Chapter 22

Electromagnetic Induction

FARADAY'S LAW OF ELECTROMAGNETIC INDUCTION

The average emf induced in a coil of *N* loops is

(The motional emf-Φ relation we derived is a special case of this.)

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

where, $\Phi = BA \cos \phi$

the minus sign reminds us that the induced emf will oppose the change in Φ
➔ *LENZ'S LAW*

SI Unit of Induced Emf: volt (V)

Faraday's law states that an emf is generated if the magnetic flux changes for **any reason**. Since $\Phi = BA \cos \phi$, any change of B, A, or ϕ will induce an emf.

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.

Magnetic field
lines

S   N

A B

R

(a)
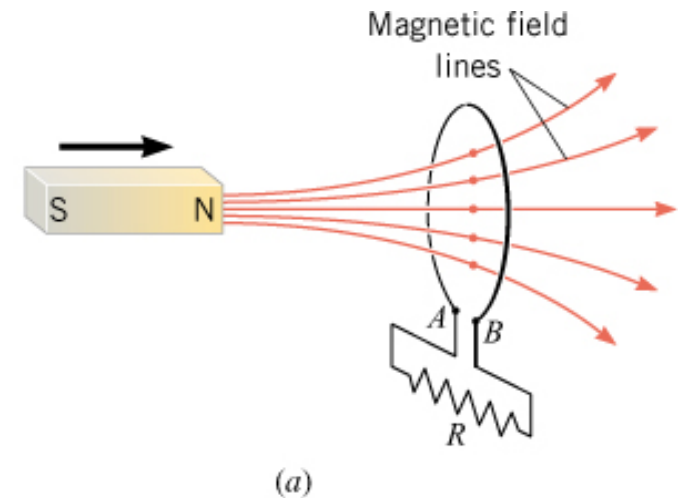
Since the applied magnetic field in
the loop is increasing and pointing
to the right, Lenz's law says an
induced current will be created in
the loop to try to oppose this change
by creating an induced magnetic
field to the left.

Induced
magnetic   Induced
field   current
lines

A B

R.H.

(b)
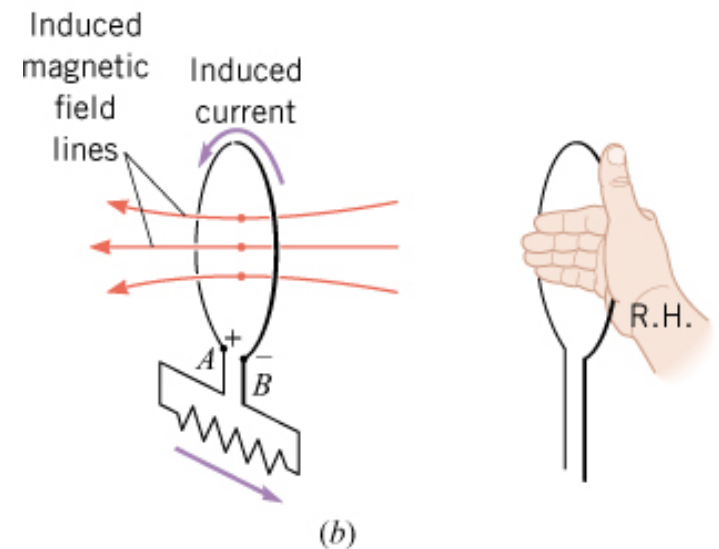
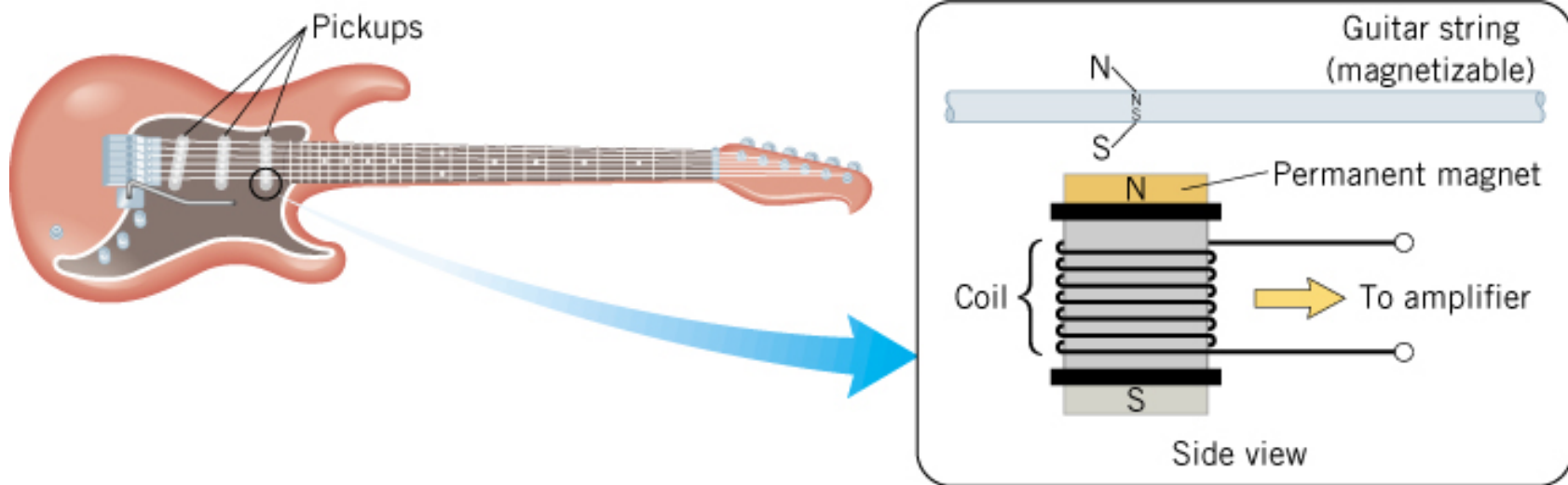*Conceptual Example 9* **The Emf Produced by a Moving Copper Ring.**
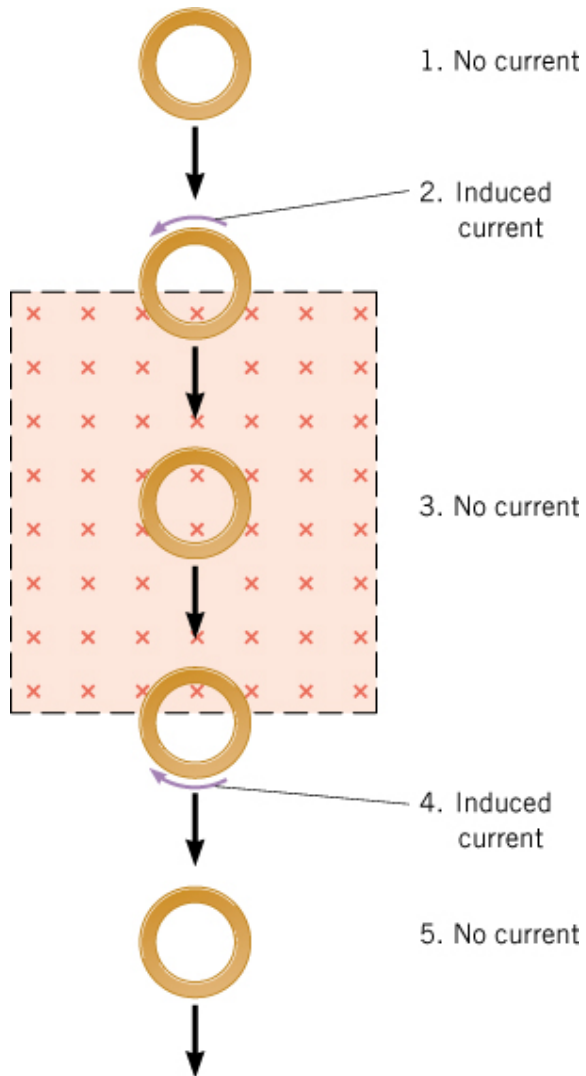
There is a constant horizontal magnetic field directed into the page in the shaded region. The field is zero outside the shaded region. A copper ring is dropped vertically through the region.

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

Is the acceleration of the ring the same as it drops through the five positions?

1. No current

2. Induced current

3. No current

4. Induced current

5. No current

Electric guitar pickup

Pickups

Guitar string
(magnetizable)

N

S

N — Permanent magnet

Coil

To amplifier

S

Side view

When the string of an electric guitar vibrates, an emf is induced in the coil of the pickup from the vibration of the induced magnetization in the string. The two ends of the coil are connected to the input of an amplifier which is connected to speakers.
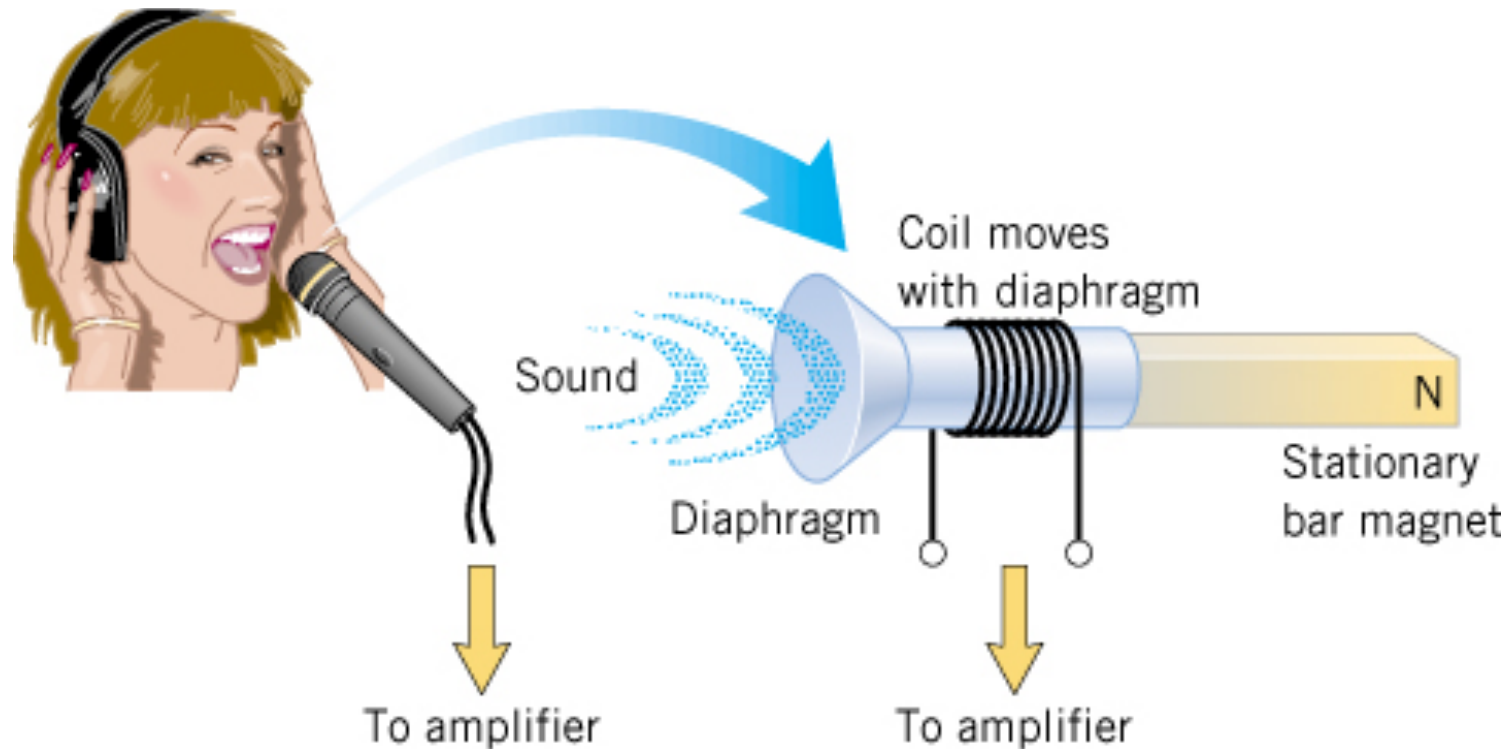
Playback head of a tape deck

As each "tape magnet" goes by the gap, some magnetic field lines pass through the iron core and coil. The changing flux in the coil creates an induced emf which is then amplified and then sent to the speakers.
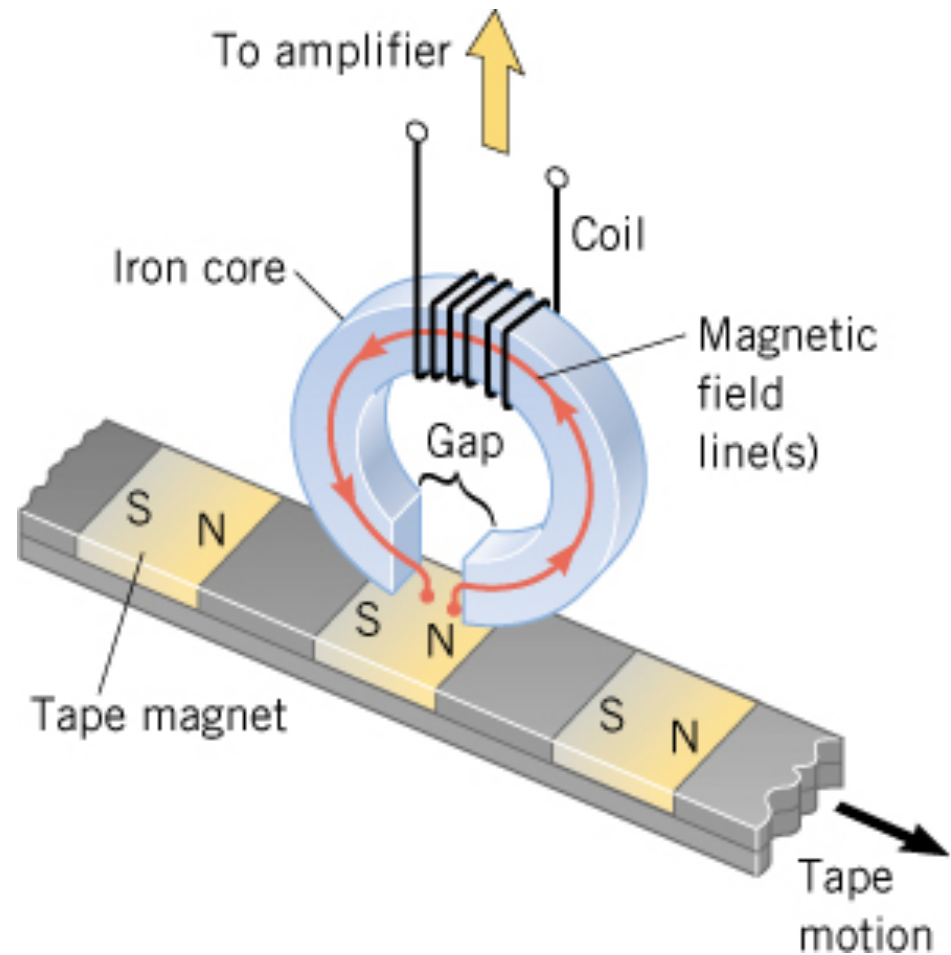
Moving coil microphone

When a sound wave strikes the diaphragm, a coil fixed to the diaphragm vibrates over a stationary bar magnet, changing the flux in the coil and inducing an emf in the coil which is then amplified and sent to, e.g., speakers.

Electric generators

A **battery** converts **chemical energy** into **electrical energy**
to produce currents and voltages in circuits.

An **electric generator** uses Faraday's Law to convert
mechanical energy into **electrical energy**.

➔ **Most of the electric power in the world is produced
by electric generators!**
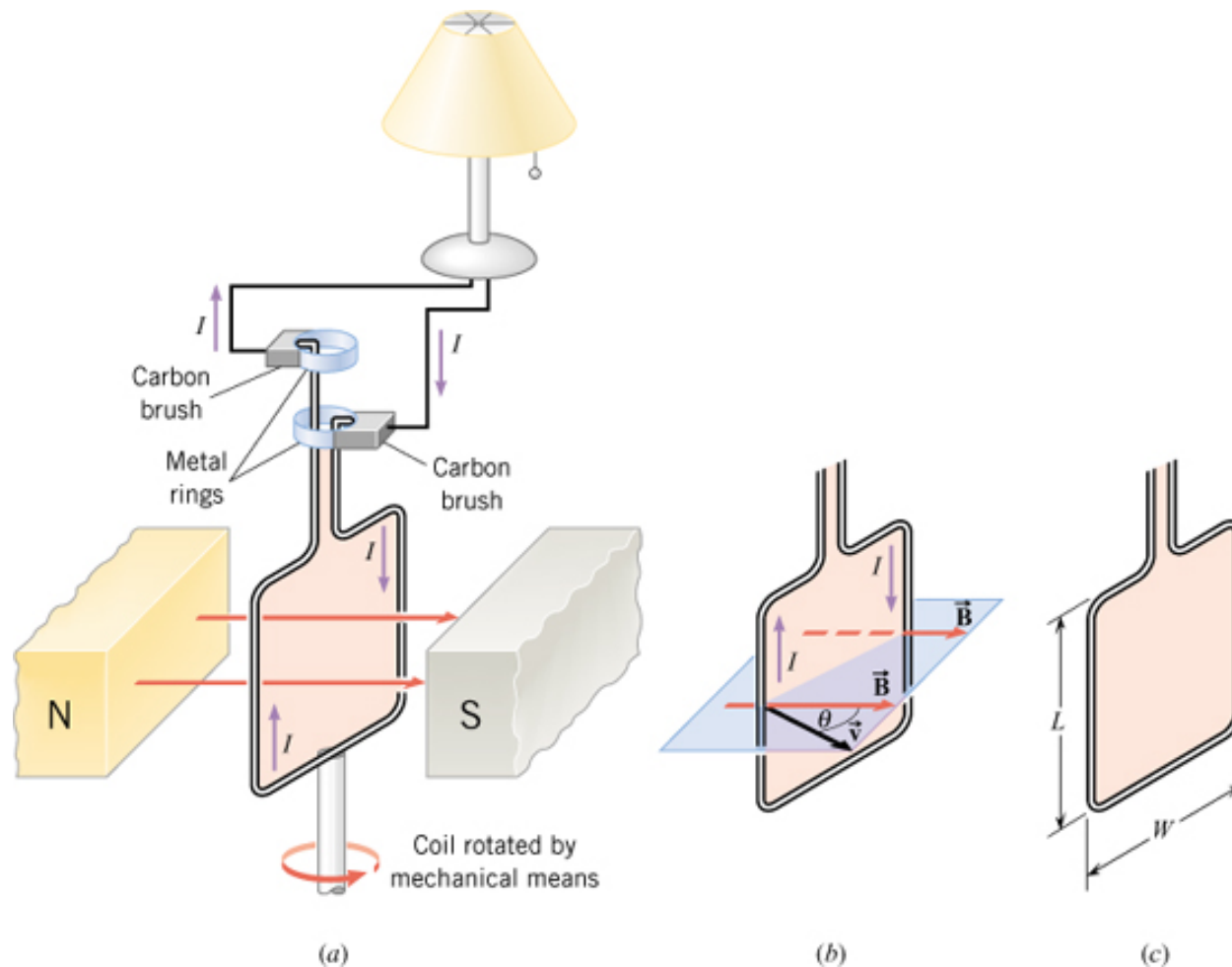
(e.g. the 120 V out of your electrical outlet)

HOW AN ELECTRIC GENERATOR PRODUCES AN EMF

An electric generator has essentially the same configuration as an electric motor, it is just used differently, i.e.,

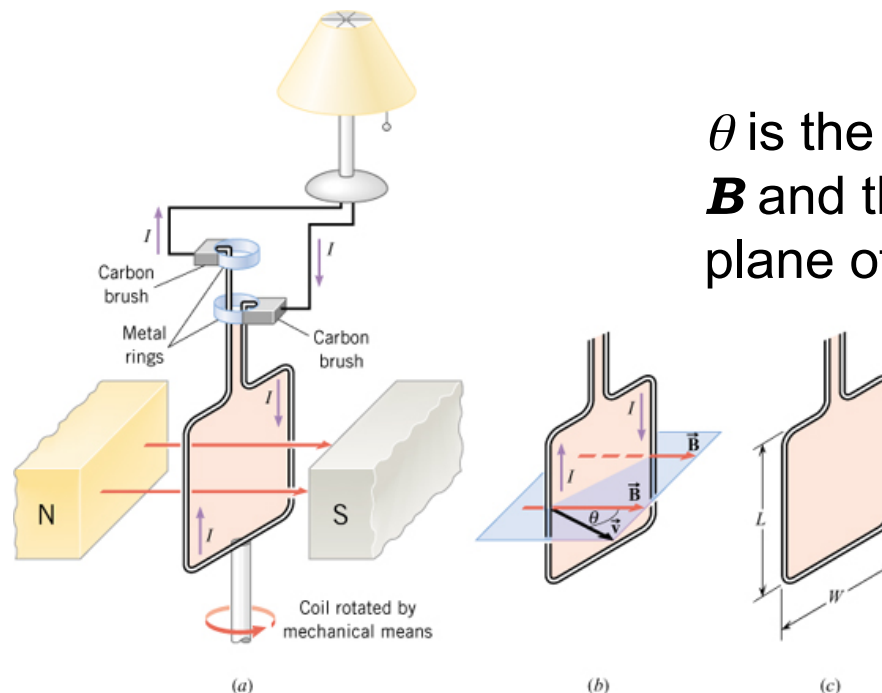**motor:** I ➔ mechanical energy   **generator:** mechanical energy ➔ I

Carbon brush

Metal rings

Carbon brush

N

S

Coil rotated by mechanical means

$\vec{B}$

θ $\vec{v}$

L

W

(a)   (b)   (c)

Derivation of the *emf induced in a rotating planar coil*

Use our motional emf equation for a straight wire ➜ $\mathcal{E} = vBL$
where v, B, and L are all perpendicular to each other

If the *left vertical side* of the spinning coil moves at velocity $\boldsymbol{v}$, the component of $\boldsymbol{v}$ perpendicular to $\boldsymbol{B}$ is $v \sin \theta$, so its contribution to the emf is $BLv \sin \theta$. Since the *right vertical side* contributes the same emf

$$\blacktriangleright \mathcal{E} = 2BLv \sin \theta$$

Carbon brush

Metal rings

Carbon brush

N

S

Coil rotated by mechanical means

$\vec{B}$

$\vec{B}$

θ $\vec{v}$

L

w

(a)   (b)   (c)

θ is the angle between $\boldsymbol{B}$ and the normal to the plane of the loop.
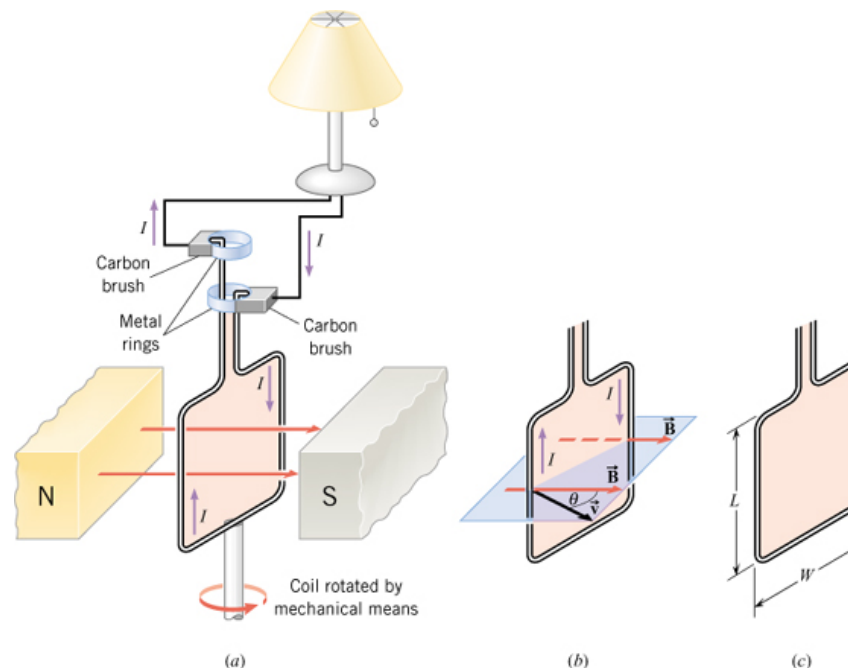
Since the angular velocity of the spinning coil is $\omega = v/r$ and in this case $r = W/2$, then $v = \omega W/2$. ω is in radians/sec, so if $\theta = 0$ at $t = 0$, then $\theta = \omega t$, and our expression for $\mathcal{E}$ becomes

$$\mathcal{E} = 2BLv \sin \theta = 2BL(\omega W/2) \sin \omega t = (LW)B\omega \sin \omega t$$

For a coil of N loops and identifying $A = LW$ (valid for **any** planar shape),

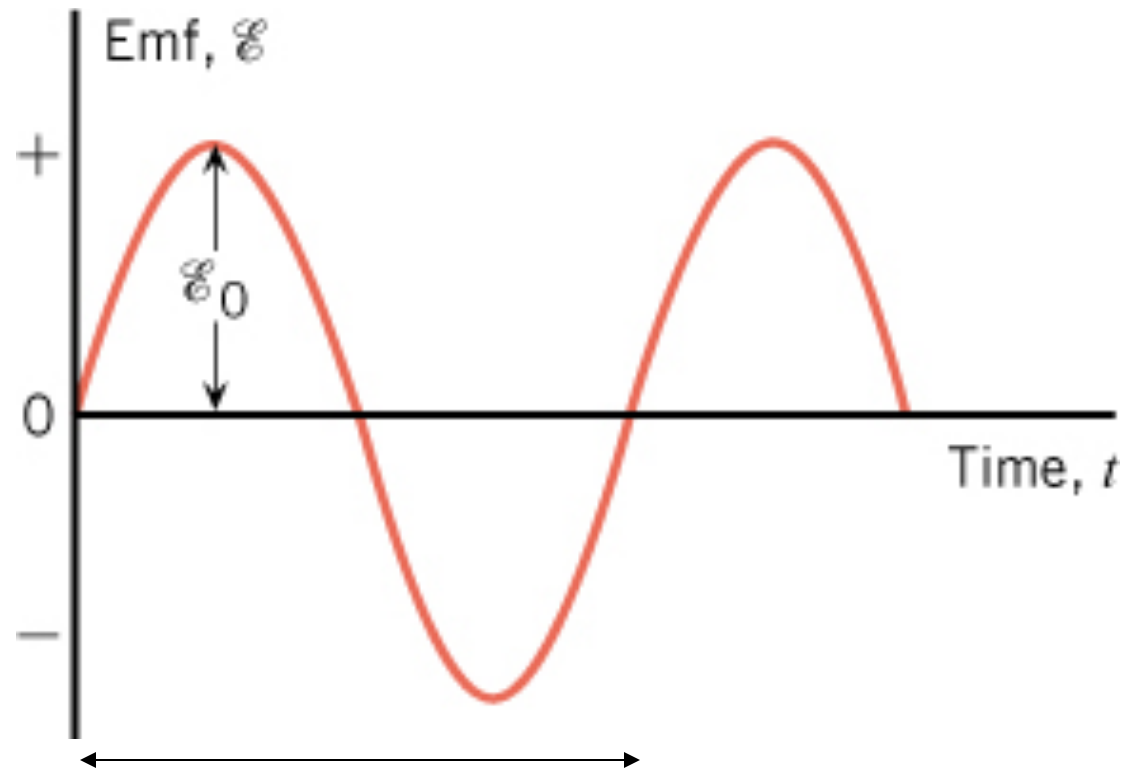$$\mathcal{E} = NAB\omega \sin \omega t = \mathcal{E}_0 \sin \omega t$$

$\omega = 2\pi f$
where f is the rotational frequency in Hertz (Hz)

Carbon brush

Metal rings

Carbon brush

N

S

Coil rotated by mechanical means

$\vec{B}$

$\vec{B}$

θ $\vec{v}$

L

W

(a)

(b)

(c)

$$\mathcal{E} = \mathcal{E}_0 \sin \omega t \ , \quad \mathcal{E}_0 = NAB\omega \text{ , maximum emf}$$

➔ emf from generators is sinusoidal in time
   ➔ alternating current (ac)

$$T = \text{period} = 1/f = 2\pi/\omega$$

Example. A generator with a circular coil of 75 turns of area 3.0 x 10^{-2} m^2 is immersed in a 0.20 T magnetic field and rotated with a frequency of 60 Hz. Find the maximum emf which is produced during a cycle.

Solution:

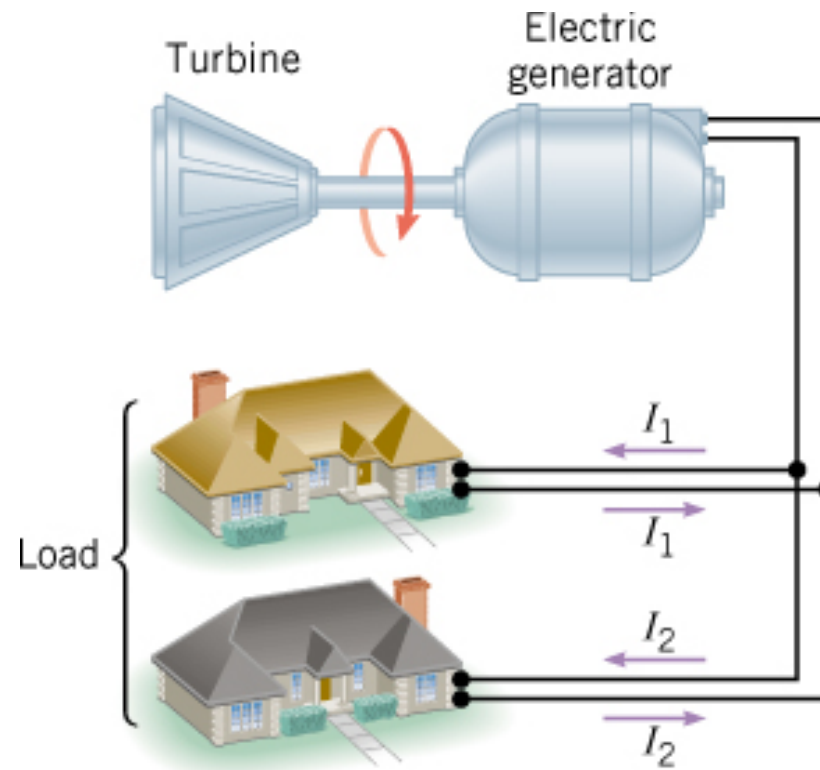The maximum emf for a generator is

$$\mathcal{E}_0 = NAB\omega$$

We know N = 75, A = 3.0 x 10^{-2} m^2, B = 0.20 T and f = 60 Hz .

Since $\omega = 2\pi f = 2\pi(60)$ = 377 radians/s

$\mathcal{E}_0$ = (75)(3.0 x 10^{-2})(0.20)(377) = **170 V**
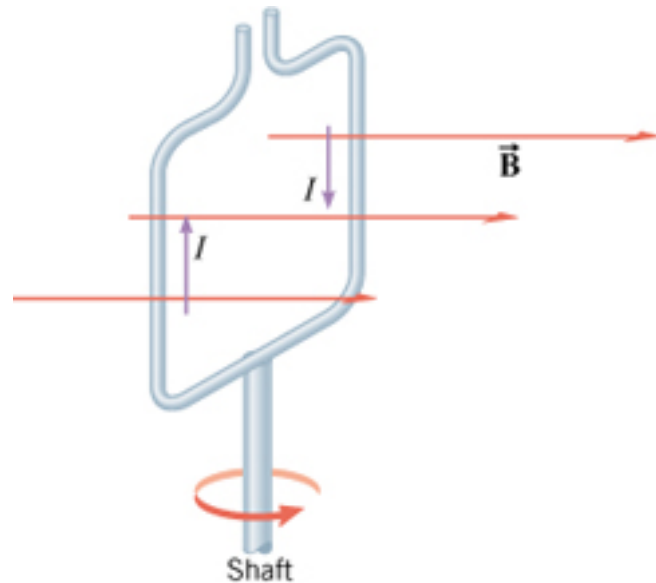
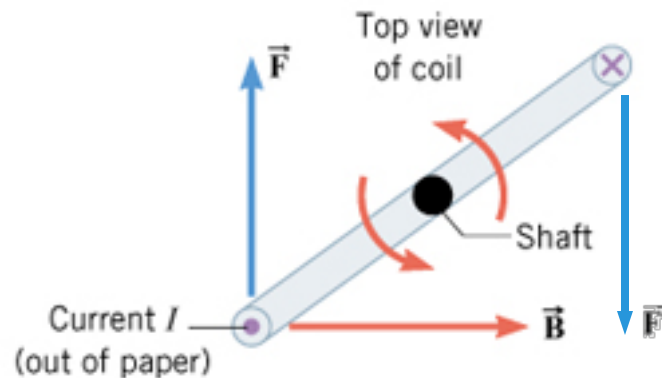## THE ELECTRICAL ENERGY DELIVERED BY A GENERATOR AND THE COUNTERTORQUE

When the generator is delivering current, there is a an induced magnetic force acting on its coils that causes the turbine to do work so that mechanical energy is converted into electrical energy, in keeping with conservation of energy.

The magnetic force gives rise to a countertorque that opposes the rotational motion. The generator has an induced motor-like action to oppose the turbine which is trying to turn it.

The induced forces acting on the loop cause the countertorque. The interaction of the induced current with the applied magnetic field produces these forces.
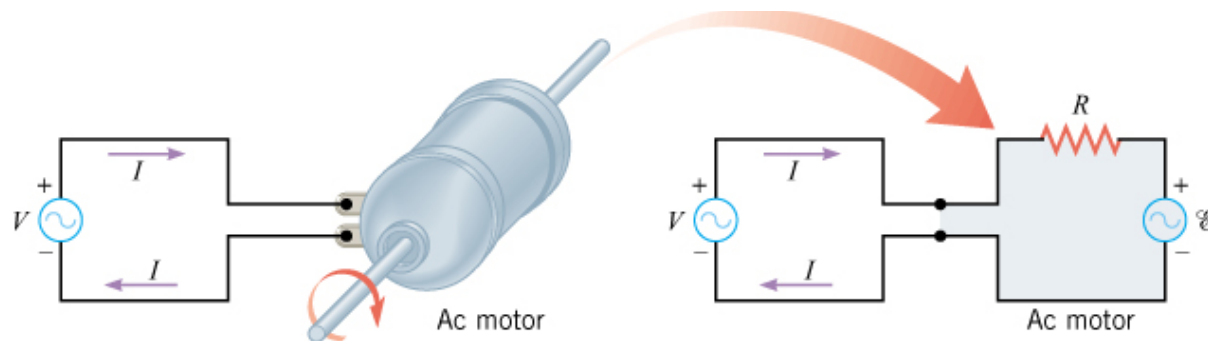
THE BACK EMF GENERATED BY AN ELECTRIC MOTOR

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.

Ac motor
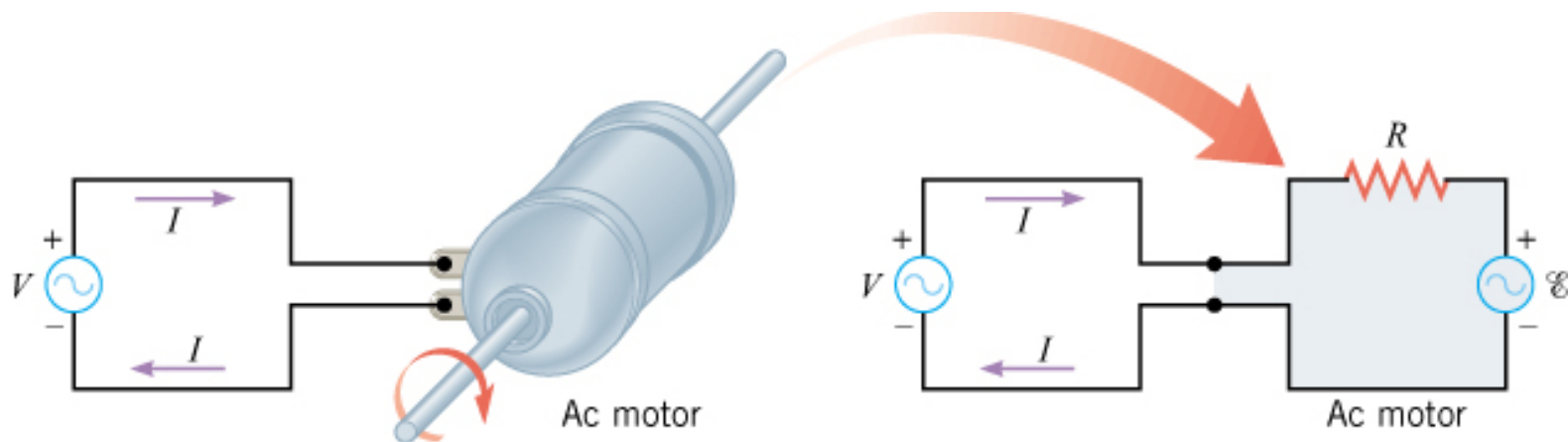
Ac motor

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

Ac motor   Ac motor

Find the **current** in the above circuit when the motor is operating at a normal speed:

$$\text{net emf} = V - \mathcal{E} = IR$$

➜ $I = (V - \mathcal{E})/R$

Example 12 Operating a Motor

The coil of an ac motor has a resistance of 4.1 Ω. The motor is plugged into an outlet where the voltage is 120.0 volts, and the coil develops a back emf of 118.0 volts 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) $I = \dfrac{V - \varepsilon}{R} = \dfrac{120 \text{ V} - 0 \text{ V}}{4.1 \Omega} = 29 \text{ A}$

This is why the motor in your vacuum cleaner starts smoking if it gets caught on something that prevents it from turning!

(b) $I = \dfrac{V - \varepsilon}{R} = \dfrac{120 \text{ V} - 118.0 \text{ V}}{4.1 \Omega} = 0.49 \text{ A}$