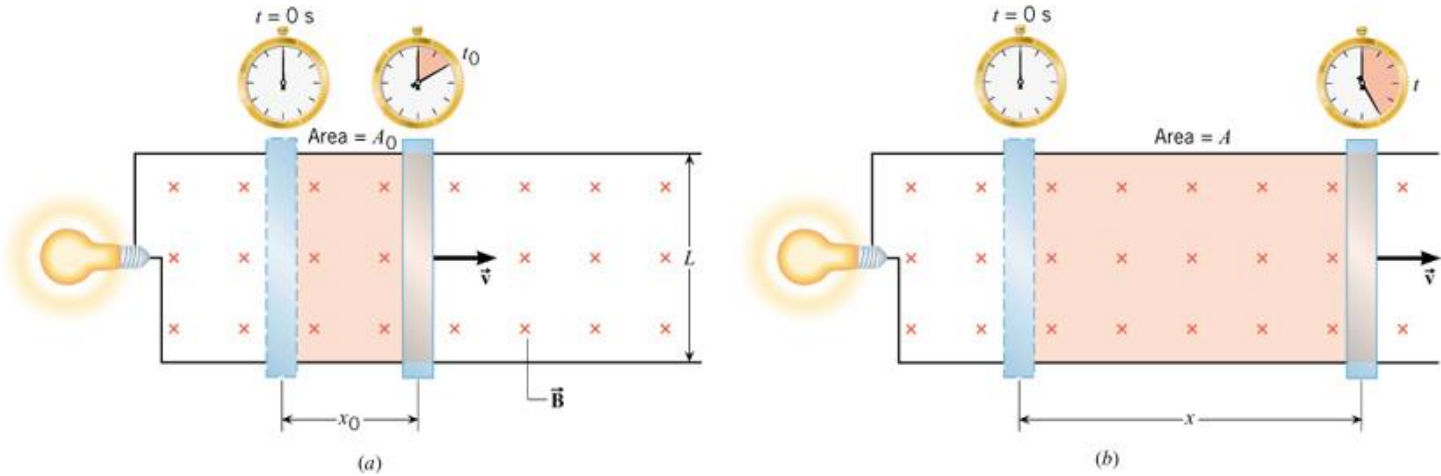


(a)



(b)

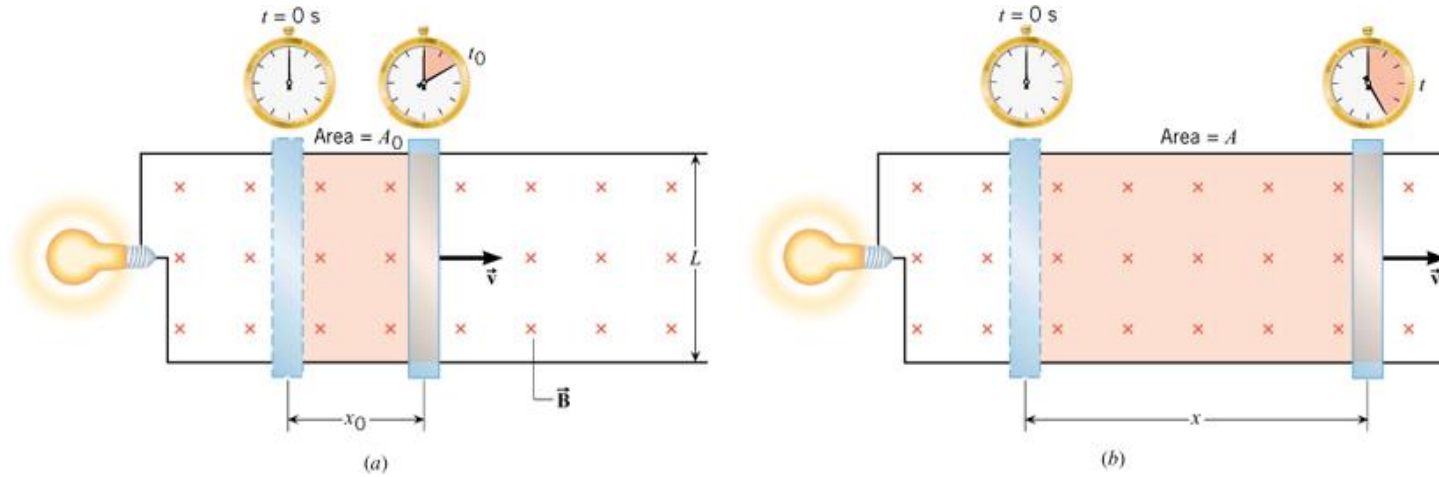
MOTIONAL EMF AND MAGNETIC FLUX



$$\mathcal{E} = vBL = \left(\frac{x - x_0}{t - t_0} \right) BL = \left(\frac{xL - x_0L}{t - t_0} \right) B = \left(\frac{A - A_0}{t - t_0} \right) B = \frac{(BA) - (BA)_0}{t - t_0}$$

magnetic flux $\Phi = BA$

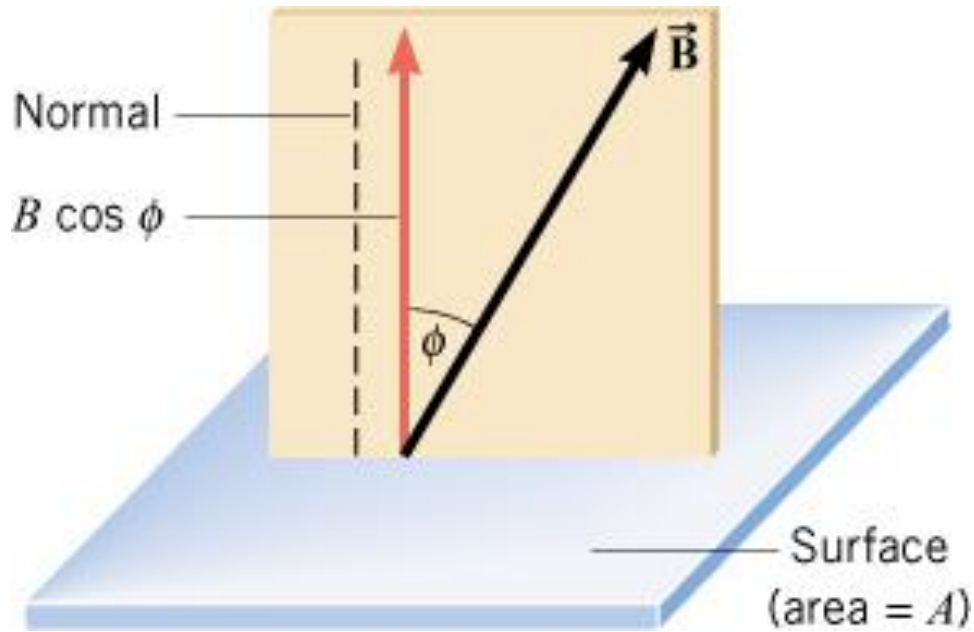
22.3 Magnetic Flux



$$\mathcal{E} = \frac{\Phi - \Phi_0}{t - t_0} = \frac{\Delta\Phi}{\Delta t}$$

22.3 Magnetic Flux

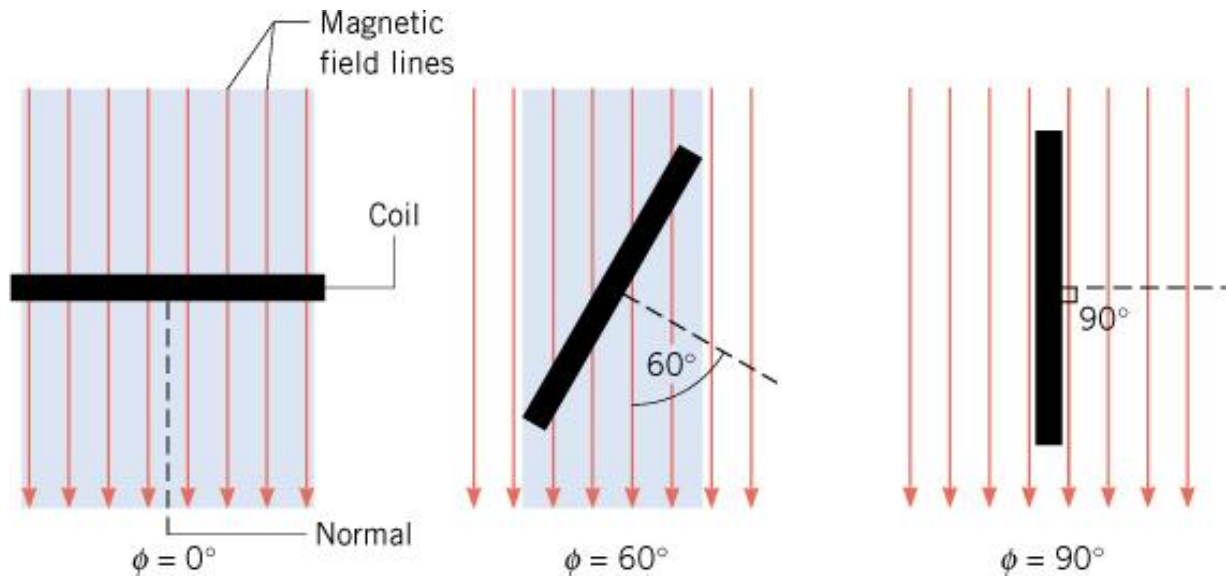
GENERAL EXPRESSION FOR MAGNETIC FLUX



$$\Phi = BA \cos \phi$$

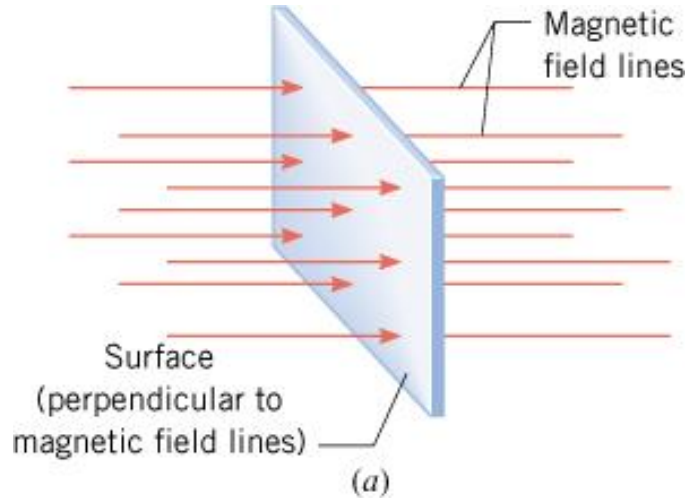
22.3 Magnetic Flux

$$\Phi = BA \cos \phi$$

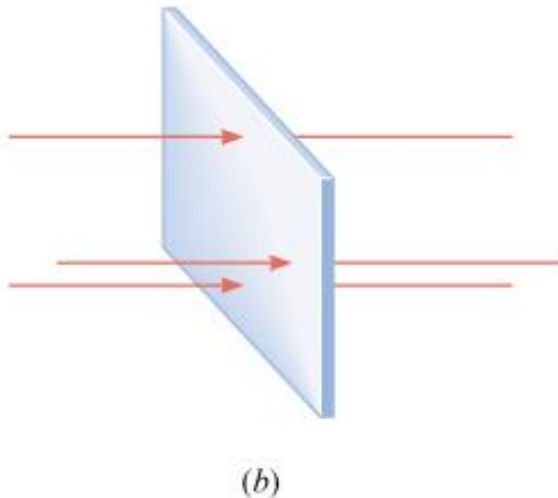


22.3 Magnetic Flux

GRAPHICAL INTERPRETATION OF MAGNETIC FLUX



The magnetic flux is proportional to the number of field lines that pass through a surface.



22.4 Faraday's Law of Electromagnetic Induction

FARADAY'S LAW OF ELECTROMAGNETIC INDUCTION

The average emf induced in a coil of N loops is

$$\mathbf{E} = -N \left(\frac{\Phi - \Phi_o}{t - t_o} \right) = -N \frac{\Delta\Phi}{\Delta t}$$

SI Unit of Induced Emf: volt (V)

22.4 Faraday's Law of Electromagnetic Induction

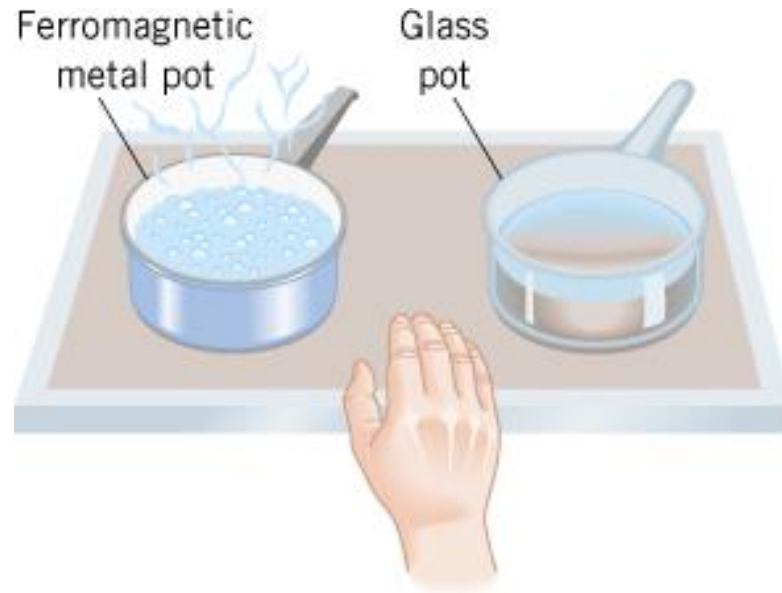
Example 5 The Emf Induced by a Changing Magnetic Field

A coil of wire consists of 20 turns each of which has an area of 0.0015 m^2 . A magnetic field is perpendicular to the surface. Initially, the magnitude of the magnetic field is 0.050 T and 0.10 s later, it has increased to 0.060 T . Find the average emf induced in the coil during this time.

$$\begin{aligned} \mathcal{E} &= -N \frac{\Delta\Phi}{\Delta t} = -N \frac{BA \cos \phi - B_o A \cos \phi}{\Delta t} \\ &= -NA \cos \phi \left(\frac{B - B_o}{\Delta t} \right) = -(20)(0.0015 \text{ m}^2) \cos(0) \frac{0.060 \text{ T} - 0.050 \text{ T}}{0.10 \text{ s}} \\ &= -3.0 \times 10^{-3} \text{ V} \end{aligned}$$

Conceptual Example 7 An Induction Stove

Two pots of water are placed on an induction stove at the same time. The stove itself is cool to the touch. The water in the ferromagnetic metal pot is boiling while that in the glass pot is not. How can such a cool stove boil water, and why isn't the water in the glass pot boiling?



LENZ'S LAW

The induced emf resulting from a changing magnetic flux has a polarity that leads to an induced current whose direction is such that the induced magnetic field opposes the original flux change.

LENZ'S LAW

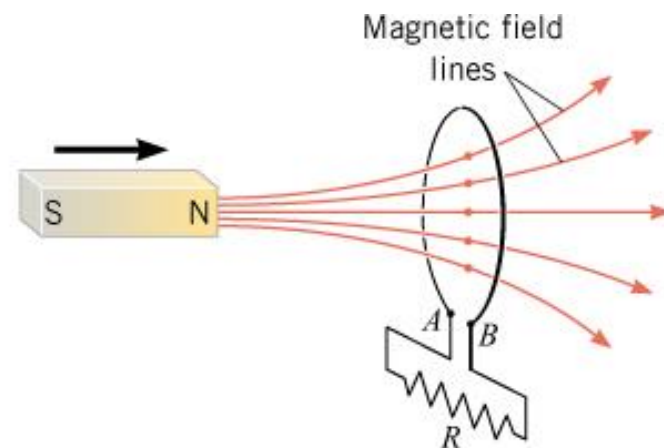
The induced emf resulting from a changing magnetic flux has a polarity that leads to an induced current whose direction is such that the induced magnetic field opposes the original flux change.

Reasoning Strategy

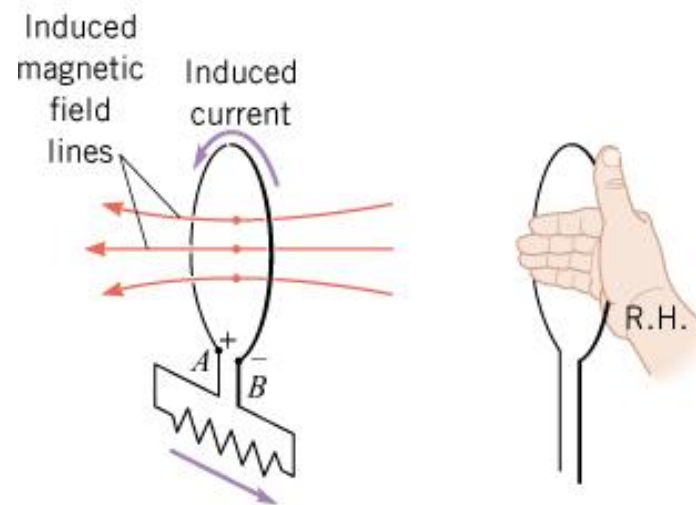
1. Determine whether the magnetic flux that penetrates the coil is increasing or decreasing.
2. Find what the direction of the induced magnetic field must be so that it can oppose the change in flux by adding or subtracting from the original field.
3. Use RHR-2 to determine the direction of the induced current.

Conceptual Example 8 The Emf Produced by a Moving Magnet

A permanent magnet is approaching a loop of wire. The external circuit consists of a resistance. Find the direction of the induced current and the polarity of the induced emf.



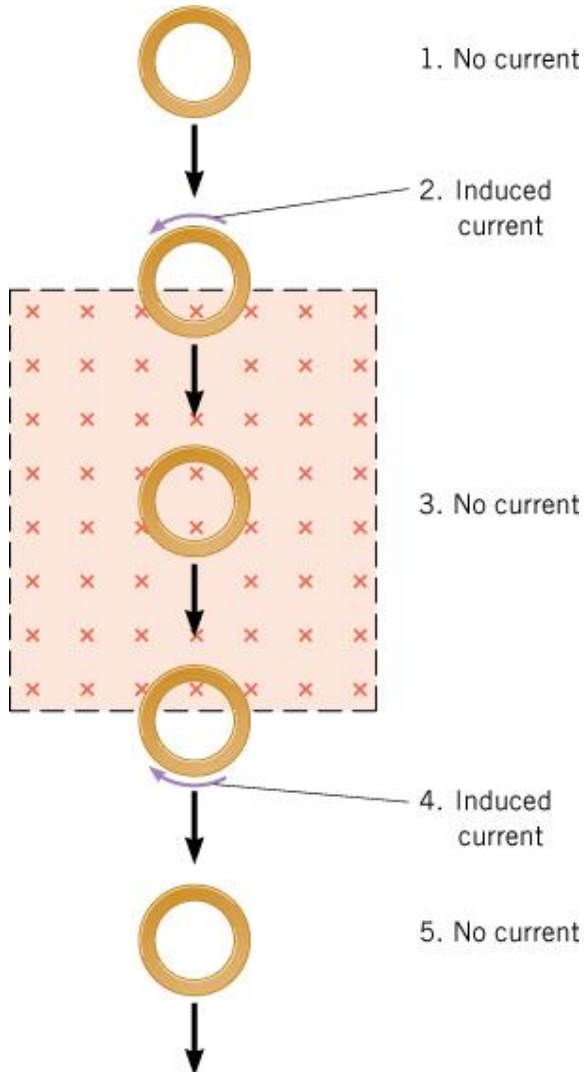
(a)



(b)

22.5 Lenz's Law

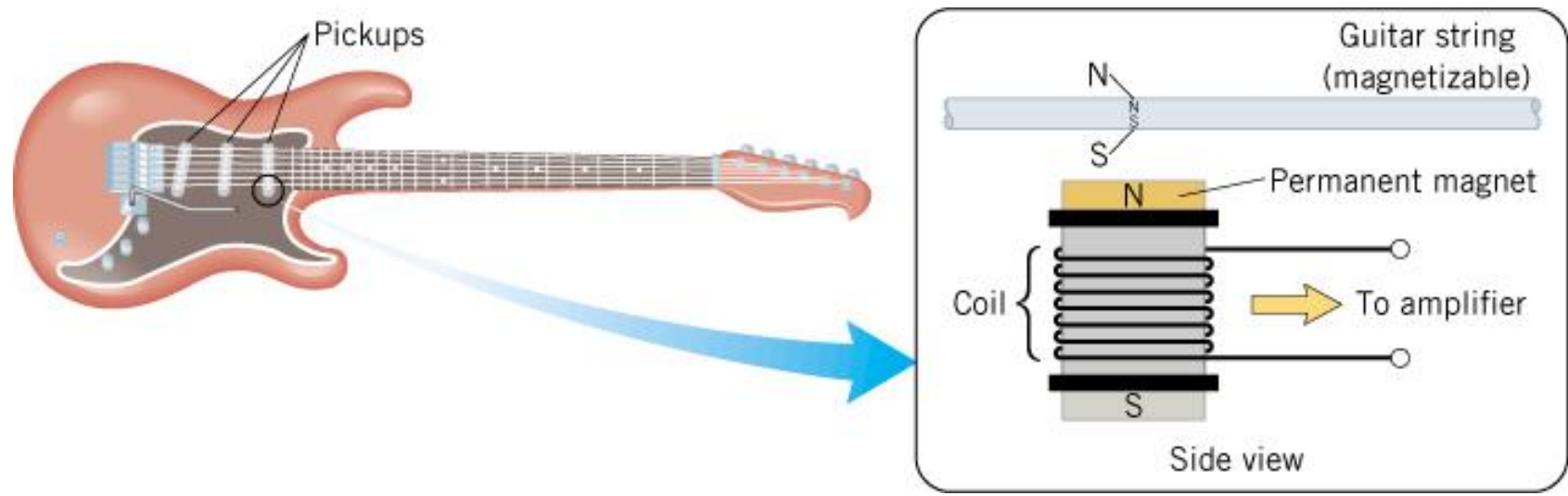
Conceptual Example 9 The Emf Produced by a Moving Copper Ring.



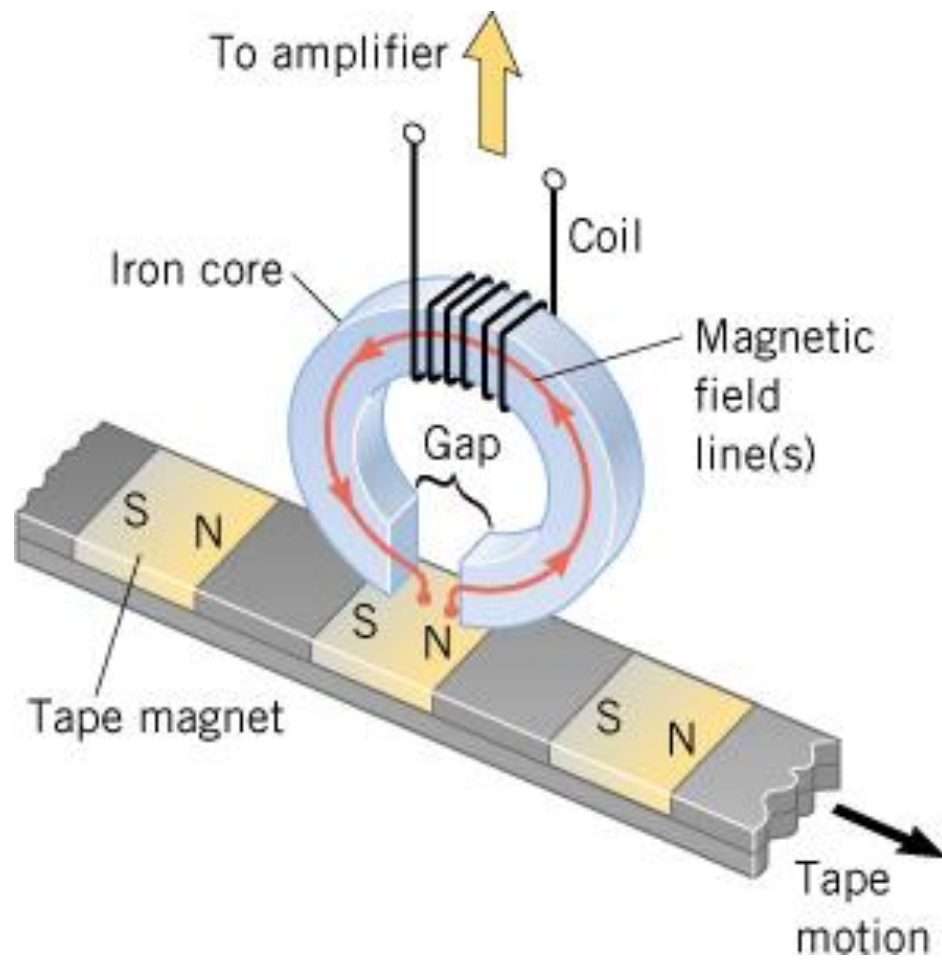
There is a constant magnetic field directed into the page in the shaded region. The field is zero outside the shaded region. A copper ring slides through the region.

For each of the five positions, determine whether an induced current exists and, if so, find its direction.

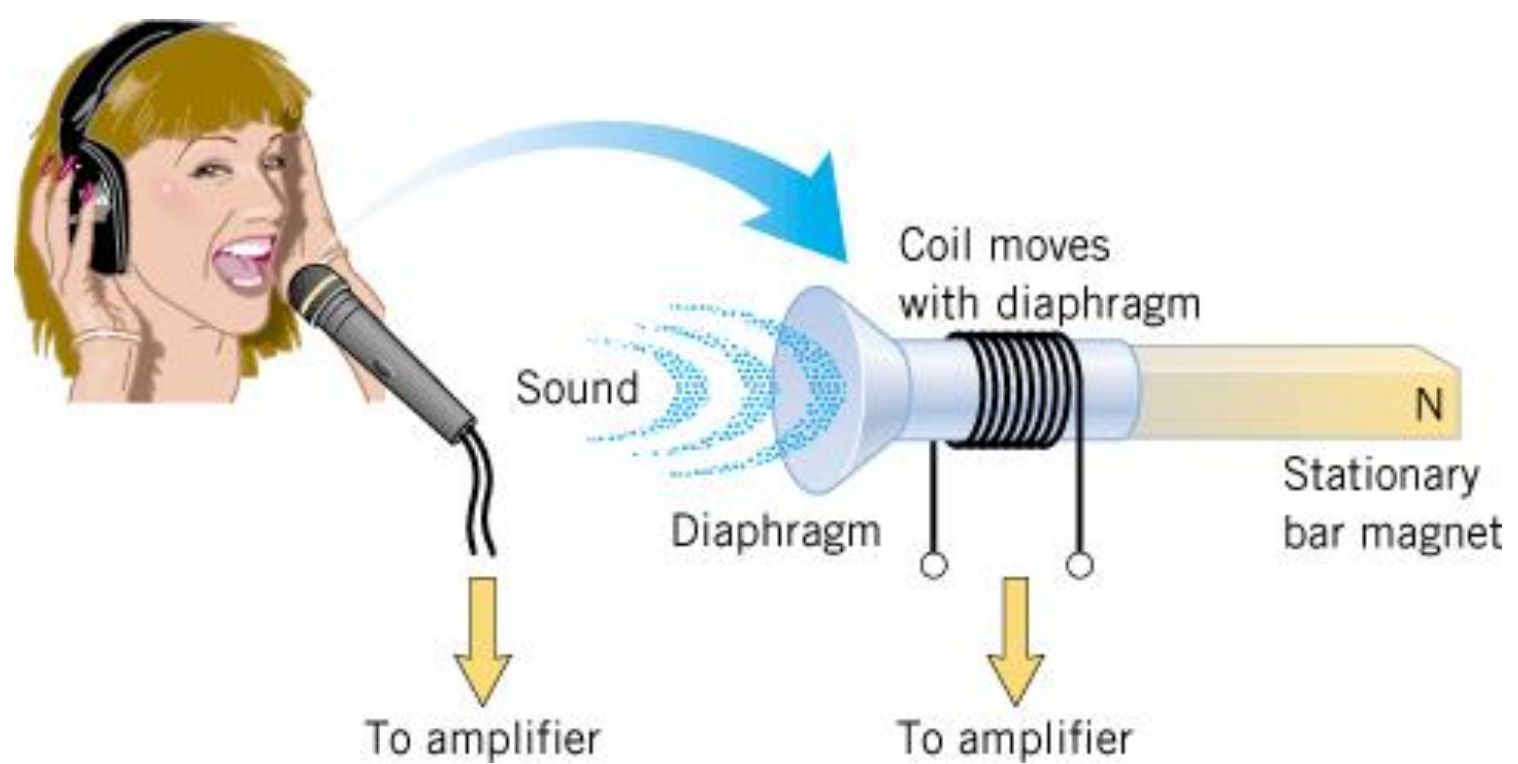
22.6 Applications of Electromagnetic Induction to the Reproduction of Sound



22.6 Applications of Electromagnetic Induction to the Reproduction of Sound

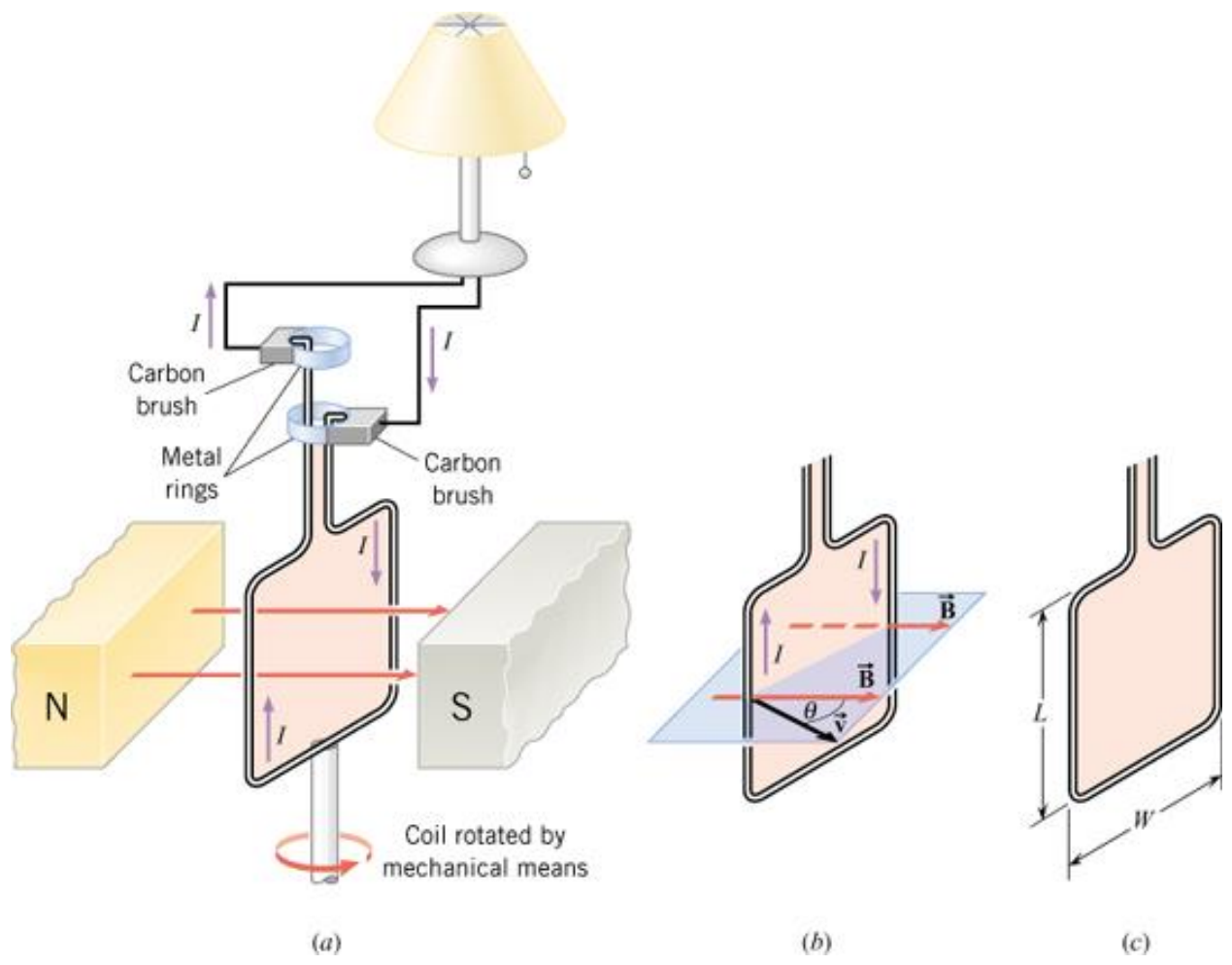


22.6 Applications of Electromagnetic Induction to the Reproduction of Sound

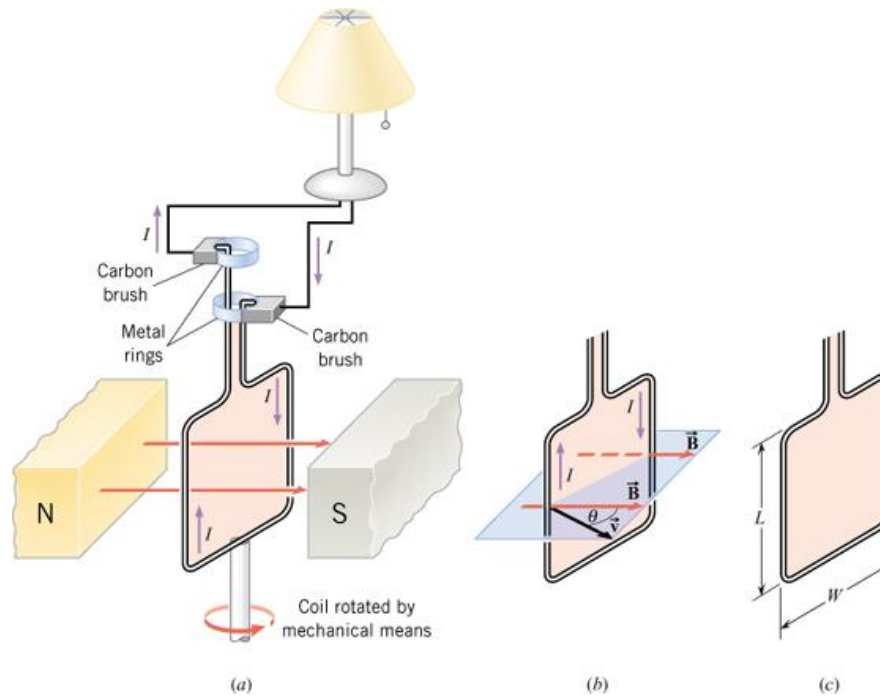


22.7 The Electric Generator

HOW A GENERATOR PRODUCES AND EMF



22.7 The Electric Generator



$$\mathbf{E} = v_{\perp} BL = BLv \sin \theta$$

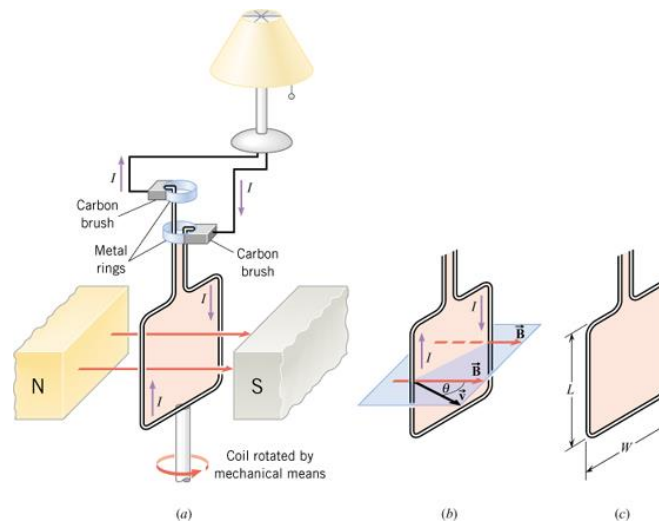
$$v = r\omega = \frac{W}{2} \omega$$

22.7 The Electric Generator

Emf induced in a rotating planar coil

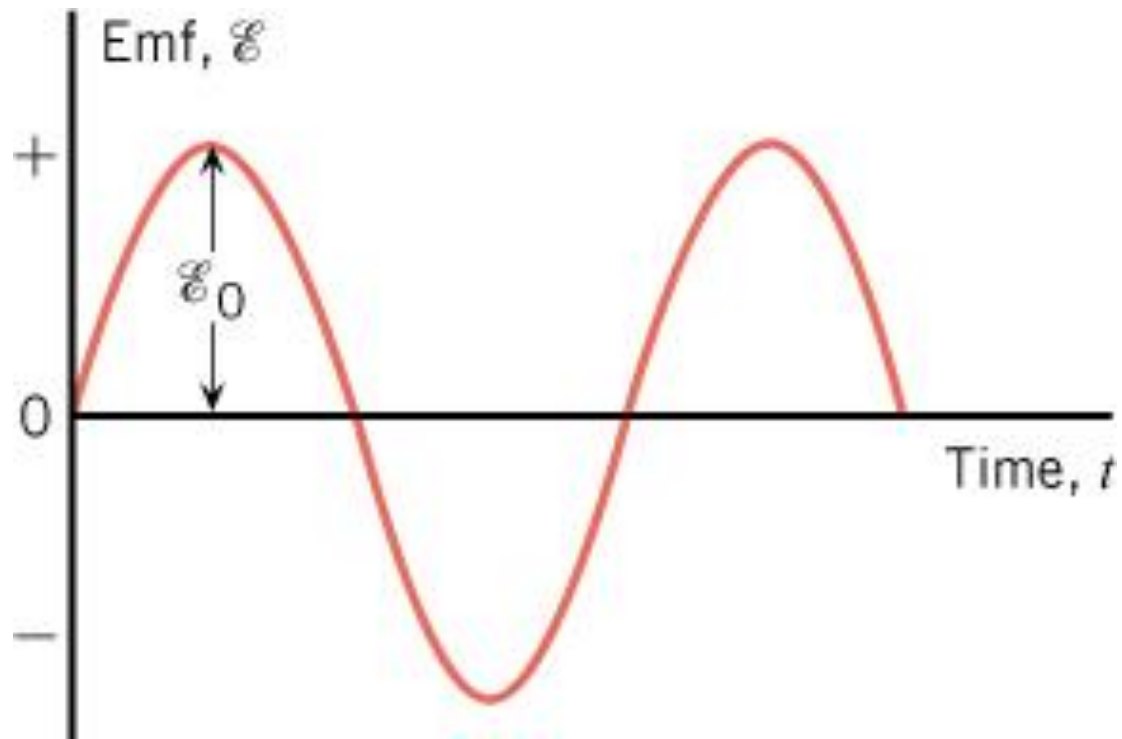
$$\mathbf{E} = NAB\omega \sin \omega t = \mathbf{E}_o \sin \omega t$$

$$\omega = 2\pi f$$



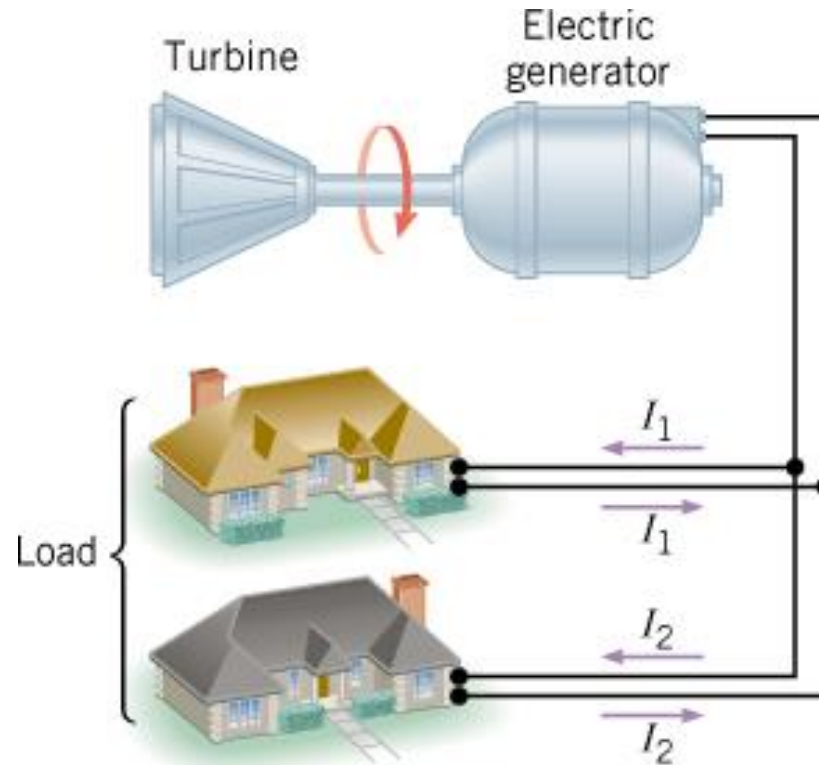
22.7 The Electric Generator

$$\mathcal{E} = \mathcal{E}_0 \sin \omega t$$



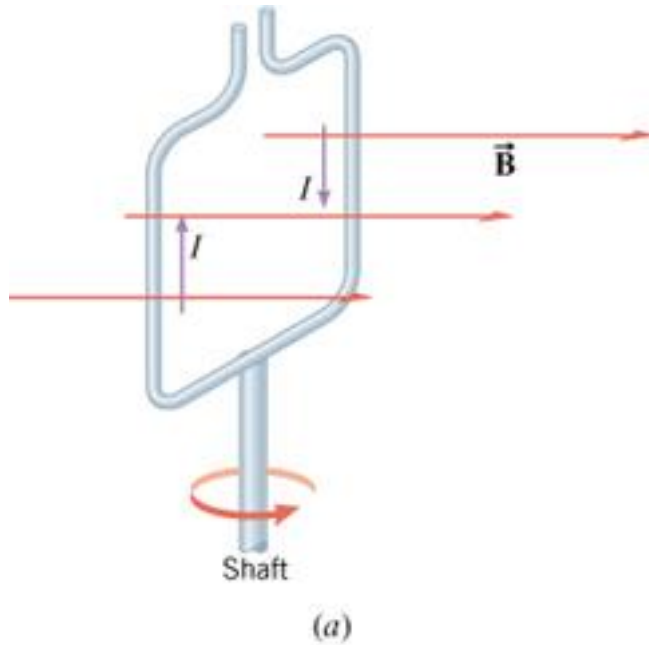
22.7 The Electric Generator

THE ELECTRICAL ENERGY DELIVERED BY A GENERATOR AND THE COUNTERTORQUE

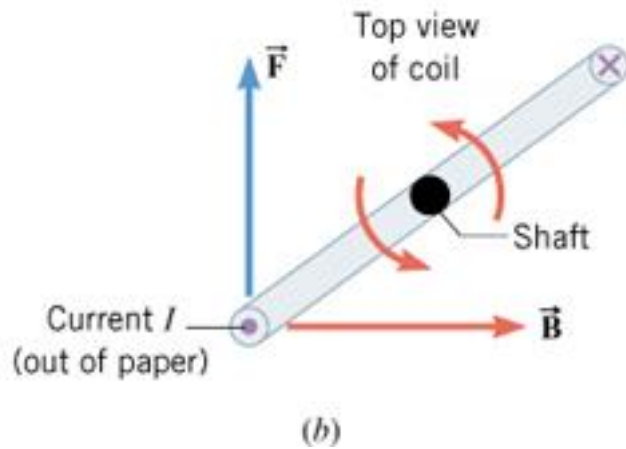


When the generator is delivering current, there is a magnetic force acting on the coils.

22.7 The Electric Generator

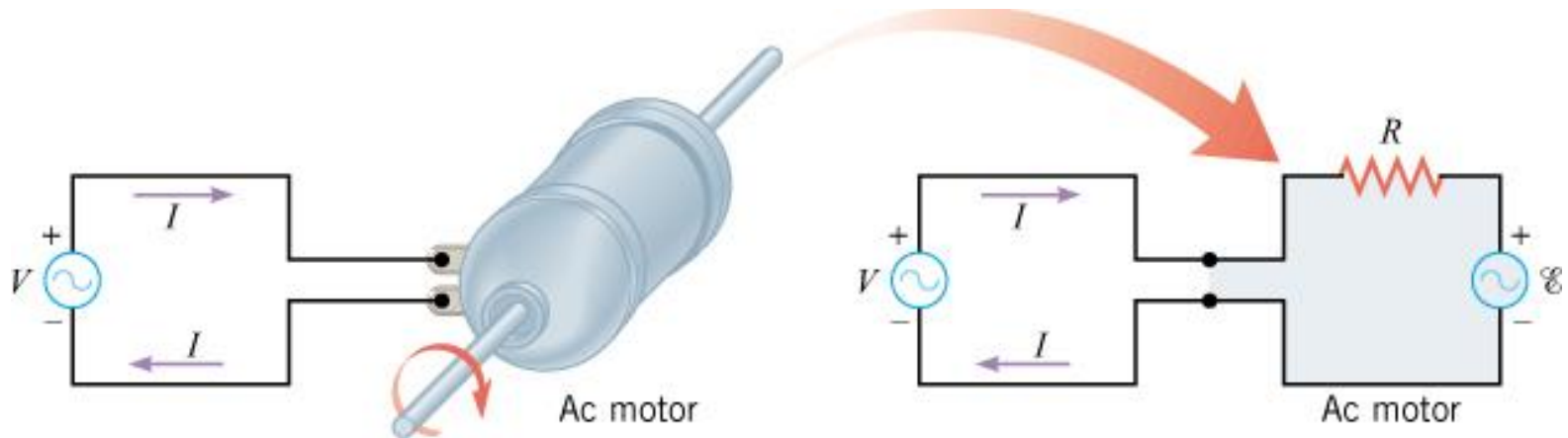


The magnetic force gives rise to a countertorque that opposes the rotational motion.



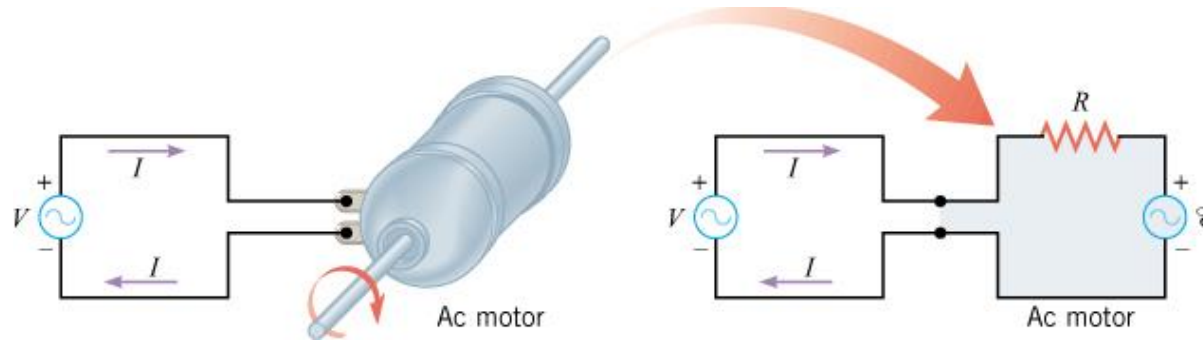
THE BACK EMF GENERATED BY AN ELECTRIC MOTOR

When a motor is operating, two sources of emf are present: (1) the applied emf V that provides current to drive the motor, and (2) the emf induced by the generator-like action of the rotating coil.



22.7 The Electric Generator

Consistent with Lenz's law, the induced emf acts to oppose the applied emf and is called **back emf**.



$$I = \frac{V - E}{R}$$

Example 12 Operating a Motor

The coil of an ac motor has a resistance of 4.1 ohms. The motor is plugged into an outlet where the voltage is 120.0 volts (rms), and the coil develops a back emf of 118.0 volts (rms) when rotating at normal speed. The motor is turning a wheel. Find (a) the current when the motor first starts up and (b) the current when the motor is operating at normal speed.

$$(a) \quad I = \frac{V - \mathbf{E}}{R} = \frac{120 \text{ V} - 0 \text{ V}}{4.1 \Omega} = 29 \text{ A}$$

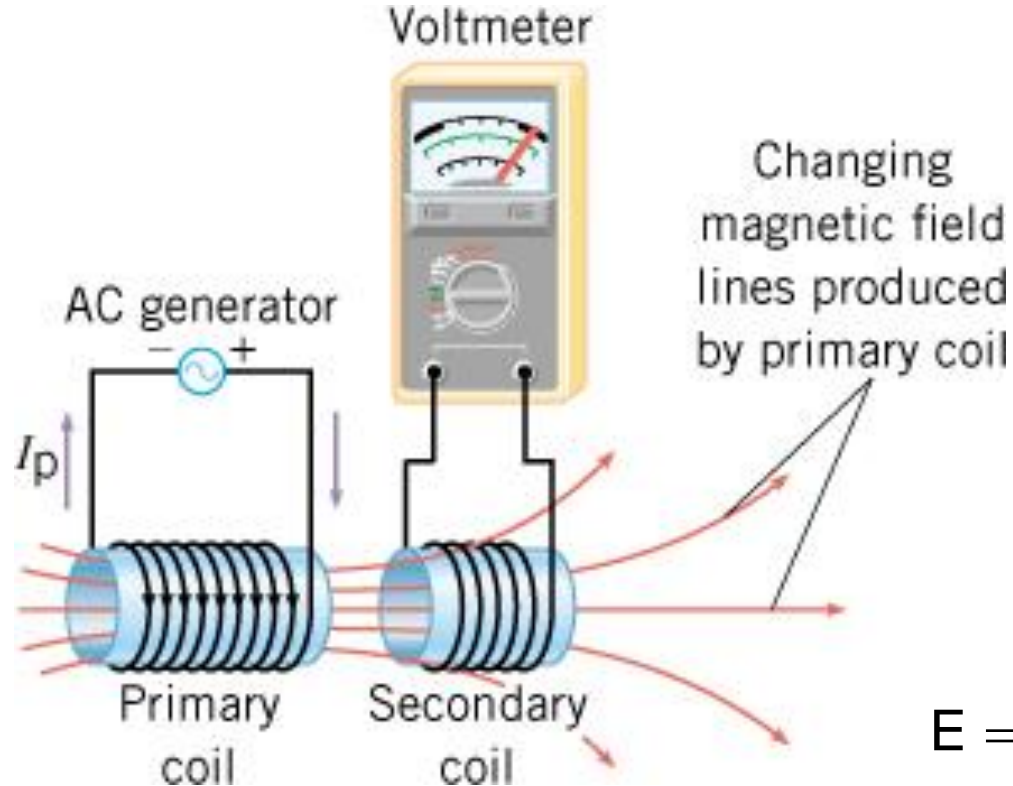
$$(b) \quad I = \frac{V - \mathbf{E}}{R} = \frac{120 \text{ V} - 118.0 \text{ V}}{4.1 \Omega} = 0.49 \text{ A}$$

22.8 Mutual Inductance and Self Inductance

MUTUAL INDUCTANCE

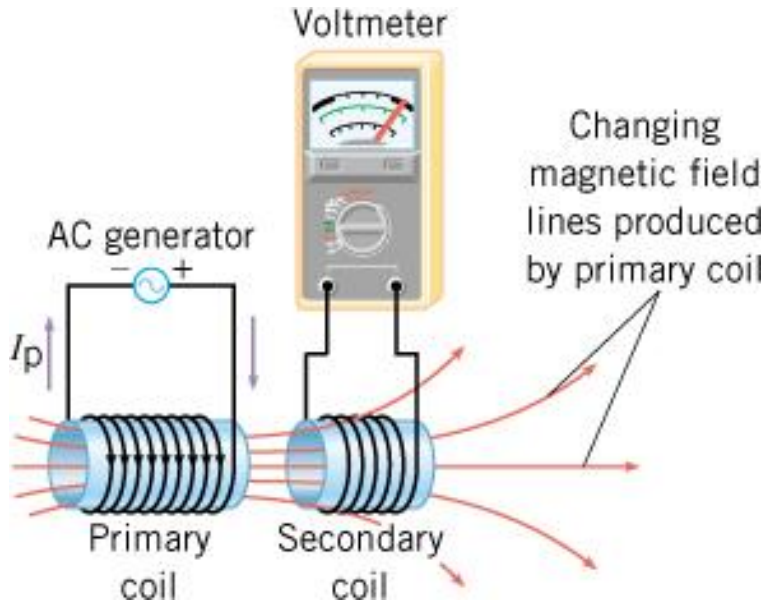
The changing current in the primary coil creates a changing magnetic flux through the secondary coil, which leads to an induced emf in the secondary coil.

The effect is called ***mutual induction***.



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

22.8 Mutual Inductance and Self Inductance



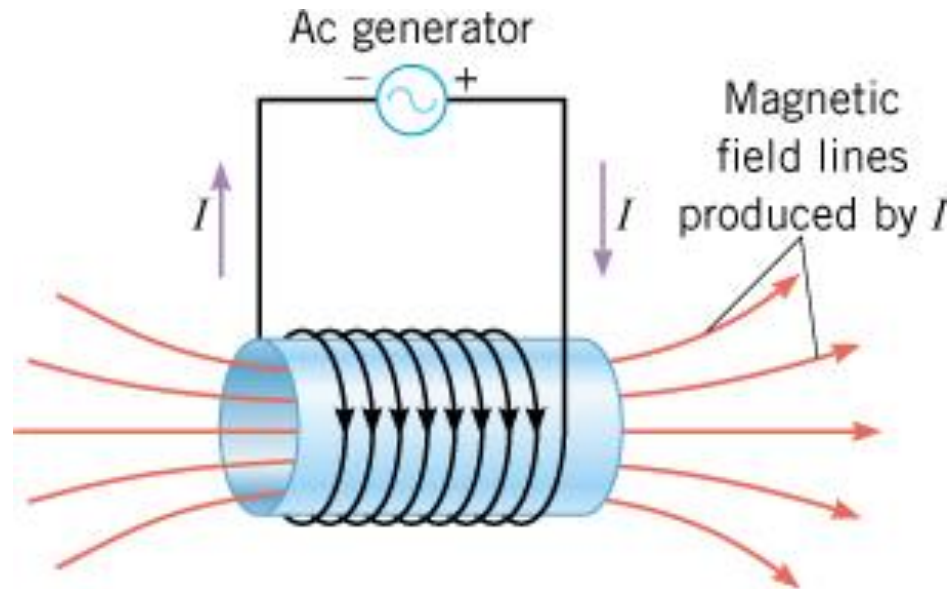
Emf due to mutual induction

$$E_s = -M \frac{\Delta I_p}{\Delta t}$$

mutual inductance

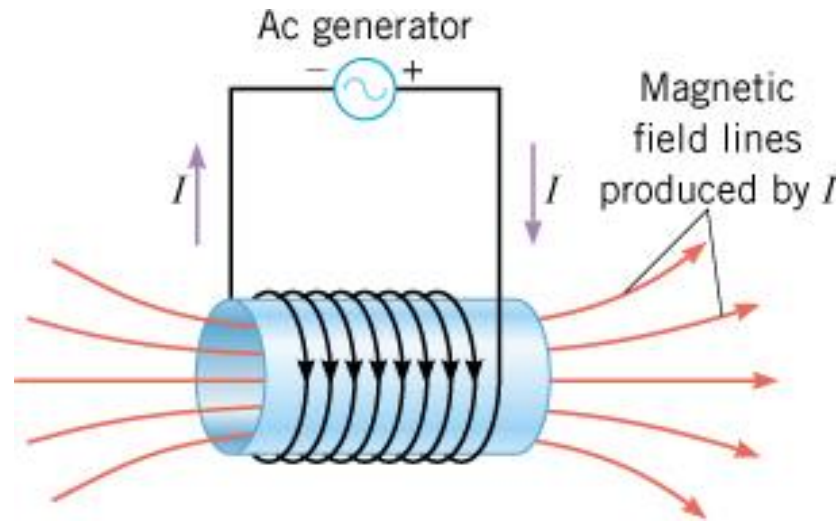
SI Unit of mutual inductance: $1 \text{ V} \cdot \text{s} / \text{A} = 1 \text{ H}$ (Henry)

SELF INDUCTANCE



The effect in which a changing current in a circuit induces an emf in the same circuit is referred to as **self induction**.

22.8 Mutual Inductance and Self Inductance



$$\mathcal{E} = -L \frac{\Delta I}{\Delta t}$$

self inductance

SI Unit of self inductance: $1 \text{ V} \cdot \text{s} / \text{A} = 1 \text{ H}$ (Henry)

THE ENERGY STORED IN AN INDUCTOR

*Energy stored in
an inductor*

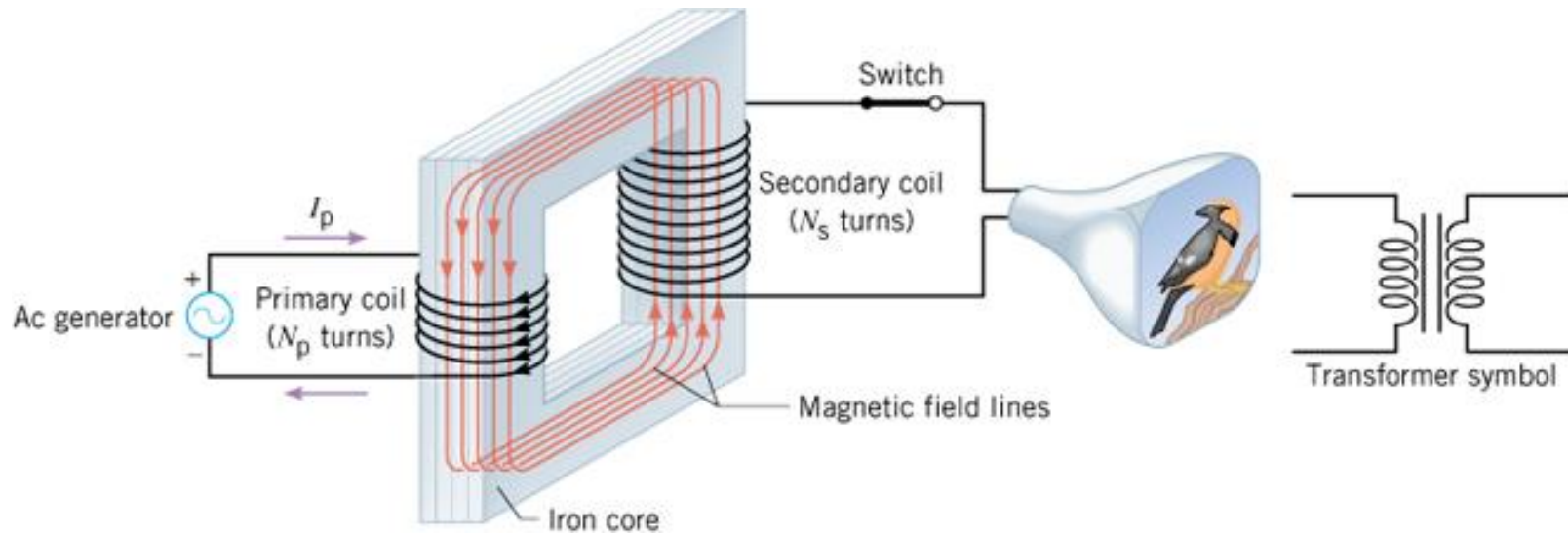
$$\text{Energy} = \frac{1}{2} LI^2$$

Energy density

$$\text{Energy density} = \frac{1}{2\mu_0} B^2$$

22.9 Transformers

A **transformer** is a device for increasing or decreasing an ac voltage.

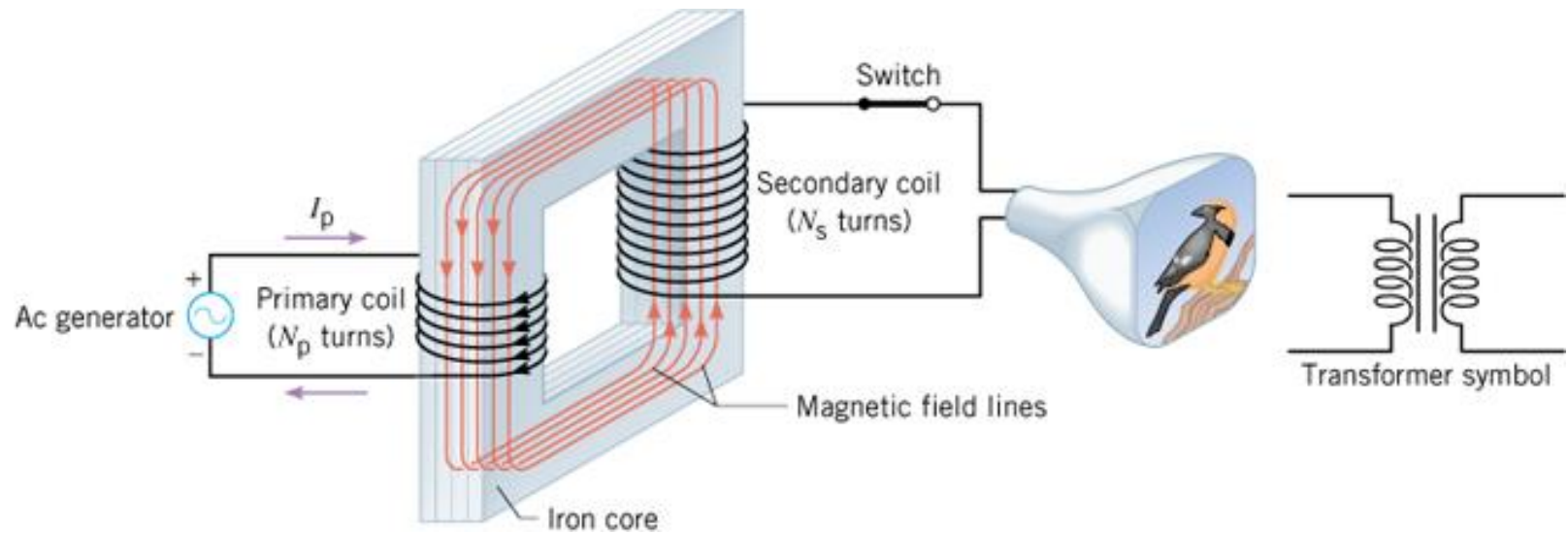


$$\mathcal{E}_s = -N_s \frac{\Delta\Phi}{\Delta t}$$

$$\mathcal{E}_p = -N_p \frac{\Delta\Phi}{\Delta t}$$

$$\frac{\mathcal{E}_s}{\mathcal{E}_p} = \frac{N_s}{N_p}$$

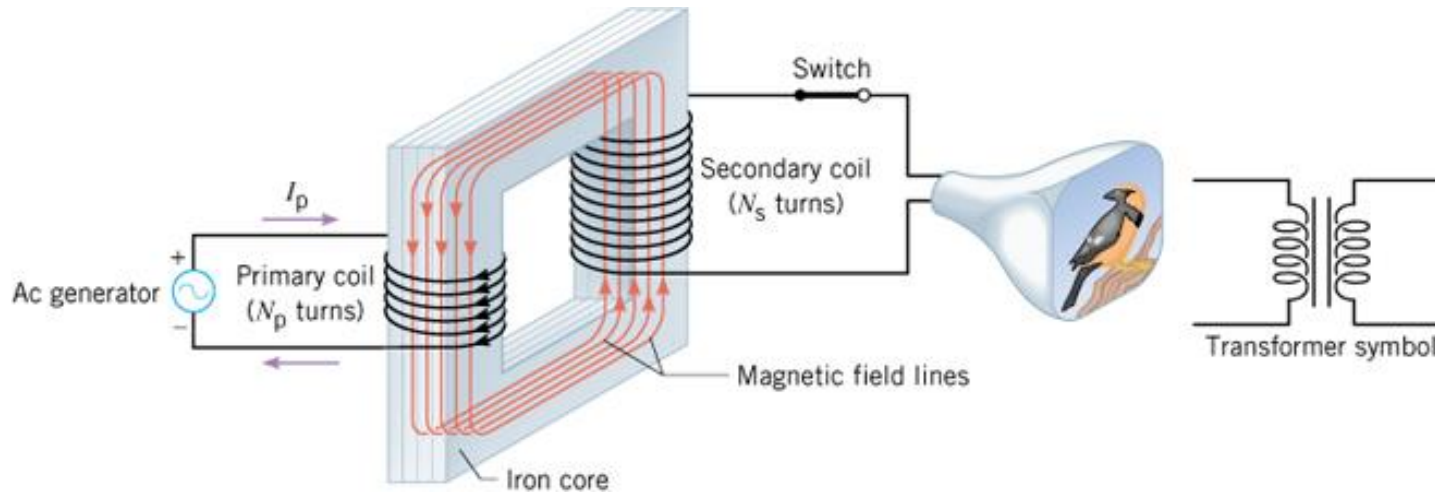
22.9 Transformers



Transformer equation

$$\frac{V_s}{V_p} = \frac{N_s}{N_p}$$

22.9 Transformers



$$\frac{I_s}{I_p} = \frac{V_p}{V_s} = \frac{N_p}{N_s}$$

A transformer that steps up the voltage simultaneously steps down the current, and a transformer that steps down the voltage steps up the current.

22.9 Transformers

