

# Chapter 23 Magnetic Flux and Faraday's Law of Induction

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23.1 Induced EMF

23.2 Magnetic Flux

23.3 Faraday's Law of Induction

23.4 Lenz's Law

23.5 Mechanical Work and Electrical Energy

23.6 Generators and Motors

23.7 Inductance

23.9 Energy Stored in a Magnetic Field

23.10 Transformers

*1 Current electricity produces Magnetic fields,*

*So can*

*2 Magnetic fields produce electricity?*

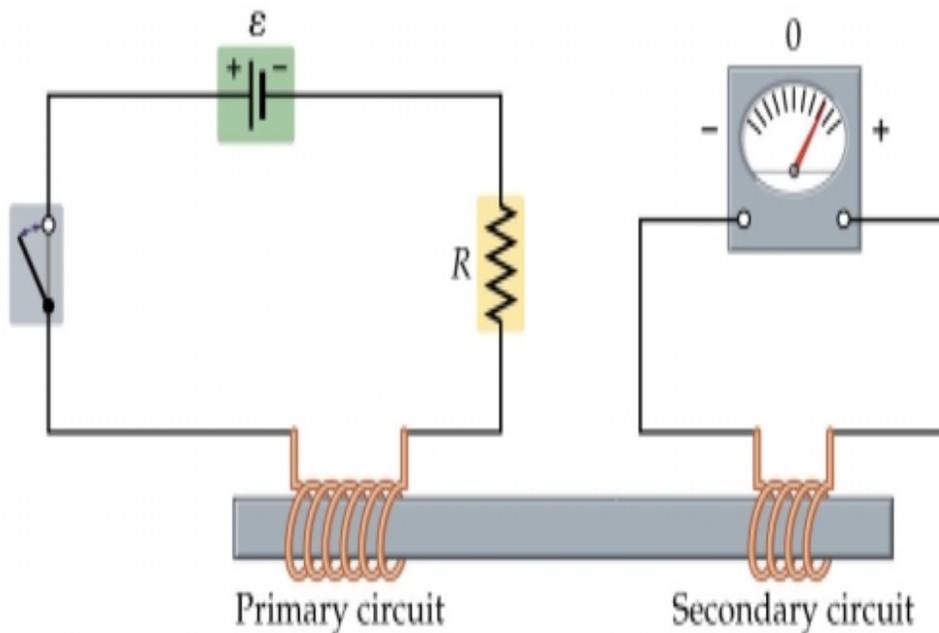
*1 Oersted, 1820*

*2 Faraday, 1831*

*Faradays discoveries are the basis of our modern electrical civilization.*

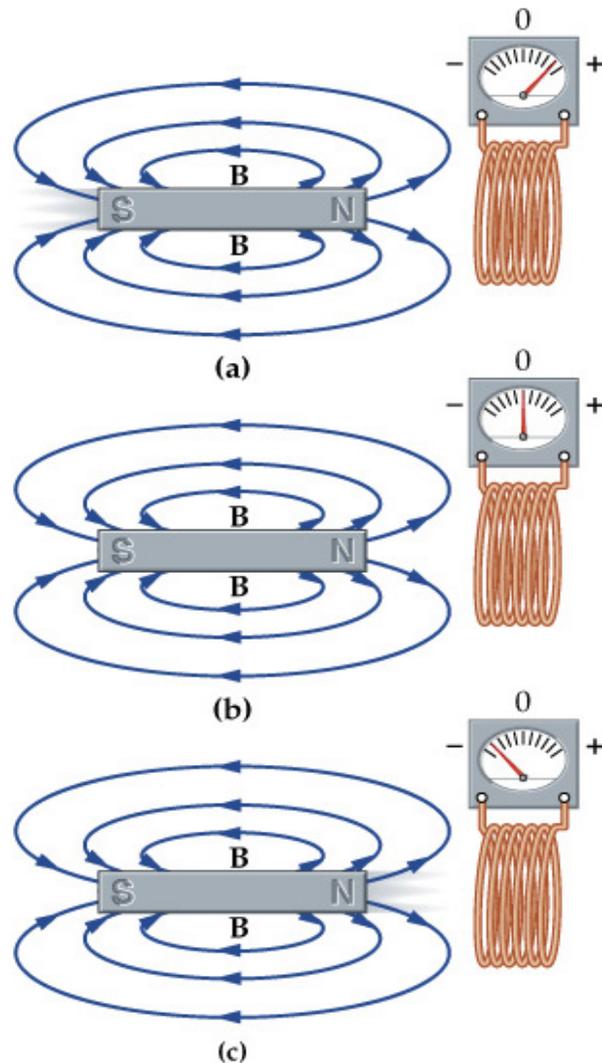
*Faraday (and Henry) noticed that a MOVING magnet near a wire loop caused a blip on his galvanometer.*

# Figure 23–1 Magnetic induction



- Basic setup of Faraday's experiment on magnetic induction. When the position of the switch on the primary circuit is changed from open to closed or from closed to open, an emf is induced in the secondary circuit. The induced emf causes a current in the secondary circuit, and the current is detected by the ammeter. If the current in the primary circuit does not change, no matter how large it may be, there is no induced current in the secondary circuit.

# Figure 23–2 Induced current produced by a moving magnet

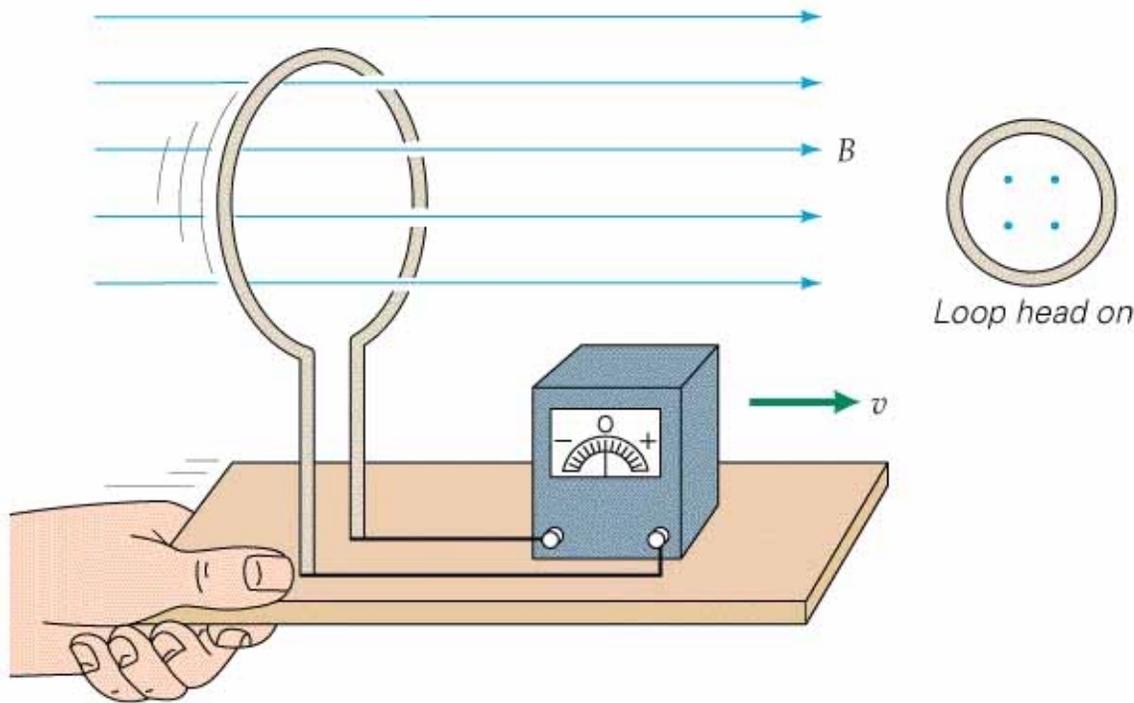


- A coil experiences an induced current when the magnetic field passing through it varies. (a) When the magnet moves toward the coil the current is in one direction. (b) No current is induced while the magnet is held still. (c) When the magnet is pulled away from the coil the current is in the other direction.

Also, changing the shape of a loop in or relative to a magnetic field would cause a blip on an ammeter.

Change in the number of field lines through a coil gives a current.

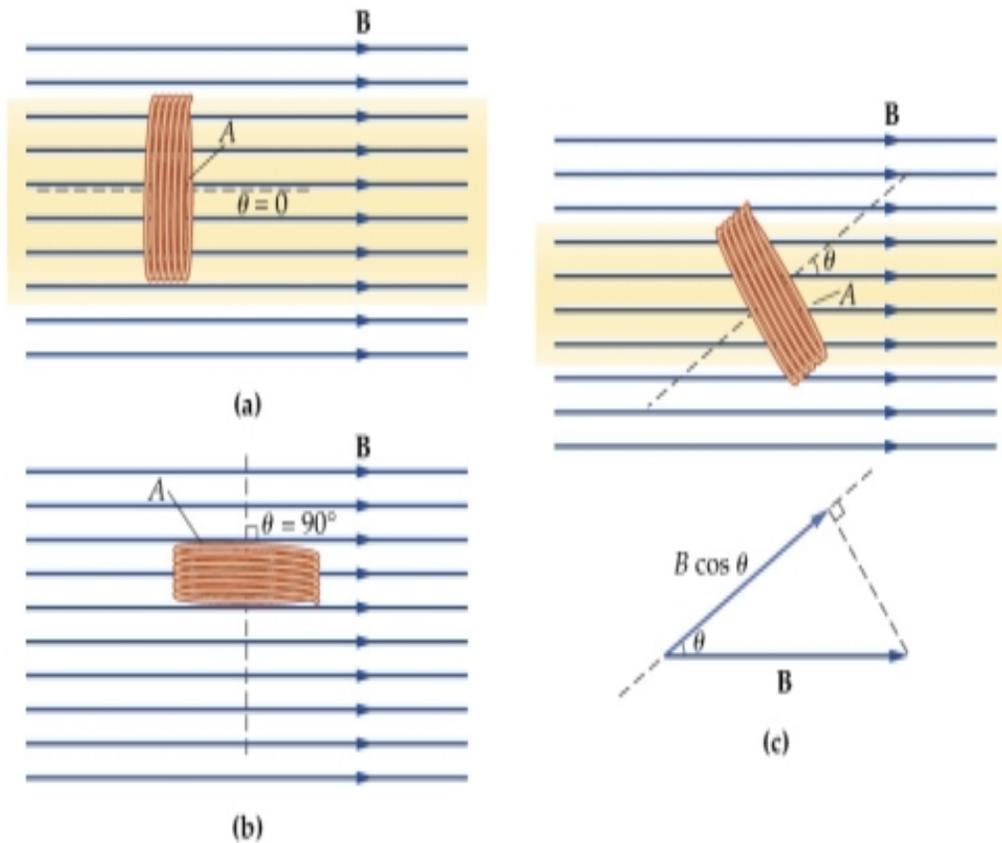
Number of field lines through a coil is called **magnetic flux**



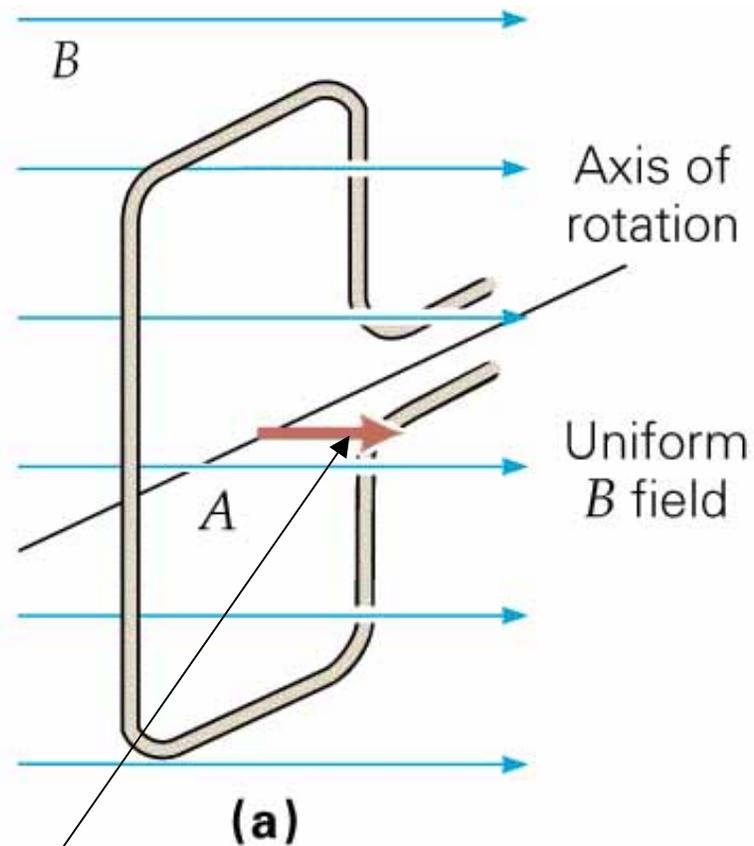
When a loop is moved parallel to a uniform magnetic field, there is no change in the number of field lines passing through the loop and no induced current.

**What would happen if the loop was moved vertically?**

# Figure 23–3 The magnetic flux through a loop



- The magnetic flux through a loop of area  $A$  is  $\Phi = BA \cos \eta$ , where  $\eta$  is the angle between the normal to the loop and the magnetic field. (a) The loop is perpendicular to the field; hence,  $\eta = 0$ , and  $\Phi = BA$ . (b) The loop is parallel to the field; therefore,  $\eta = 90^\circ$  and  $\Phi = 0$ . (c) For a general angle  $\eta$  the component of the field that is perpendicular to the loop is  $B \cos \eta$ ; hence, the flux is  $\Phi = BA \cos \eta$ .



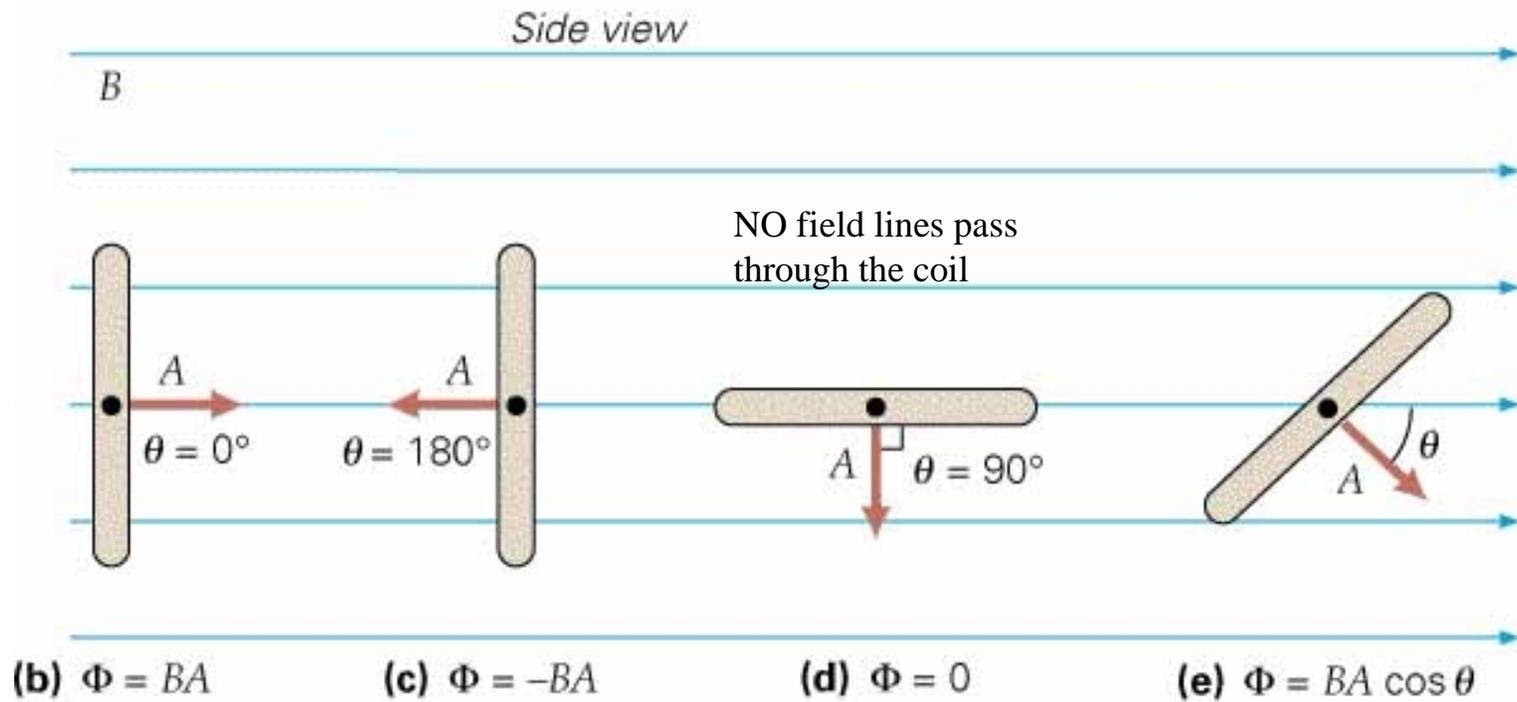
MAGNETIC FLUX,

$$\Phi = BA \cos \theta$$

Here  $\theta=0$  so  $\cos \theta = 1$

Units:  $T \cdot m^2 = Wb$

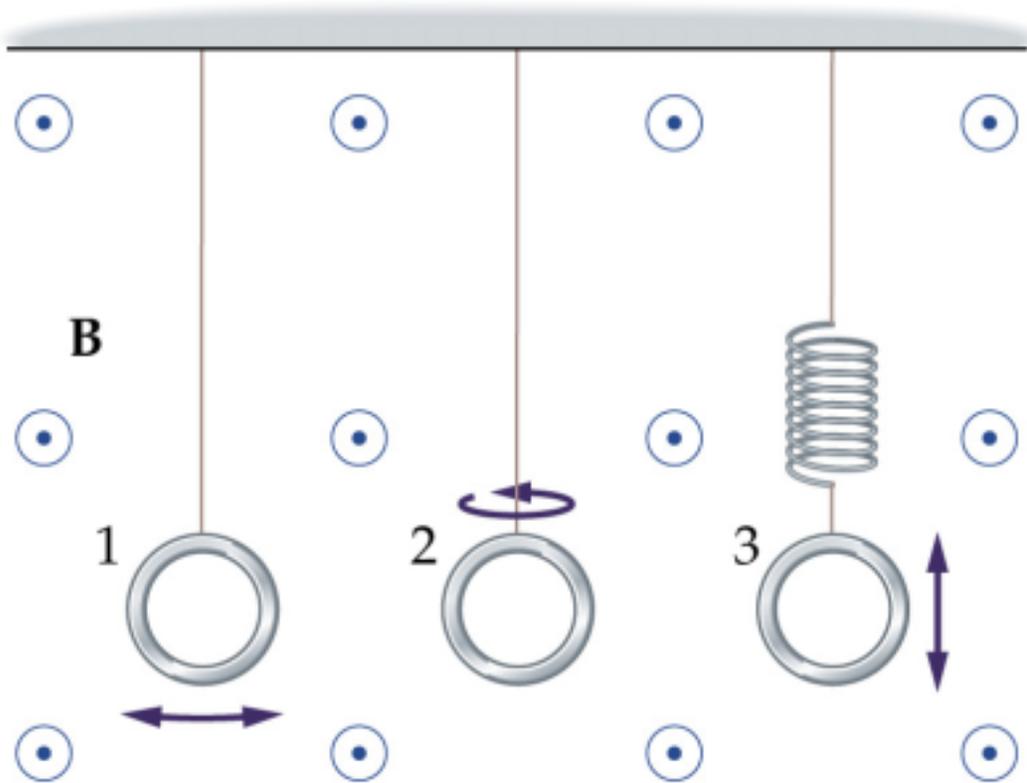
**Area Vector:** Direction is perpendicular to plane.  
Magnitude is equal to the area of the loop



Max. # field lines pass through the coil

Max. # field lines pass through the coil

Magnetic Flux is continually changing as coil rotates.



*Which of the three loops have a changing magnetic flux through it?*

If the magnetic flux through a loop of wire changes for any reason either by changing the area,  $A$ , of the loop or the field,  $B$ , through the loop

Then an EMF (voltage) will be induced in the wire. This voltage will cause a current to flow (the induced current in the loop).

Faraday quantified the size of the induced voltage:

## Faraday's Law

Induced EMF

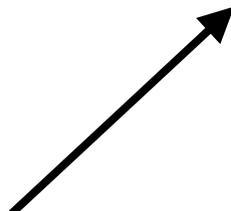
$$\mathcal{E} = -N \frac{\Delta\Phi}{\Delta t} = -N \frac{\Phi_f - \Phi_i}{t_f - t_i}$$

The size of the induced EMF depends on how quickly the flux through the coil is changing. There is only an induced EMF if there is a changing flux change through the coil.

$$\mathcal{E} = -N \frac{\Delta\Phi}{\Delta t} = -N \frac{\Delta(BA \cos\theta)}{\Delta t}$$

$$= -N \left[ (A \cos\theta) \frac{\Delta B}{\Delta t} + (B \cos\theta) \frac{\Delta A}{\Delta t} + (BA) \frac{\Delta \cos\theta}{\Delta t} \right]$$

Field changes



Loop area changes

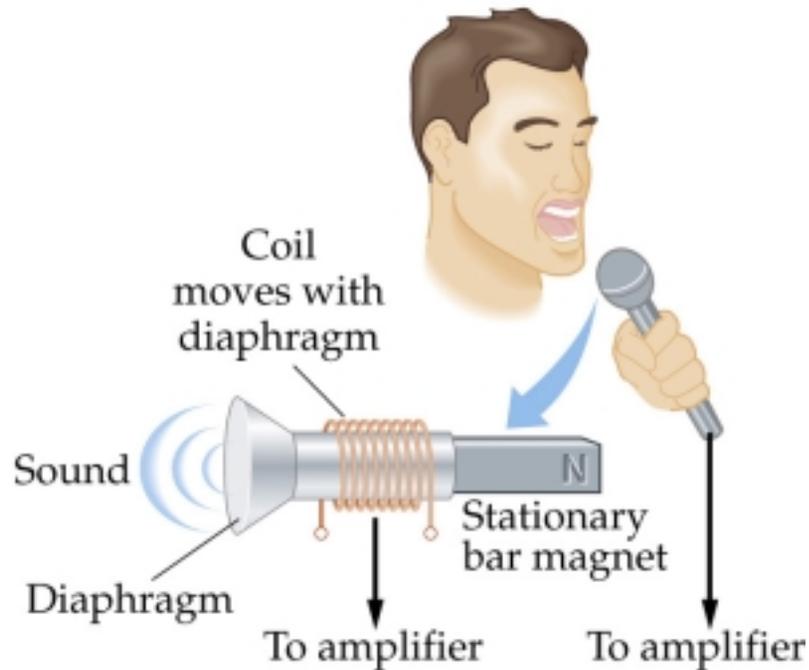


Orientation of Loop  
relative to field changes



# Figure 23–4 A dynamic microphone

- An example of Faraday's law.



The direction of the induced EMF will control the direction of the induced current. The direction of the induced EMF follows from Lenz's Law

## **Lenz's Law**

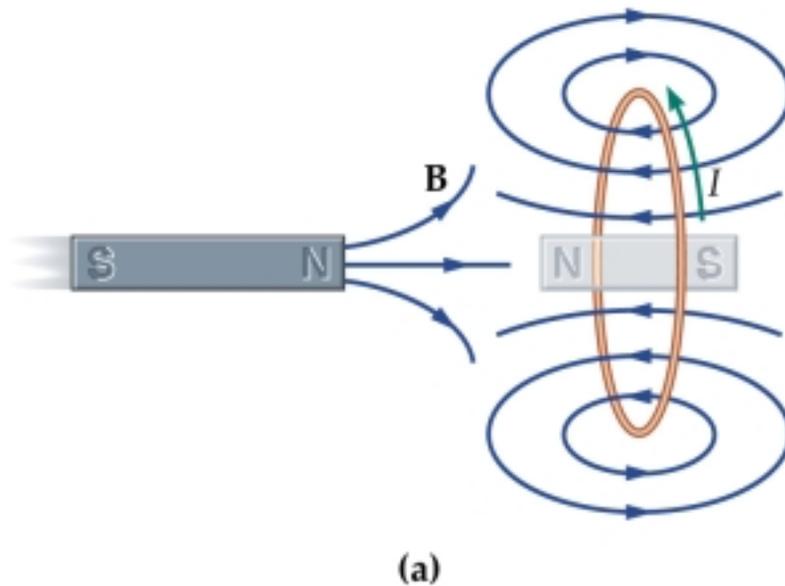
The current that is induced in a coil  
(due to a magnetic flux change through the coil)  
will always be such that it opposes the change that caused it.

Put another way:

Any induced current in a coil will result in a magnetic flux that is opposite to the original *changing* flux.

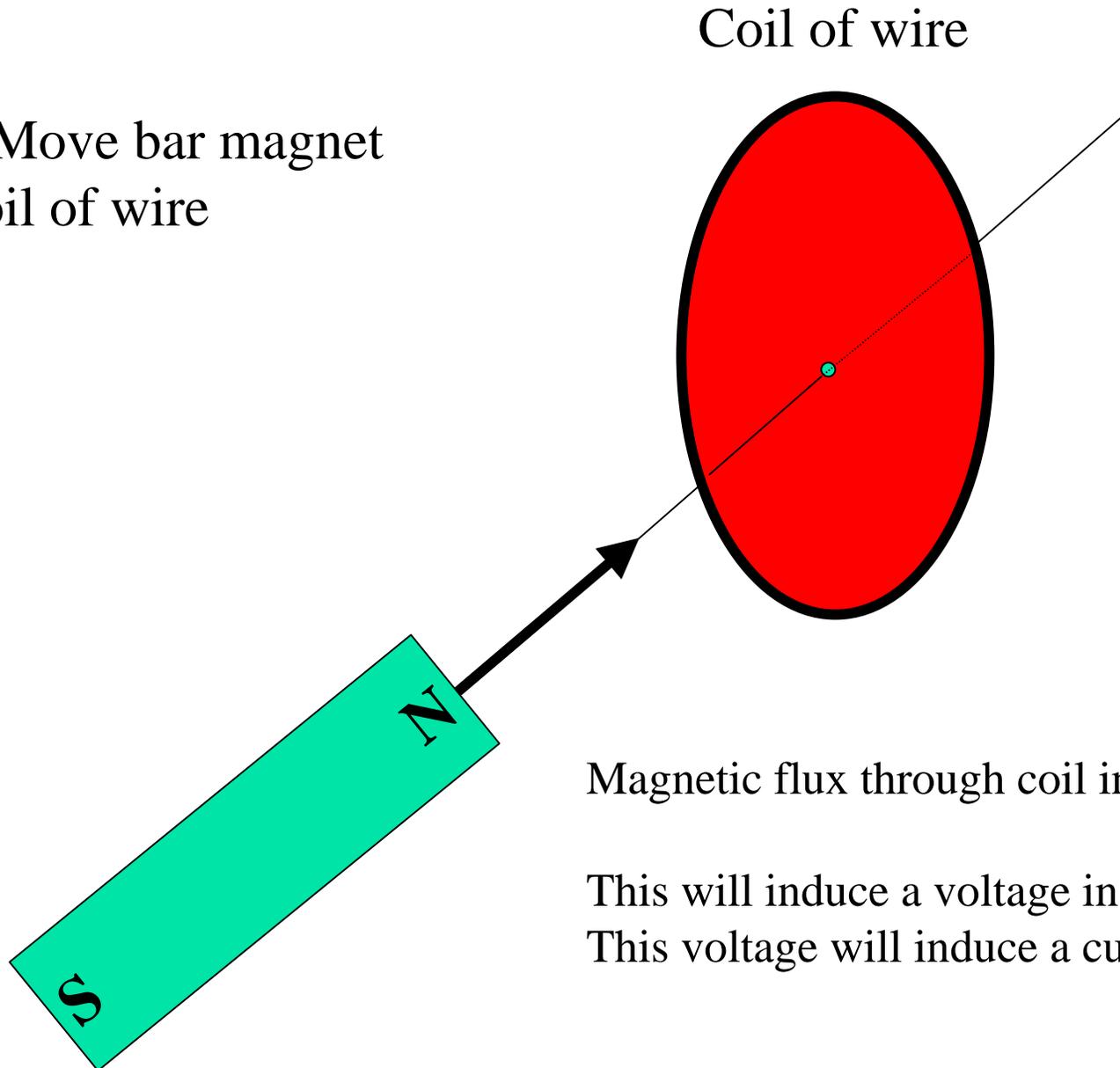
This is the origin of the negative sign in Faradays Law

## Figure 23–8 (a) Applying Lenz's law to a magnet moving toward a current loop



- (a) If the north pole of a magnet is moved toward a conducting loop, the induced current produces a north pole pointing toward the magnet's north pole. This creates a repulsive force opposing the change that caused the current.

Example: Move bar magnet  
towards coil of wire

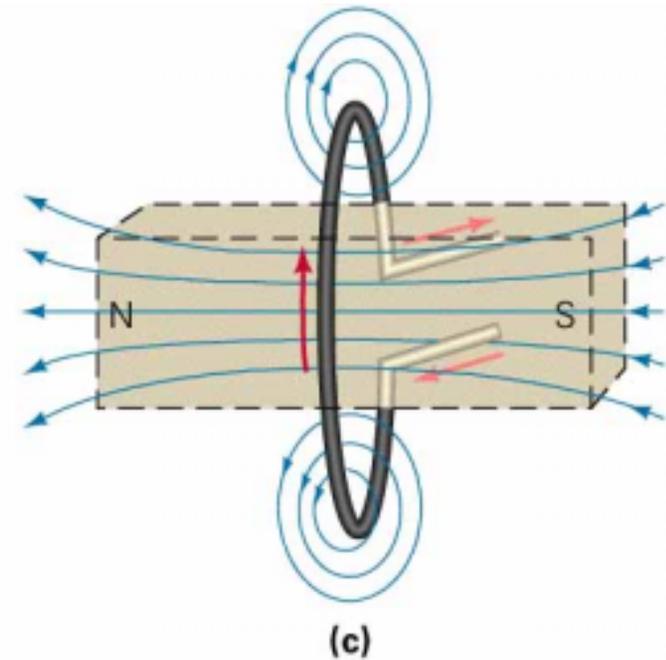
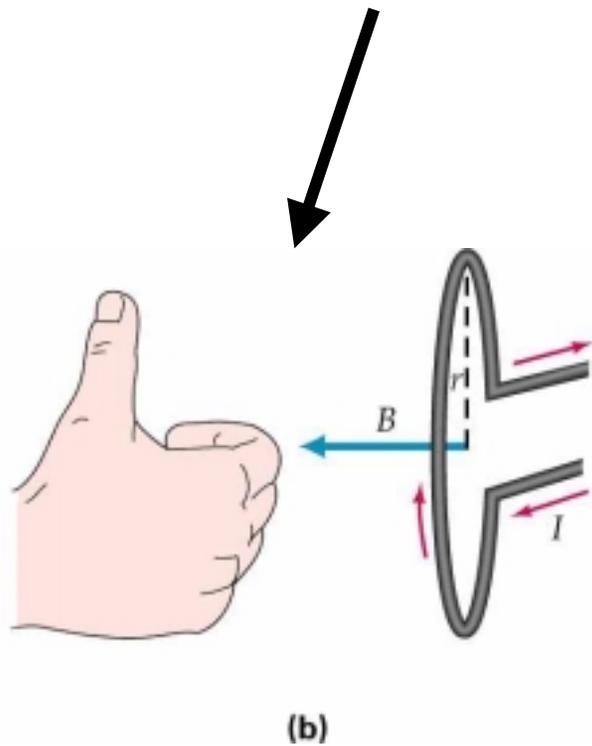


Magnetic flux through coil increases.

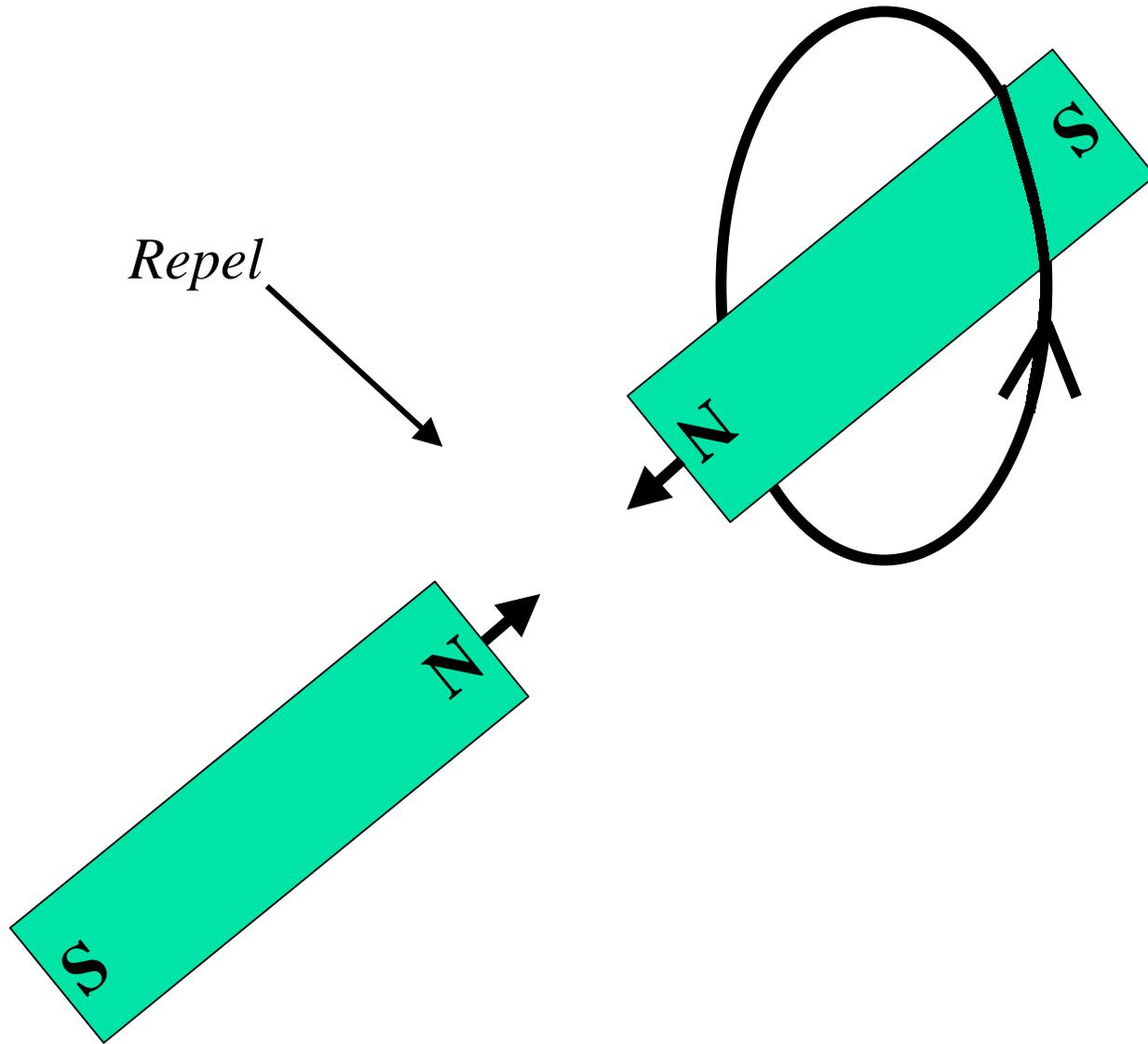
This will induce a voltage in the coil.

This voltage will induce a current.

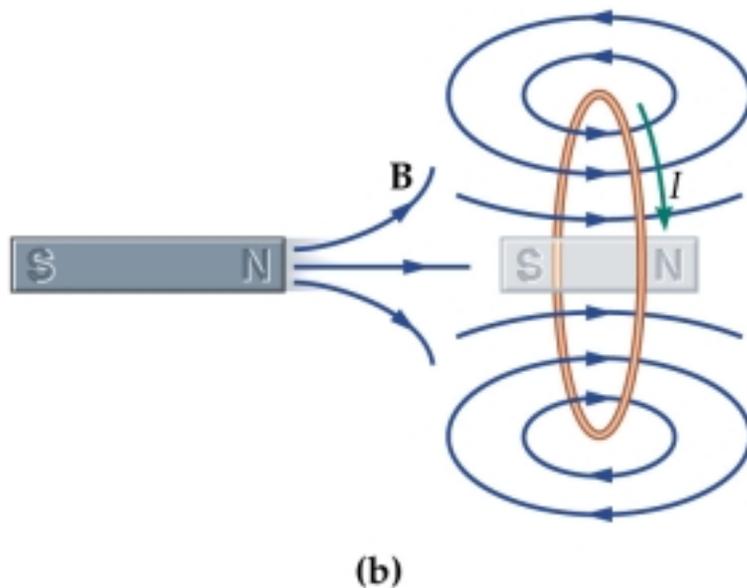
*Remember: When you have a current in a coil, it produces a magnetic field.*



*Remember: A current in a coil is like a little bar magnet.*

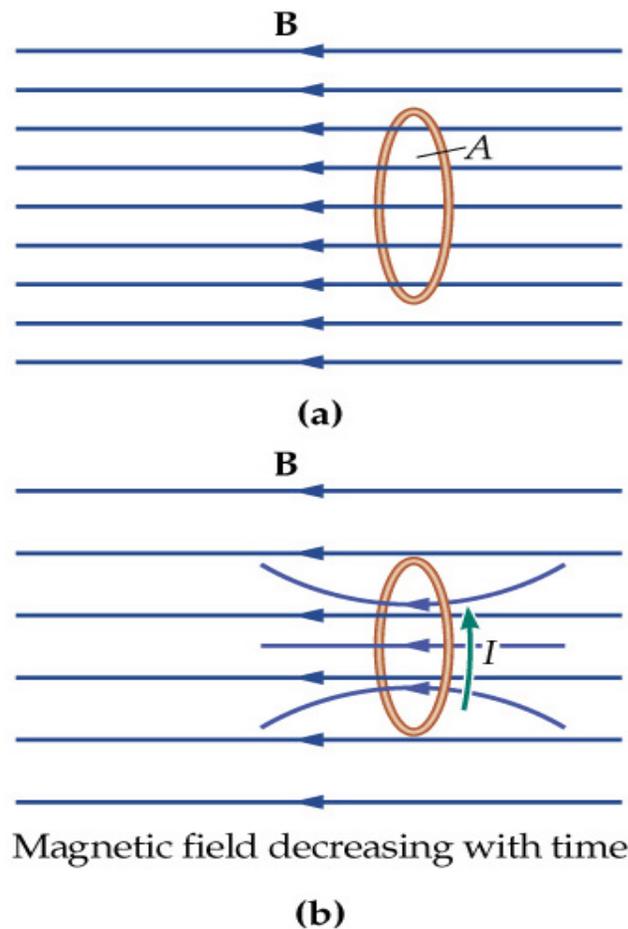


# Figure 23–8 Applying Lenz's law to a magnet moving away from a current loop



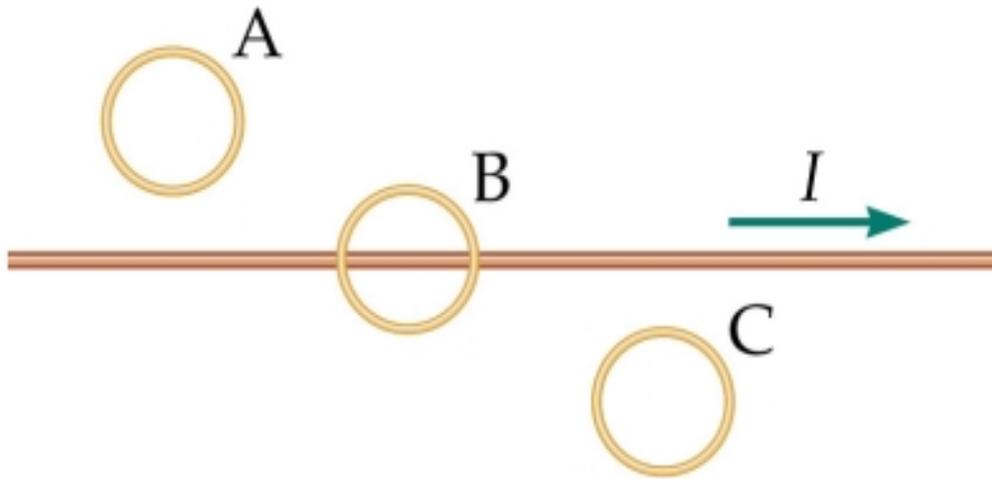
- (b) If the north pole of a magnet is pulled away from a conducting loop, the induced current produces a south magnetic pole near the magnet's north pole. The result is an attractive force opposing the motion of the magnet.

# Figure 23–9 Lenz's law applied to a decreasing magnetic field

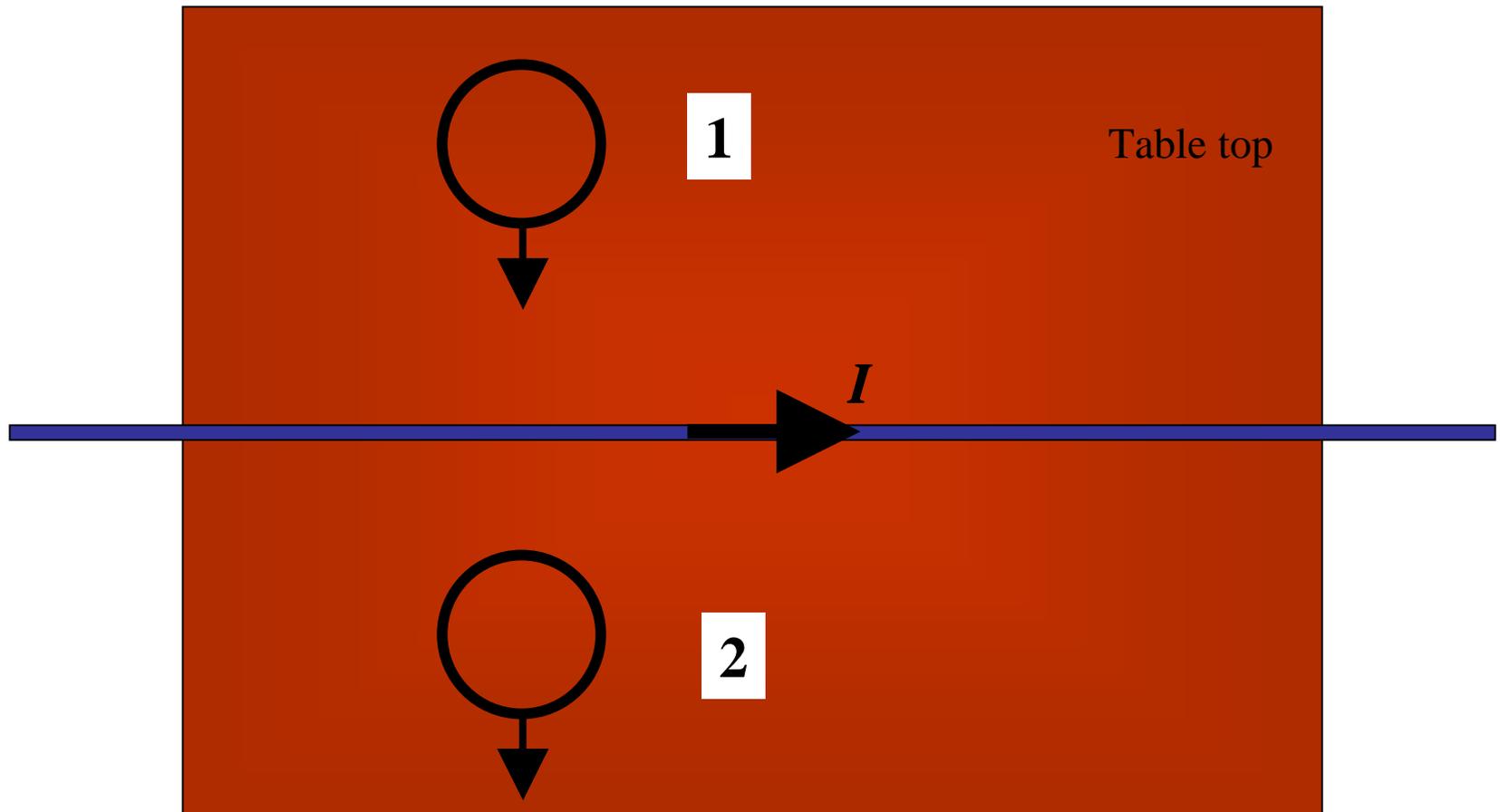


- As the magnetic field is decreased the induced current produces a magnetic field that passes through the ring in the same direction as  $B$ .

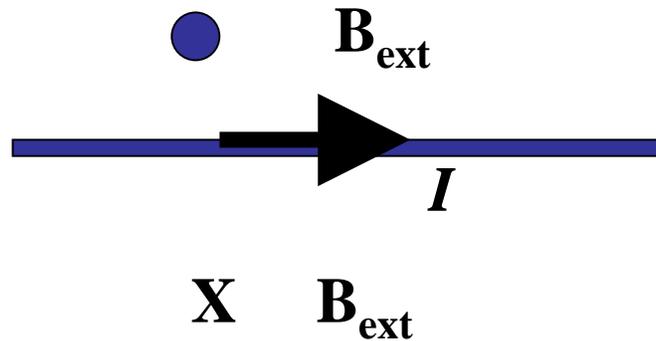
Problem 23: If the current through the wire is increased, what direction is the induced current in each of the coils?



A long straight wire lies on a table and carries a current  $I$ . A small circular loop of wire is pushed across the top of the table from position 1 to 2. Determine the direction of the induced current (clockwise OR counter-clockwise) as the loop moves past (A) position 1 and (B) position 2. Explain in complete detail.



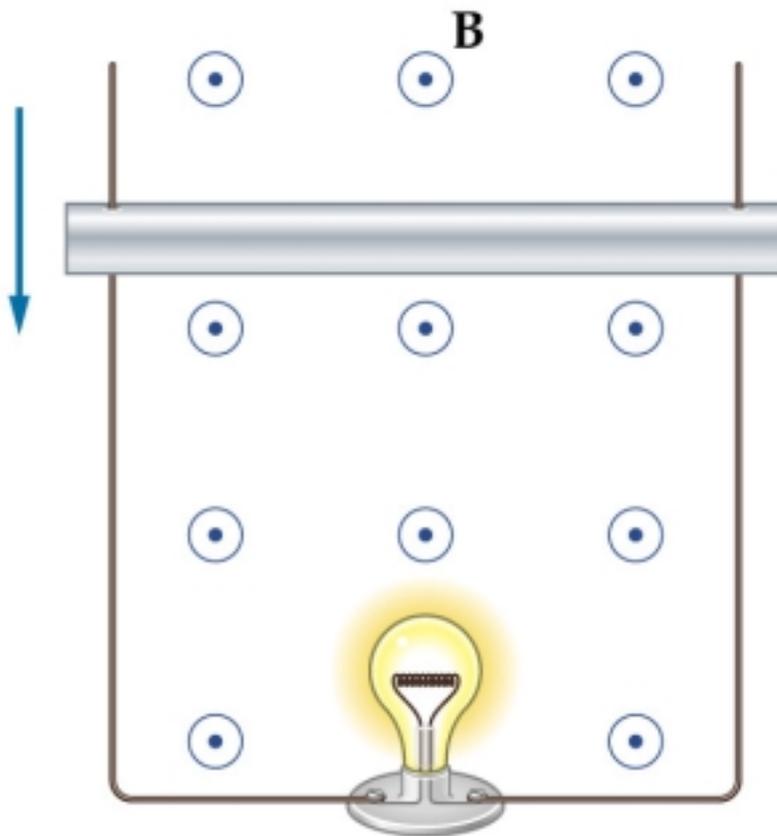
The current in the wire produces a magnetic field. At point 1 this external field is OUT of the page. At point 2 the external field is INTO the page. This magnetic field passes through the loop and is the source of magnetic flux through the coil. As the loop slides by position 1, the flux through the loop is INCREASING and it is Pointing OUT OF THE PAGE. As the loop slides by position 2 the flux through the loop is DECREASING and it is pointing INTO THE PAGE.



At point 1 the induced magnetic field will point into the page to oppose the increasing external field. This means the current must be CLOCKWISE (use RHR2)

At point 2 the induced magnetic field will point into the page, in the same direction as the decreasing external field. To oppose a decrease you add to the field in the same direction. This means the current must be CLOCKWISE (use RHR2) also.

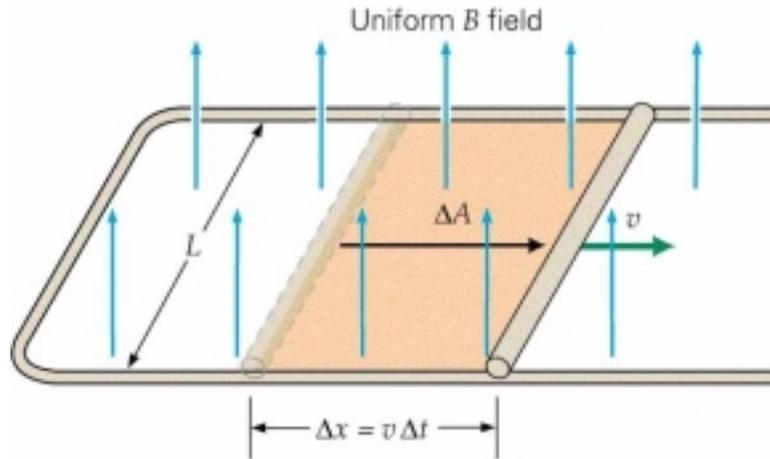
## Figure 23–10 Motional emf



- Motional emf is created in this system as the rod falls. The result is an induced current, which causes the light to shine.

## Electrical Energy Generation.

## Motional emf



$$\Delta A = L\Delta x = Lv\Delta t$$

$$\Delta\Phi = B\Delta A = LvB\Delta t$$

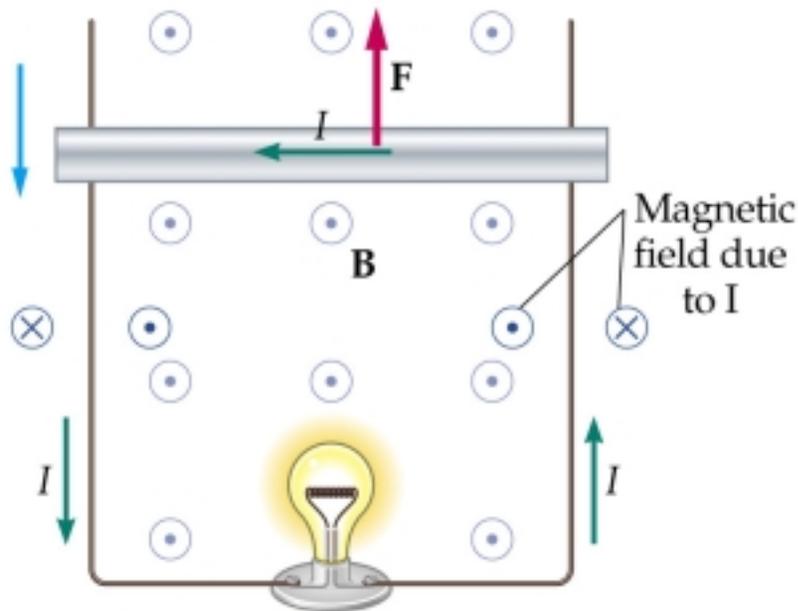
$$|\varepsilon| \propto \left| \frac{\Delta\Phi}{\Delta t} \right| = LvB$$

**Note:**  $v$  is perpendicular to  $B$

As the metal rod is **pulled** (you do work) on the metal frame, the area of the rectangular loop varies with time. A current is induced in the loop as a result of the changing flux.

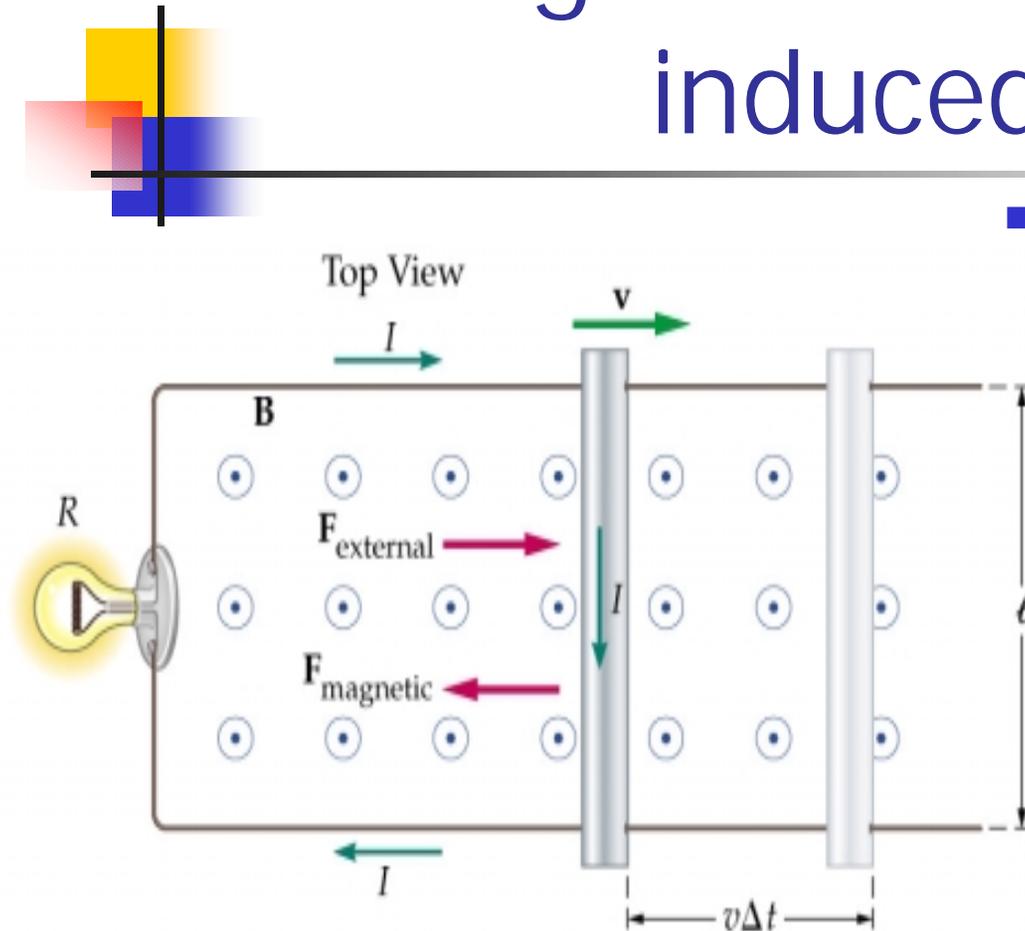
What is the direction of the induced current? (clockwise). Two ways to show this.

# Figure 23–11 Determining the direction of an induced current

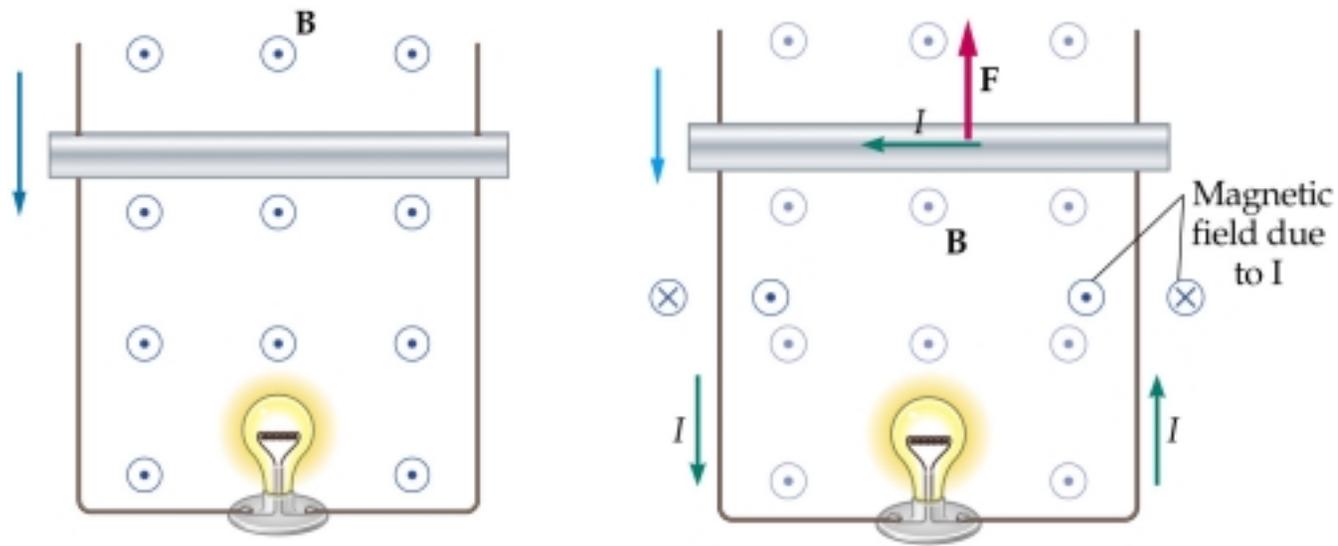


- The direction of the current induced by the rod's downward motion is counterclockwise, since this direction produces a magnetic field within the loop that points out of the page—in the same direction as the original field. Notice that a current flowing in this direction through the rod interacts with the original magnetic field to give an upward force, opposing the downward motion of the rod.

# Figure 23–13 Force and induced current



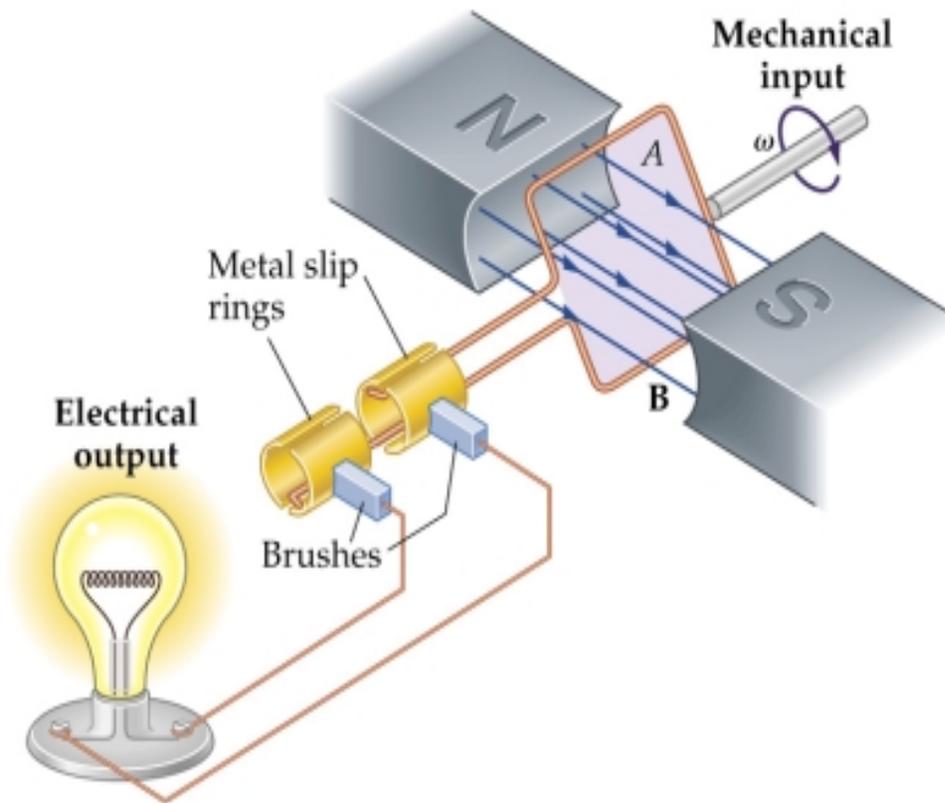
- A conducting rod slides without friction on horizontal wires in a region where the magnetic field is uniform and pointing out of the page. The motion of the rod to the right induces a clockwise current and a corresponding magnetic force to the left. An external force of magnitude  $F = B^2v\ell^2/R$  is required to offset the magnetic force and to keep the rod moving with a constant speed  $v$ .



$$\varepsilon = LvB = V = EL \Rightarrow E = Bv$$

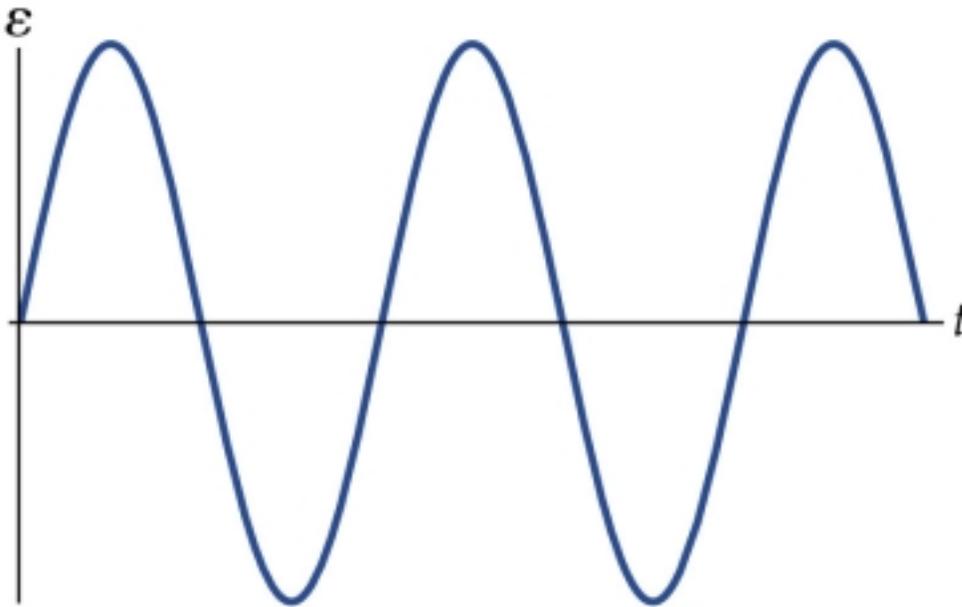
$$I = \frac{V}{R} = \frac{LvB}{R}$$

# Figure 23–14 An electric generator



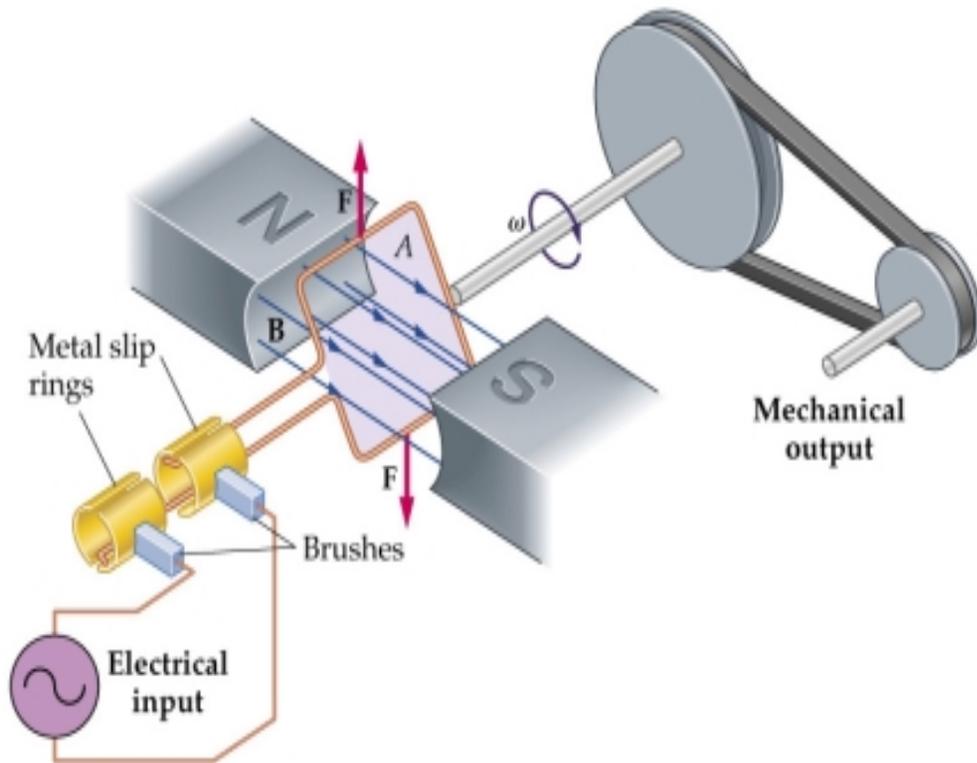
- The basic operating elements of an electric generator are shown in a schematic representation. As the coil is rotated by an external source of mechanical work it produces an emf that can be used to power an electrical circuit.

# Figure 23–15 Induced emf of a rotating coil



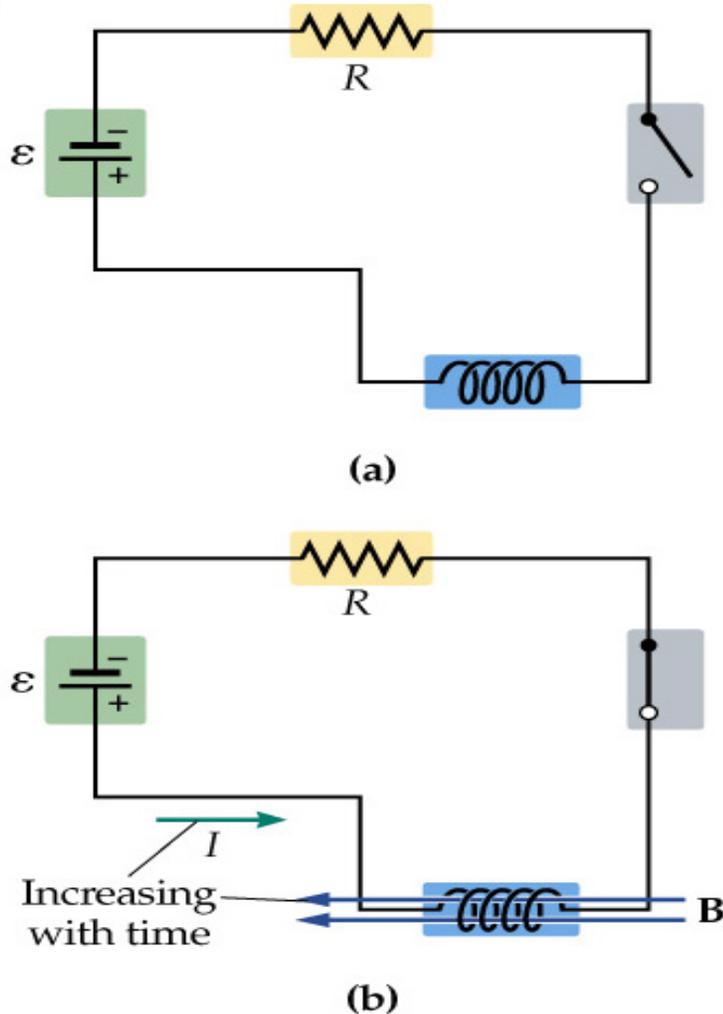
- Induced emf produced by an electric generator like the one shown in Figure 23–14. The emf alternates in sign, so the current changes sign as well. We say that a generator of this type produces an “alternating current.”

# Figure 23–16 A simple electric motor



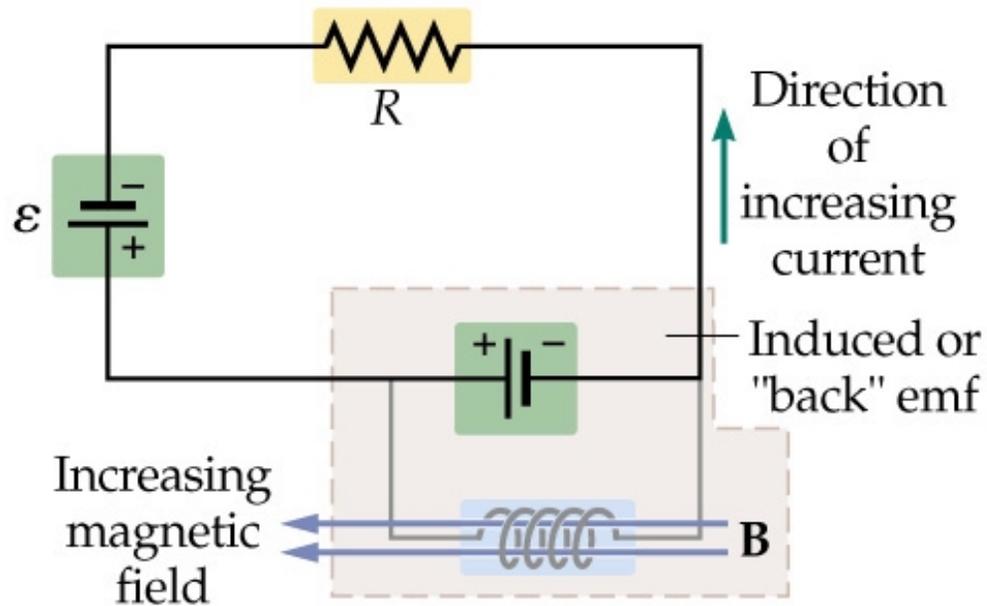
- An electric current causes the coil of a motor to rotate and deliver mechanical work to the outside world.

# Figure 23–17 A changing current in an inductor



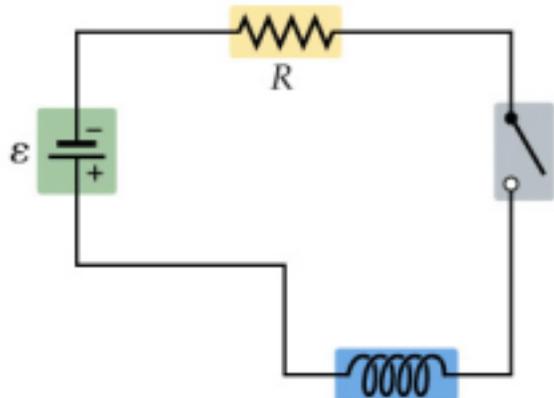
- (a) A coil of wire with no current and no magnetic flux.
- (b) The current is now increasing with time, which produces a magnetic flux that also increases with time.

# Figure 23–18 The back emf of an inductor

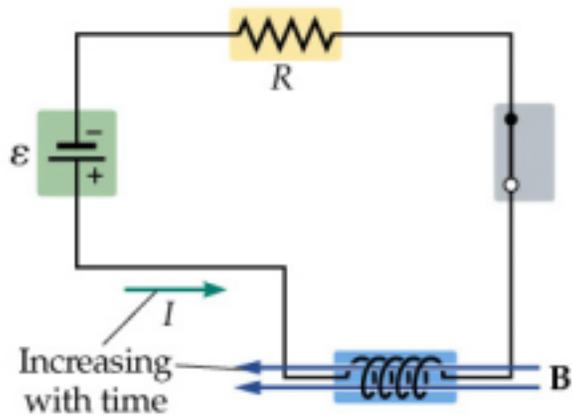


- The effect of an increasing current in a coil is an induced emf that opposes the increase. This is indicated schematically by replacing the coil with the opposing, or "back," emf.

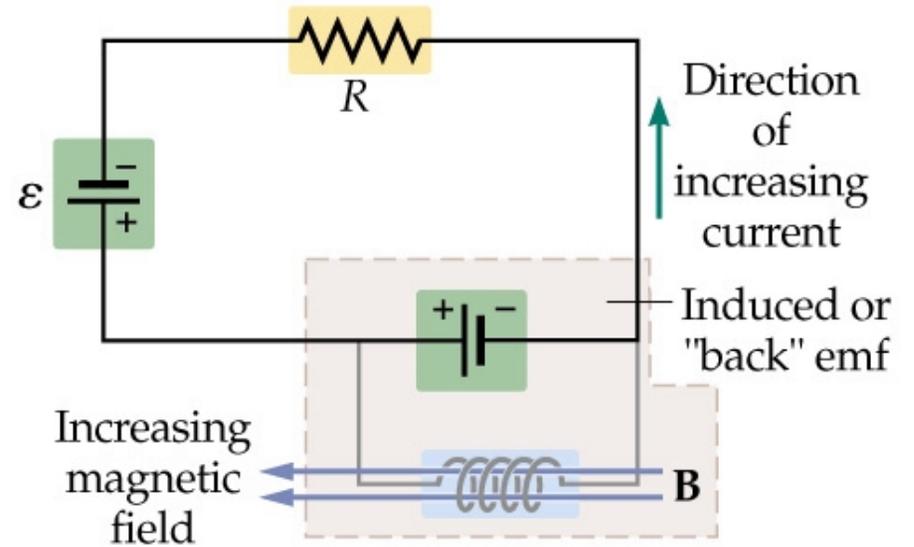
## *Self inductance and BACK EMF's*



(a)



(b)

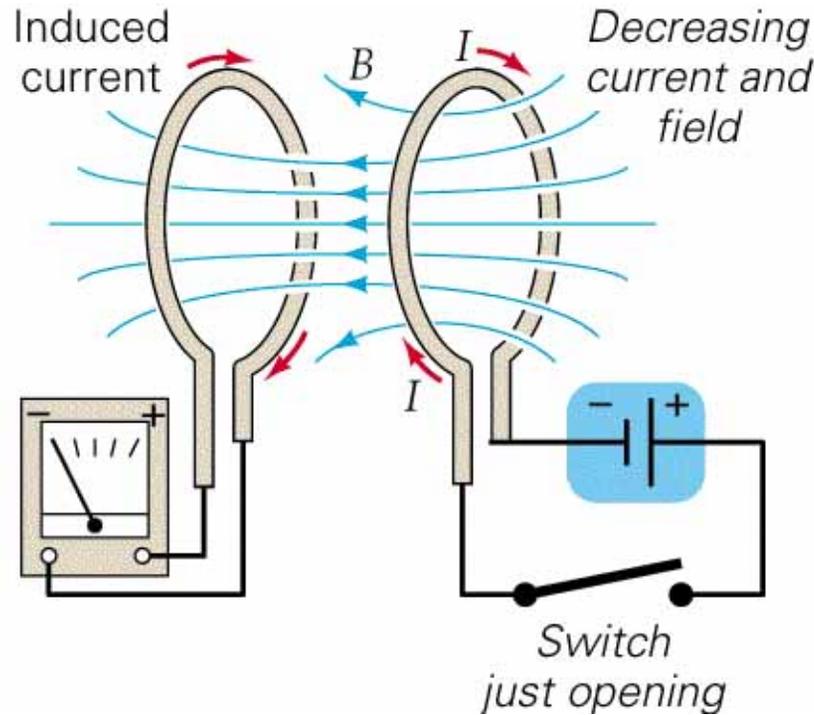


$$\epsilon = N \left| \frac{\Delta \Phi}{\Delta t} \right| = L \left| \frac{\Delta I}{\Delta t} \right|$$

$$L = N \left| \frac{\Delta \Phi}{\Delta I} \right|$$

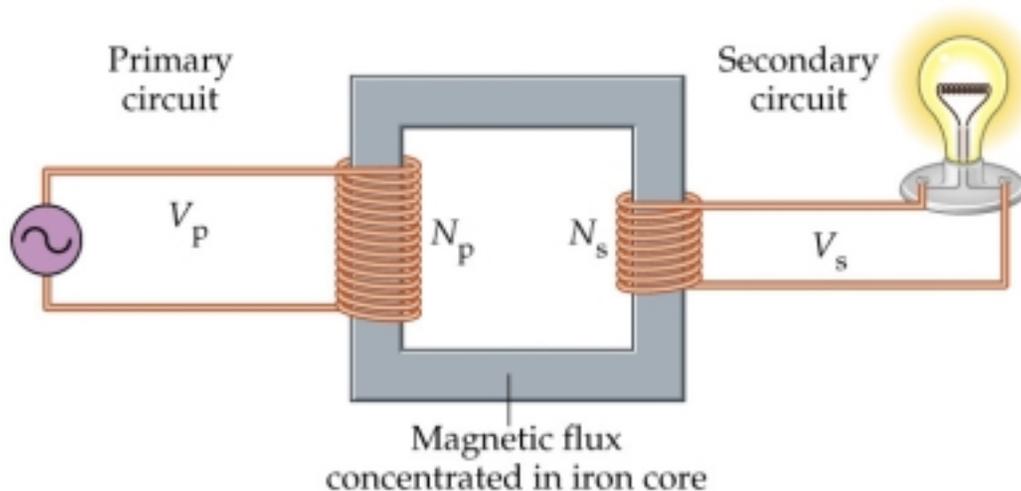
*L is in Henries*

*Remember the idea of mutual induction introduced earlier.*



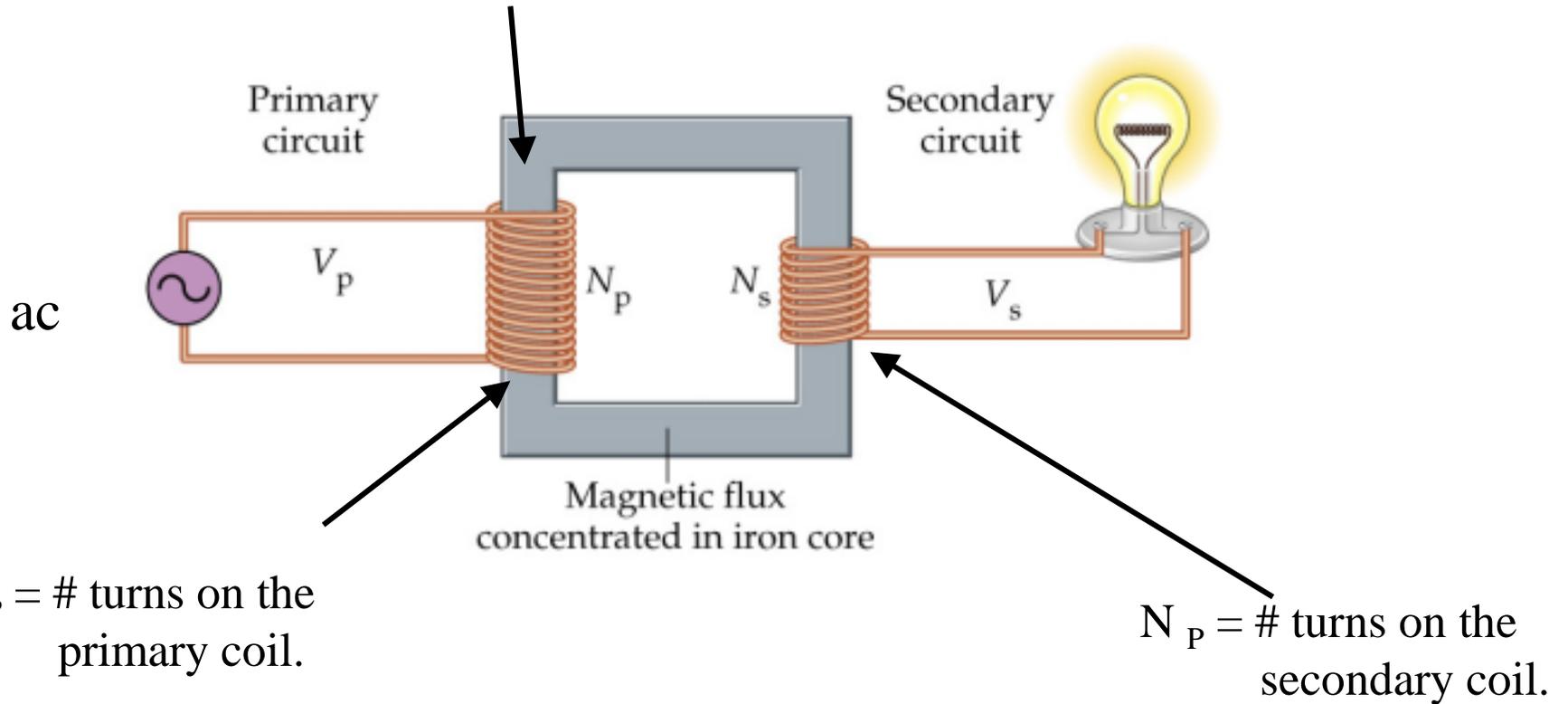
If the source is AC then the field from the loop will continually change.  
So an AC current will be induced in coil 2.

# Figure 23–22 The basic elements of a transformer

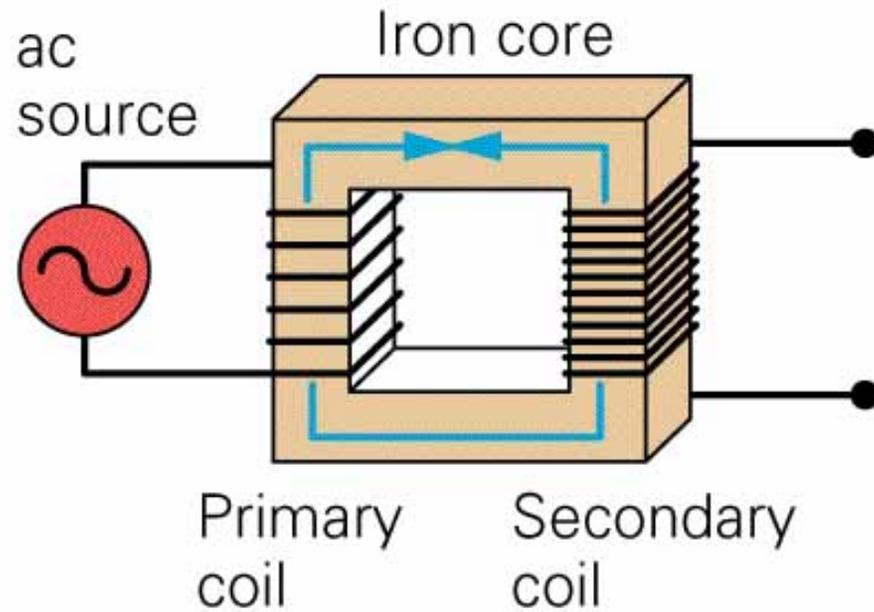


- An alternating current in the primary circuit creates an alternating magnetic flux, and hence an alternating induced emf, in the secondary circuit. The ratio of emfs in the two circuits,  $V_s/V_p$  is equal to the ratio of the number of turns in each circuit,  $N_s/N_p$ .

Changing magnetic field of the primary coil.  
Leads to changing flux in secondary coil

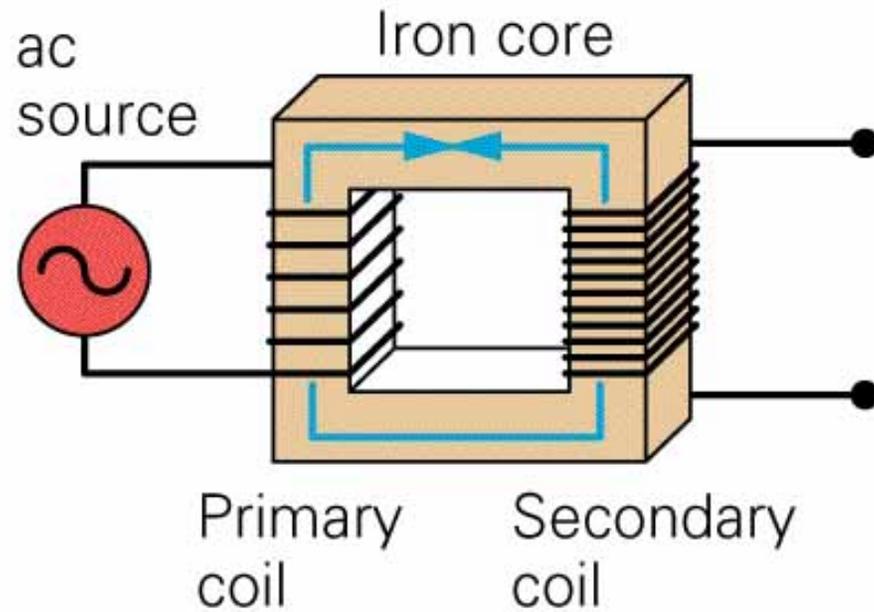


$$\frac{V_P}{V_S} = \frac{N_P}{N_S} = \frac{I_S}{I_P} \quad \text{Because } P_S = P_P = I_S V_S = I_P V_P$$



**(a)** Step-up transformer:  
high-voltage  
(low-current) output

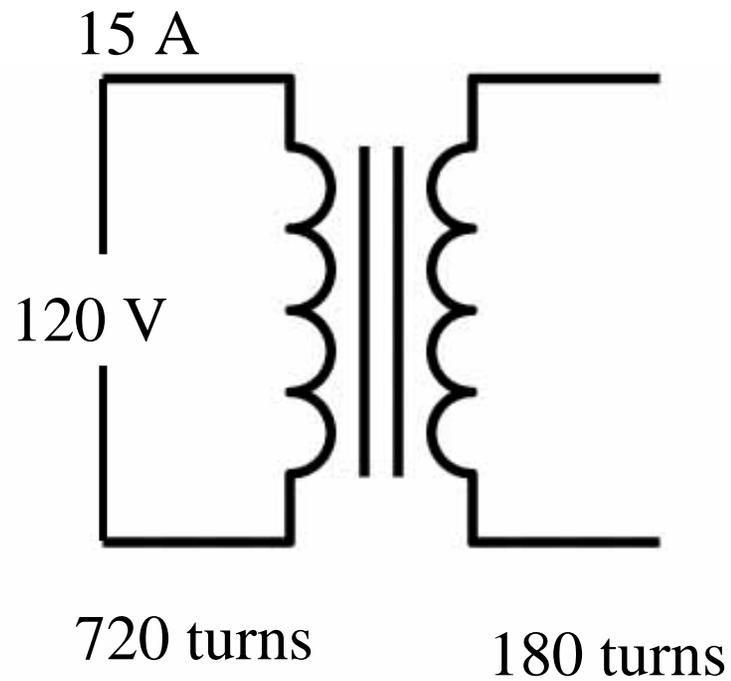
$$N_S > N_P \Rightarrow V_S > V_P \Rightarrow I_P > I_S$$



**(a)** Step-up transformer:  
high-voltage  
(low-current) output

$$N_S > N_P \Rightarrow V_S > V_P \Rightarrow I_P > I_S$$

Problem: What is  $V_S$  and  $V_P$  ?



**(c)** Transformer  
circuit symbol

*Notice: AC is required to step up and down voltages.  
That is, transformers only work with AC.*

*The fact that we can step up and down voltages  
is the main reason we live in an AC powered world.*

*Because*

*The fact that we can step up and down voltages  
allows us to transmit power over large distances  
without much loss.*

*A power station generates 1.2 MW of power. The power is to be transmitted to a town that is 7 km away. The transmission wire has a resistance of  $5 \times 10^{-2} \Omega/\text{km}$ . With what efficiency can the power be transmitted to the town if it is sent at (A) 1200 V and (B) 120,000 V.*

*A Power will be lost due to resistive heating of the wires.*

$$P_{\text{loss}} = I^2 R$$

*R is the total resistance of the wires.  $(14 \text{ km})(5 \times 10^{-2} \Omega/\text{km}) = 0.70 \Omega$*

*Now the current flowing to the town is given by*

$$I = P / V = (1.2 \times 10^6 \text{ W}) / (1200 \text{ V}) = \mathbf{1000 \text{ A}}$$

$$P_{\text{loss}} = I^2 R = (10^3 \text{ A})^2 (0.70 \Omega) = 700,000 \text{ W}$$

*Efficiency =  $(700000 / 1200000) \times 100 = 58 \%$ , 58% of the power is **LOST**.*

***Note the power transmitted is NOT the same as power heating losses in the wires***

*B The voltage is stepped up by 100. That is  $N_s / N_p = 100 = I_p / I_s$*

*So  $I_s = 1000 \text{ A} / 100 = 10 \text{ A}$*

$$P_{\text{loss}} = I^2 R = (10^1 \text{ A})^2 (0.70 \Omega) = 70 \text{ W}$$

*Efficiency =  $(70 / 1200000) \times 100 = 0.0058 \%$*

*Virtually all the power is **TRANSMITTED***