Chapter 29

Faraday's Law

PHYS 2321
Week 11: Faraday's Law

Day 1 Outline

1) Hwk: Ch. 29 P. Due Fri
   Read 29.1-5,7

2) Faraday's Law
   a. Faraday's experiments showing induced EMF
   b. Demo
   c. Magnetic flux, $\int \vec{B} \cdot d\vec{A} = \Phi_B$
   d. Faraday's Law: $EMF = \frac{-d\Phi_B}{dt}$

Notes: "NEW STUFF" – 3 links added.
Try Ch. 28 & 29 practice quizzes.
Exam II will be next week.

Michael Faraday

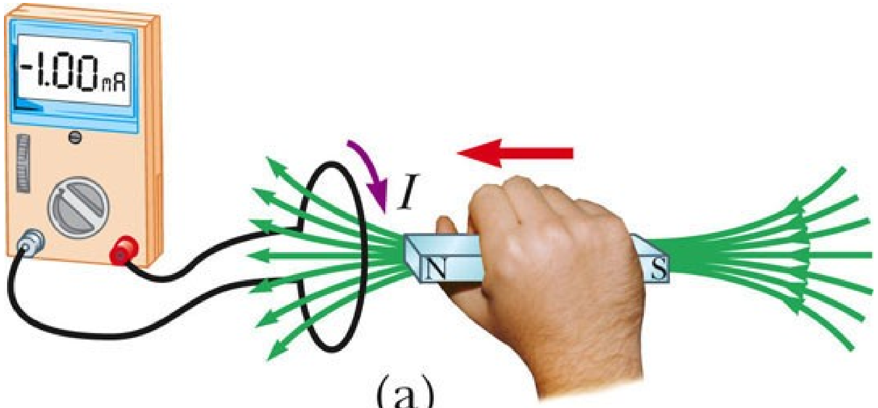
- 1791 – 1867
- British physicist and chemist
- Great experimental scientist
- Contributions to early electricity include:
  - Invention of motor, generator, and transformer
  - Electromagnetic induction
  - Laws of electrolysis

Induction

- An *induced current* is produced by a changing magnetic field
- There is an *induced emf* associated with the induced current
- A current can be produced without a battery present in the circuit
- Faraday’s law of induction describes the induced emf

EMF Produced by a Changing Magnetic Field, 1

- A loop of wire is connected to a sensitive ammeter
- When a magnet is moved toward the loop, the ammeter deflects
  - The direction was arbitrarily chosen to be negative



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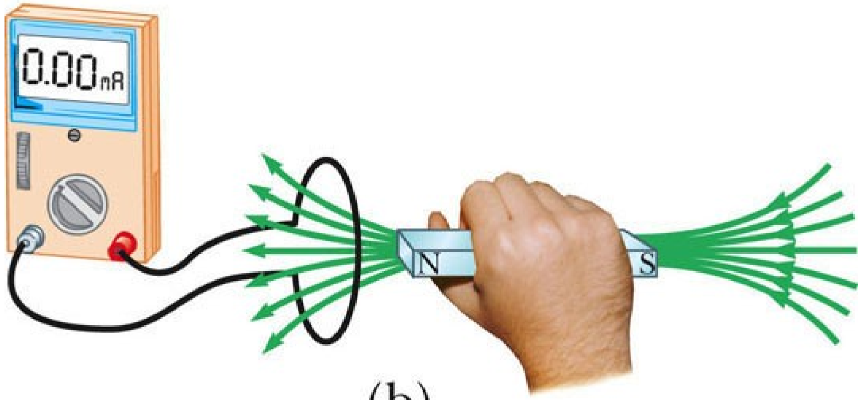
EMF Produced by a Changing Magnetic Field, 2

- When the magnet is held stationary, there is no deflection of the ammeter
- Therefore, there is no induced current
  - Even though the magnet is in the loop



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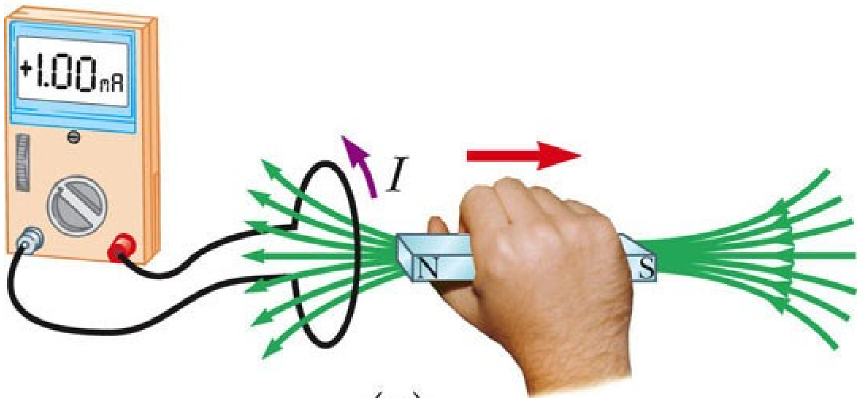
EMF Produced by a Changing Magnetic Field, 3

- The magnet is moved away from the loop
- The ammeter deflects in the opposite direction
- Use the active figure to move the wires and observe the deflection on the meter



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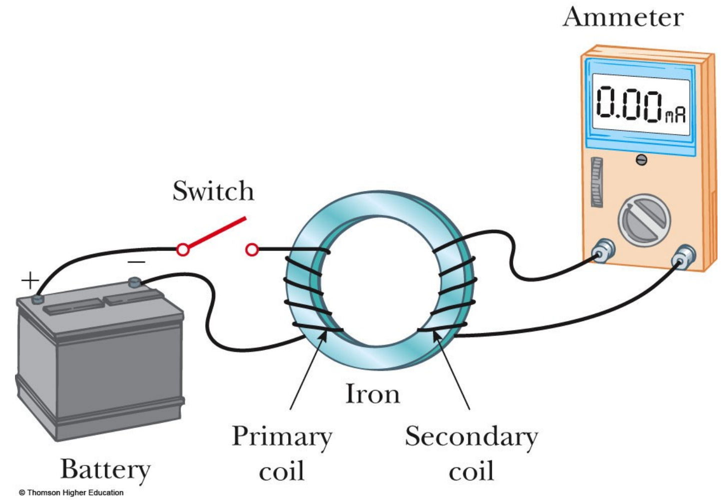
EMF Produced by a Changing Magnetic Field, Summary

- The ammeter deflects when the magnet is moving toward or away from the loop
- The ammeter also deflects when the loop is moved toward or away from the magnet
- Therefore, the loop detects that the magnet is moving relative to it
  - We relate this detection to a change in the magnetic field
  - This is the induced current that is produced by an induced emf

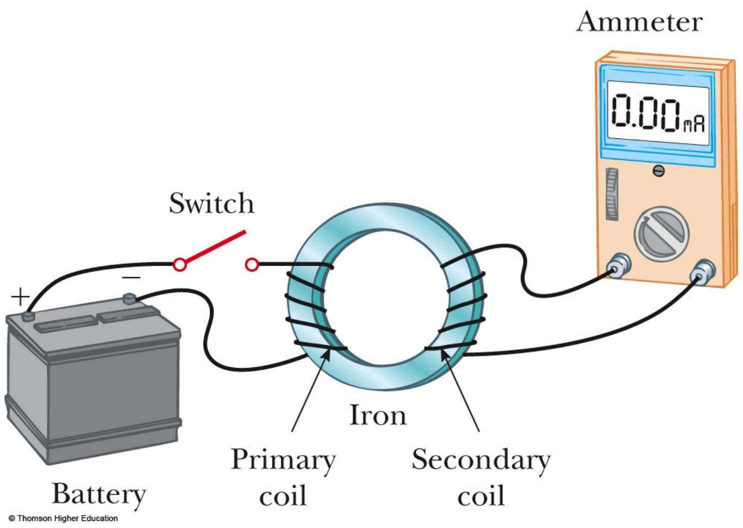
Faraday's Experiment #2 – Set Up

- A primary coil is connected to a switch and a battery
- The wire is wrapped around an iron ring
- A secondary coil is also wrapped around the iron ring
- There is **no battery** present in the secondary coil
- The secondary coil is not directly connected to the primary coil



Active Figure 31.2

- Closing the switch creates momentary current reading on the ammeter
- Opening the switch creates current in opposite direction



Faraday's Experiment – Findings

- At the instant the switch is closed, the ammeter changes from zero in one direction and then returns to zero
- When the switch is opened, the ammeter changes in the opposite direction and then returns to zero
- The ammeter reads zero when there is a steady current or when there is no current in the primary circuit

Faraday's Experiment – Conclusions

- An electric current can be induced in a loop by a changing magnetic field
  - This would be the current in the secondary circuit of this experimental set-up
- The induced current exists only while the magnetic field through the loop is changing
- This is generally expressed as: ***an induced emf is produced in the loop by the changing magnetic flux***
  - The actual existence of the magnetic flux is not sufficient to produce the induced emf, the flux must be changing

Faraday's Law – Statements

- Faraday's law of induction states that "the emf induced in a circuit is directly proportional to the time rate of change of the magnetic flux through the circuit"

Mathematically, $\varepsilon_{ind} = EMF = \frac{-d\Phi_B}{dt}$

Faraday's Law – Statements, cont

- Remember Φ_B is the magnetic flux through the circuit and is found by

$$\Phi_B = \int \vec{B} \cdot d\vec{A}$$

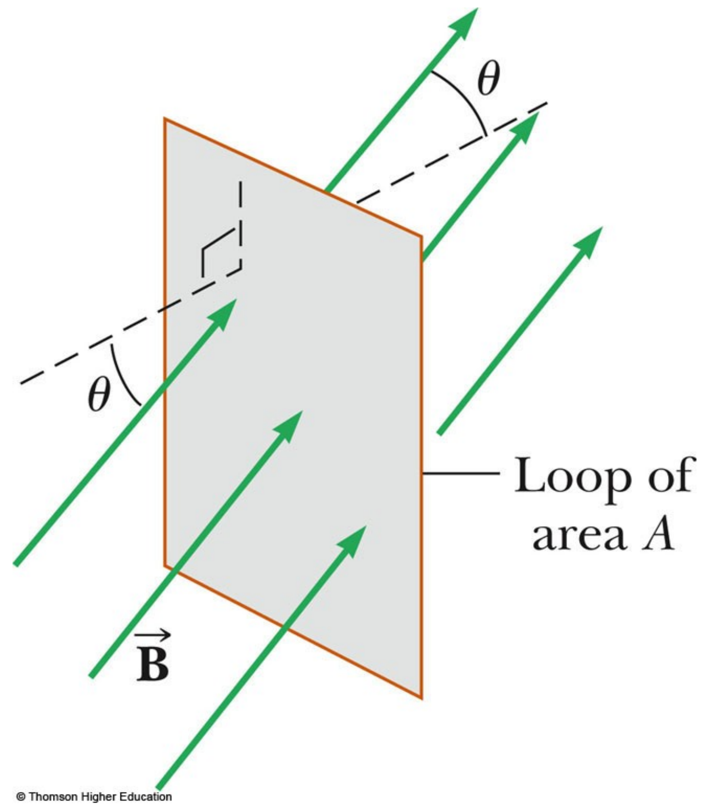
- If the circuit consists of N loops, all of the same area, and if Φ_B is the flux through one loop, every loop contributes to the EMF and Faraday's law becomes

$$EMF = -N \frac{d\Phi_B}{dt}$$

Faraday's Law – Example

- Assume a loop enclosing an area *A* lies in a uniform magnetic field ***B***
- The magnetic flux through the loop is $\Phi_B = BA \cos\theta$
- The induced emf is

  $\varepsilon = - d/dt\,(BA \cos\theta)$

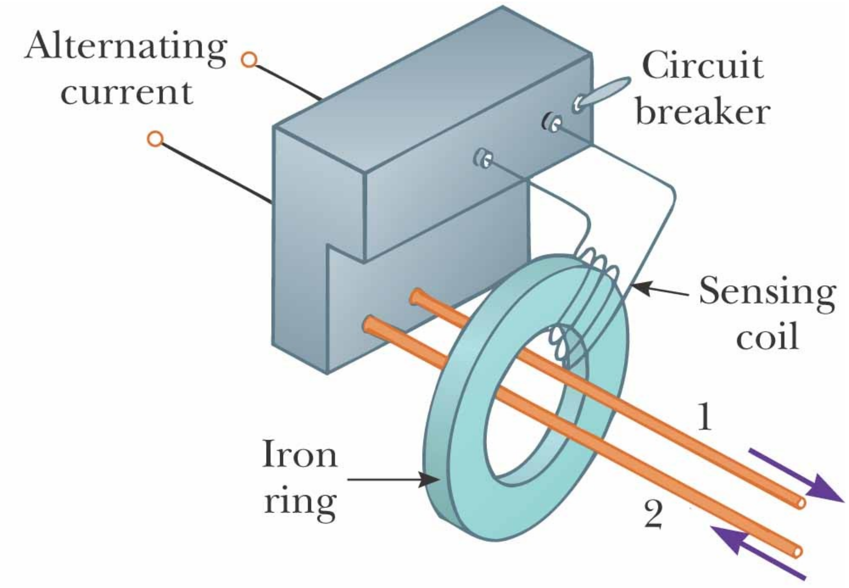


Ways of Inducing an emf

- The magnitude of ***B*** can change with time
- The area enclosed by the loop can change with time
- The angle θ between ***B*** and the normal to the loop can change with time
- Any combination of the above can occur

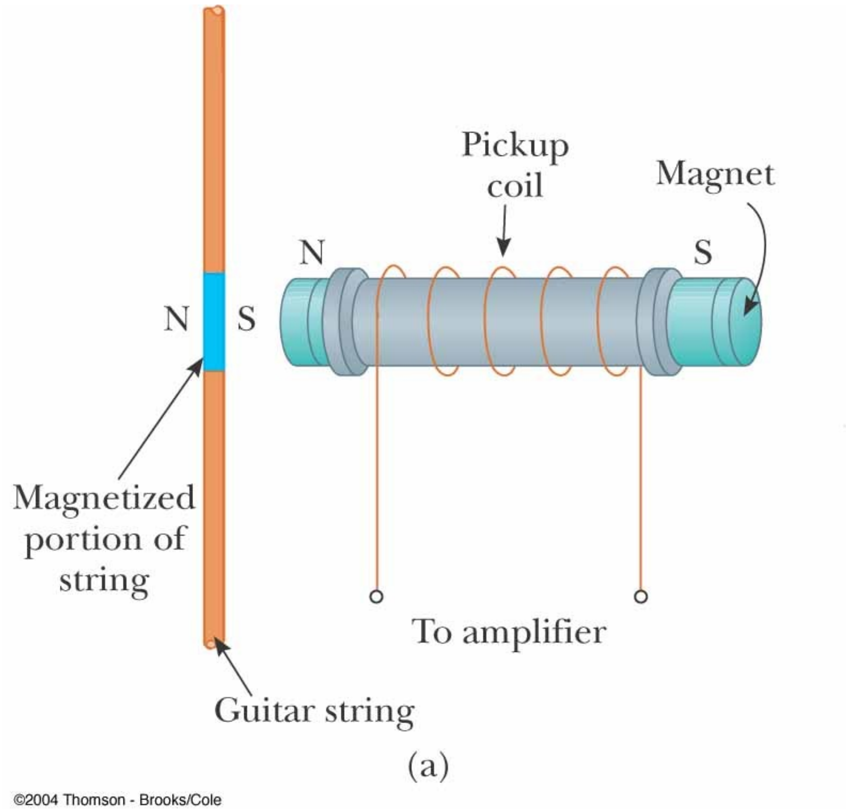
Applications of Faraday's Law – GFI

- A GFI (ground fault indicator) protects users of electrical appliances against electric shock
- When the currents in the wires are in opposite directions, the flux is zero
- When the return current in wire 2 changes, the flux is no longer zero
- The resulting induced emf can be used to trigger a circuit breaker



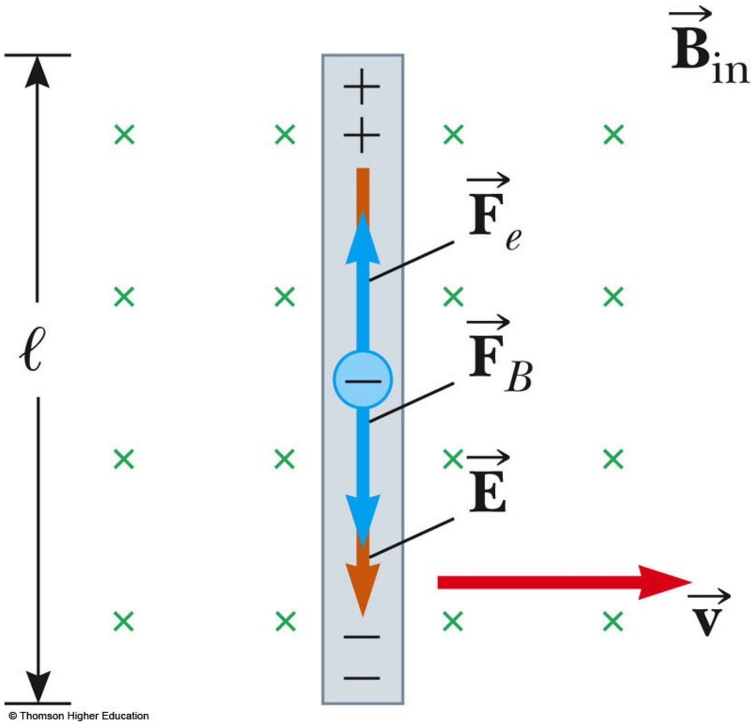
Applications of Faraday's Law – Pickup Coil

- The pickup coil of an electric guitar uses Faraday's law
- The coil is placed near the vibrating string and causes a portion of the string to become magnetized
- When the string vibrates at some frequency, the magnetized segment produces a changing flux through the coil
- The induced emf is fed to an amplifier



Motional emf

- A **motional emf** is the emf induced in a conductor moving through a constant magnetic field
- The electrons in the conductor experience a force, $\mathbf{F}_B = q_e \mathbf{v} \times \mathbf{B}$ that is directed along ℓ



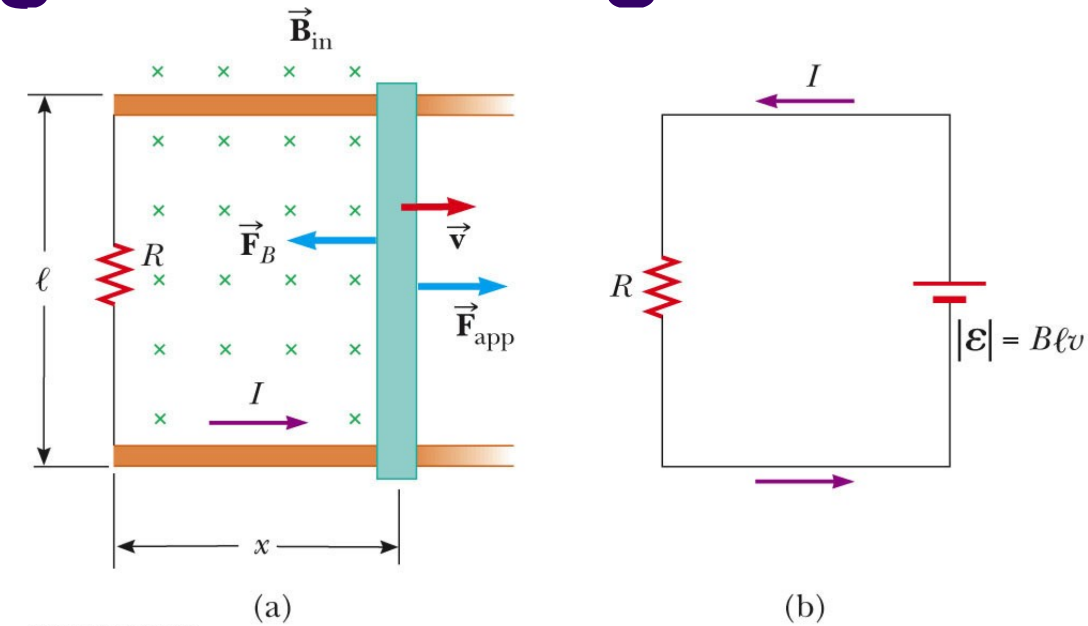
Motional emf, cont.

- Under the influence of the force, the electrons move to the lower end of the conductor and accumulate there
- As a result of the charge separation, an electric field is produced inside the conductor
- The charges accumulate at both ends of the conductor until they are in equilibrium with regard to the electric and magnetic forces

Motional emf, final

- For equilibrium, $qE = qvB$ or $E = vB$
- The electric field is related to the potential difference across the ends of the conductor: $\Delta V = E\,\ell = B\,\ell\,v$
- A potential difference is maintained between the ends of the conductor as long as the conductor continues to move through the uniform magnetic field
- If the direction of the motion is reversed, the polarity of the potential difference is also reversed

Sliding Conducting Bar



- A bar moving through a uniform field and the equivalent circuit diagram
- Assume the bar has zero resistance
- The stationary part of the circuit has a resistance *R*
- $F_B = I\mathbf{l} \times \mathbf{B}$ on current carrying bar → F_{app} needed!

Sliding Conducting Bar, cont.

- The induced emf around loop = the motional emf

  $\mathcal{E} = \dfrac{-d\Phi_B}{dt} = -Bl\dfrac{dx}{dt} = -Blv$

Also, since the resistance in the circuit is *R*, the current is

$$|I| = \mathcal{E}/R = Blv/R$$

Sliding Conducting Bar, Energy Considerations

- The applied force does work on the conducting bar
- This moves the charges through a magnetic field and establishes a current
- The change in energy of the system during some time interval must be equal to the transfer of energy into the system by work

The power input is equal to the rate at which energy is delivered to the resistor

$$P = F_{app} v = (IlB) v = \mathcal{E}^2 / R$$

Lenz’s Law

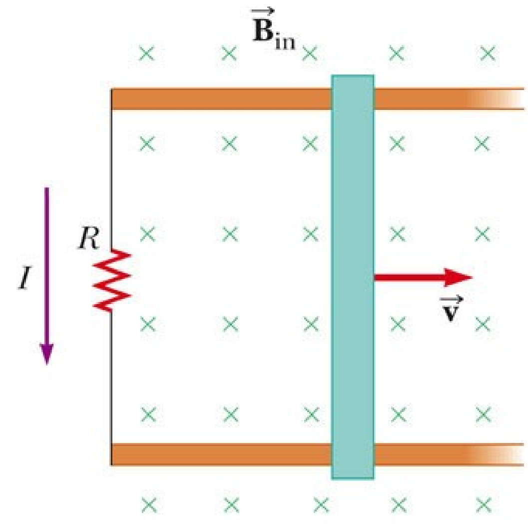
- Faraday’s law contains a minus sign.
- How can the induced emf and the change in flux have opposite algebraic signs?
- There is a physical interpretation referred to as Lenz’s law

Lenz’s Law, cont.

- **Lenz’s law**: *the induced current in a loop is in the direction that creates a magnetic field that opposes the change in magnetic flux through the area enclosed by the loop*
- The induced current tries to keep the original magnetic flux through the circuit from changing

Lenz' Law, Example

- The conducting bar slides on the two fixed conducting rails
- The magnetic flux due to the external magnetic field through the enclosed area increases with time
- The induced current must produce a magnetic field out of the page
  - The induced current must be counterclockwise
- If the bar moves in the opposite direction, the direction of the induced current will also be reversed



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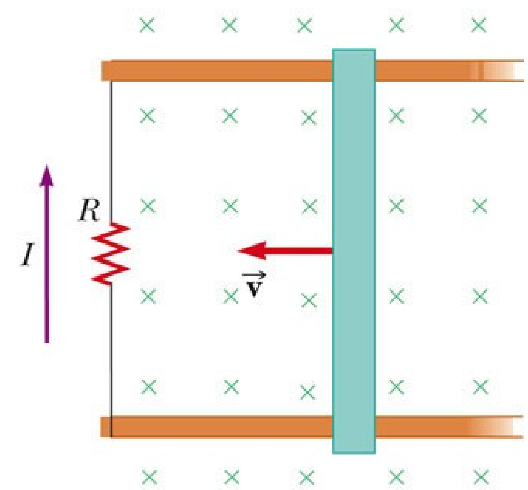

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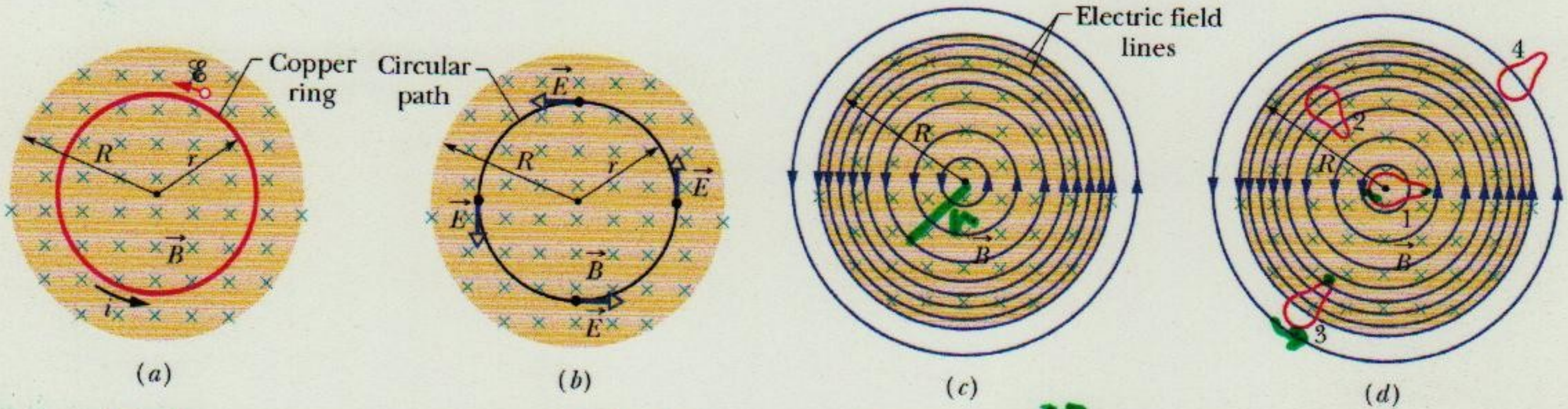
Induced emf and Electric Fields

- An electric field is created in the conductor as a result of the changing magnetic flux
- Even in the absence of a conducting loop, a changing magnetic field will generate an electric field in empty space
- This induced electric field is nonconservative
  - Unlike the electric field produced by stationary charges

Induced emf and Electric Field

$\vec{B}$ in, increasing



Work to move q once around

$W = q\mathcal{E}$

or

$W = qE2\pi r$

$\mathcal{E} = \oint \vec{E}\cdot d\vec{s}$

$\mathcal{E} = E2\pi r$

$\mathcal{E} = -A\frac{dB}{dt}$

$\mathcal{E} = -\pi r^2 \frac{dB}{dt}$

$E = -\frac{r}{2}\frac{dB}{dt}$ (out to R)

$E = -\frac{R^2}{2r}\frac{dB}{dt}$ $(r > R)$

Induced emf and Electric Fields, cont.

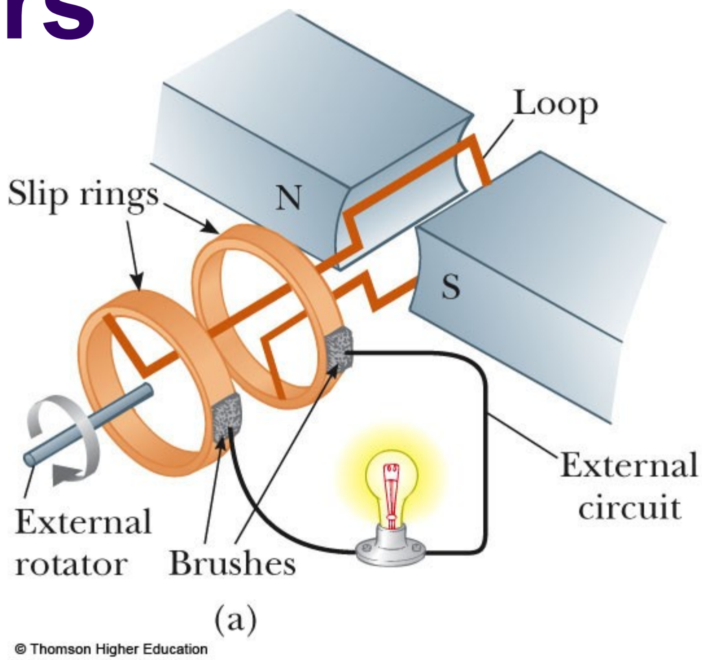
- The emf for any closed path can be expressed as the line integral of $\oint E \cdot dl$ over the path
- Faraday's law can be written in a general form:

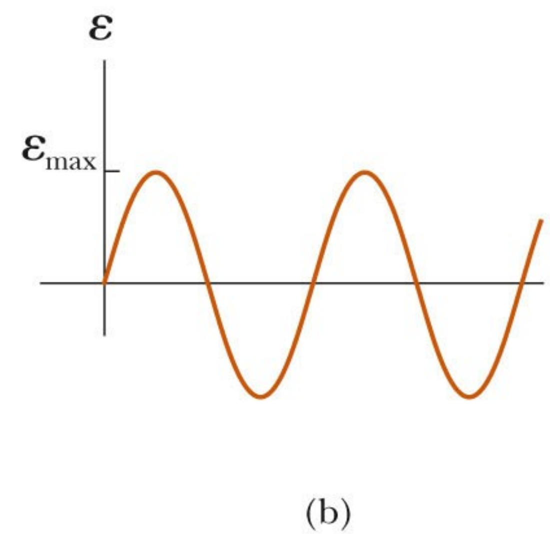
$$\oint E \cdot dl = \frac{-d\Phi_B}{dt}$$

Induced emf and Electric Fields, final

- The induced electric field is a nonconservative field that is generated by a changing magnetic field
- The field cannot be an electrostatic field because if the field were electrostatic, and hence conservative, the line integral of $\boldsymbol{E} \cdot d\boldsymbol{l}$ would be zero and it isn't

Generators

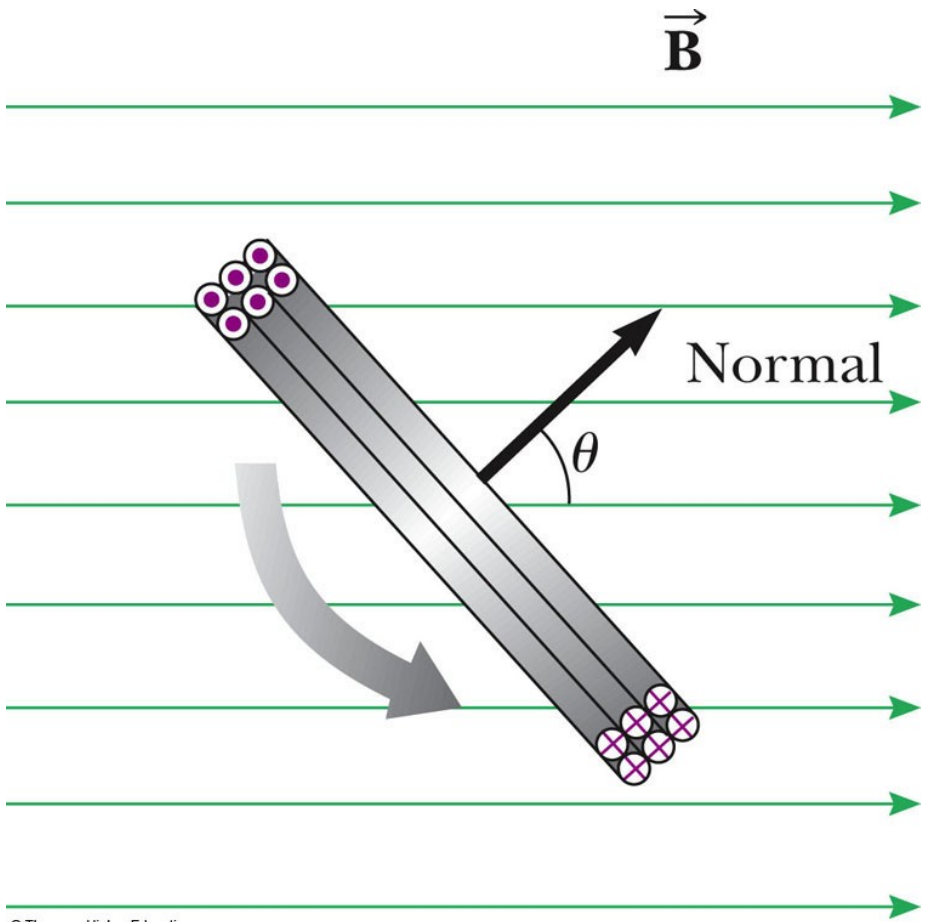




- Electric generators take in energy by work and transfer it out by electrical transmission
- The AC generator consists of a loop of wire rotated by some external means in a magnetic field

Rotating Loop

- Assume a loop with *N* turns, all of the same area rotating in a magnetic field
- The flux through the loop at any time *t* is $\Phi_B = BA \cos \theta = BA \cos \omega t$

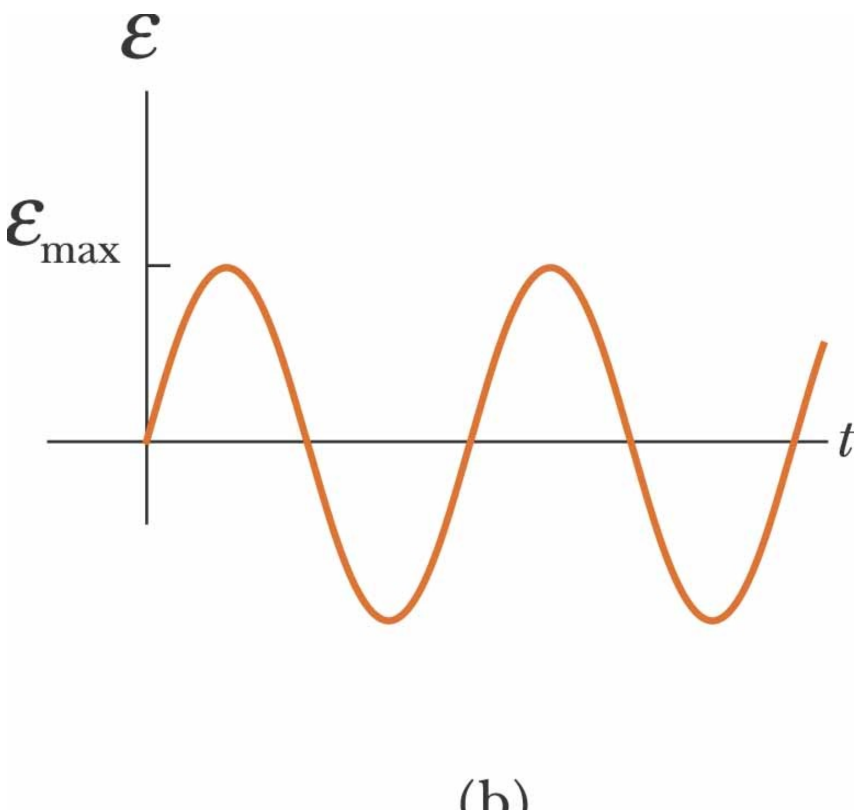


Induced emf in a Rotating Loop

- The induced emf in the loop is

$$\mathcal{E} = -N\frac{d\Phi_B}{dt} = NAB\omega\sin(\omega t)$$

- This is sinusoidal, with $\mathcal{E}_{max} = NAB\omega$



Induced emf in a Rotating Loop, cont.

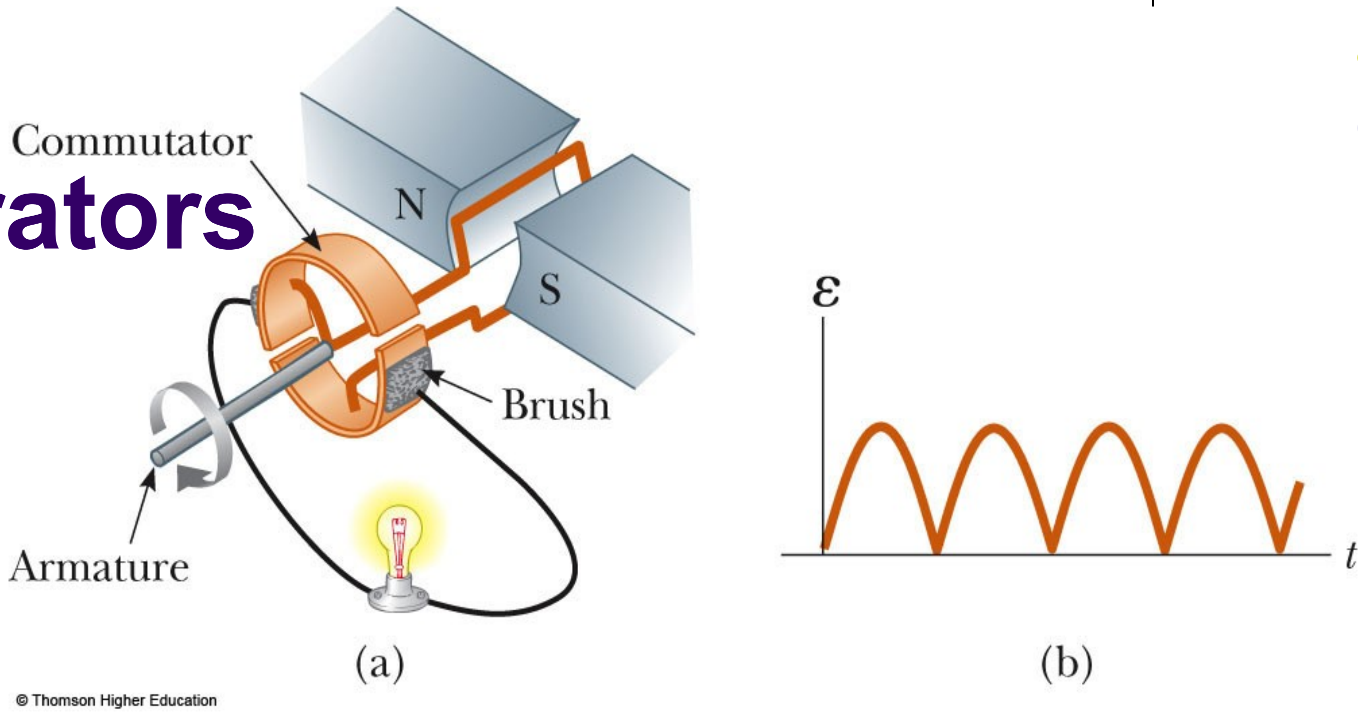
ε_{max} occurs when ωt = 90º or 270º

- This occurs when the magnetic field is in the plane of the coil and the time rate of change of flux is a maximum

ε = 0 when ωt = 0º or 180º

- This occurs when the magnetic field is perpendicular to the plane of the coil and the time rate of change of flux is zero

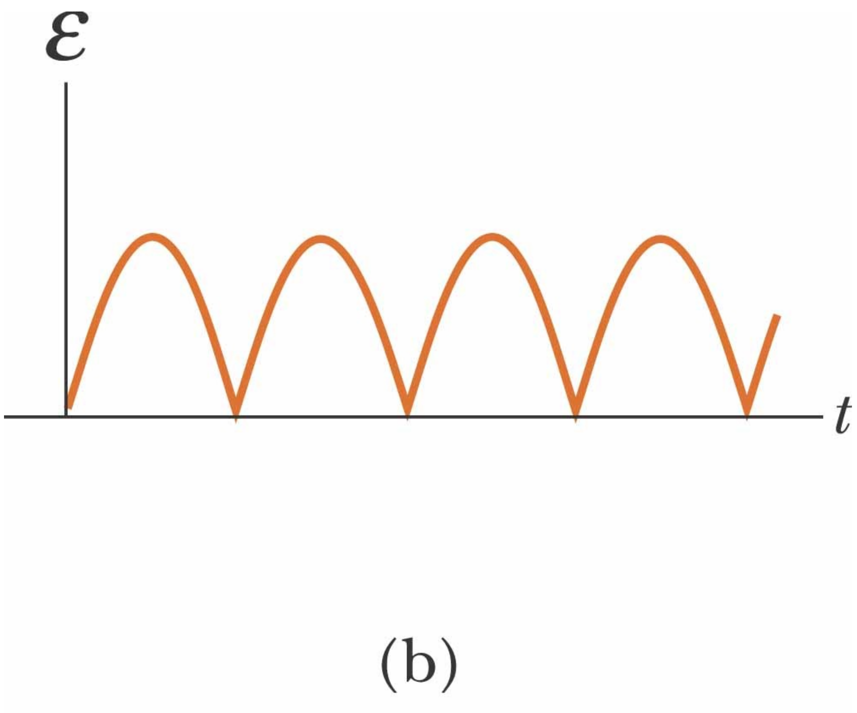
DC Generators



- The DC (direct current) generator has essentially the same components as the AC generator
- The main difference is that the contacts to the rotating loop are made using a split ring called a *commutator*

DC Generators, cont.

- In this configuration, the output voltage always has the same polarity
- It also pulsates with time
- To obtain a steady DC current, commercial generators use many coils and commutators distributed so the pulses are out of phase



Motors

- Motors are devices into which energy is transferred by electrical transmission while energy is transferred out by work
- A motor is a generator operating in reverse
- A current is supplied to the coil by a battery and the torque acting on the current-carrying coil causes it to rotate

Motors, cont.

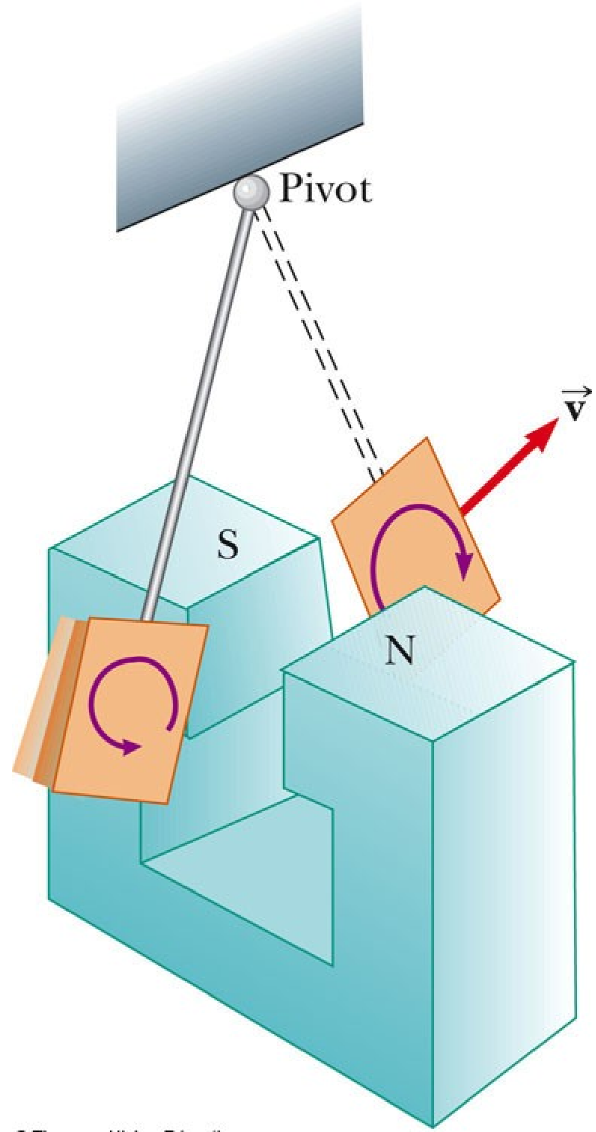
- Useful mechanical work can be done by attaching the rotating coil to some external device
- However, as the coil rotates in a magnetic field, an emf is induced
  - This induced emf always acts to reduce the current in the coil
  - The **back emf** increases in magnitude as the rotational speed of the coil increases

Motors, final

- The current in the rotating coil is limited by the back emf
  - The term *back emf* is commonly used to indicate an emf that tends to reduce the supplied current
- The induced emf explains why the power requirements for starting a motor and for running it are greater for heavy loads than for light ones

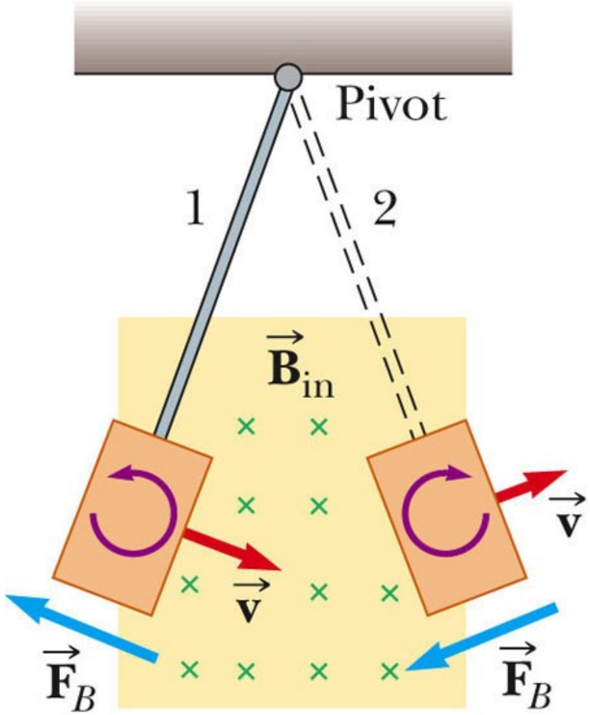
Eddy Currents

- Circulating currents called **eddy currents** are induced in bulk pieces of metal moving through a magnetic field
- The eddy currents are in opposite directions as the plate enters or leaves the field
- Eddy currents are often undesirable because they represent a transformation of mechanical energy into internal energy



Eddy Currents, Example

- The magnetic field is directed into the page
- The induced eddy current is counterclockwise as the plate enters the field
- It is opposite when the plate leaves the field
- The induced eddy currents produce a magnetic retarding force and the swinging plate eventually comes to rest



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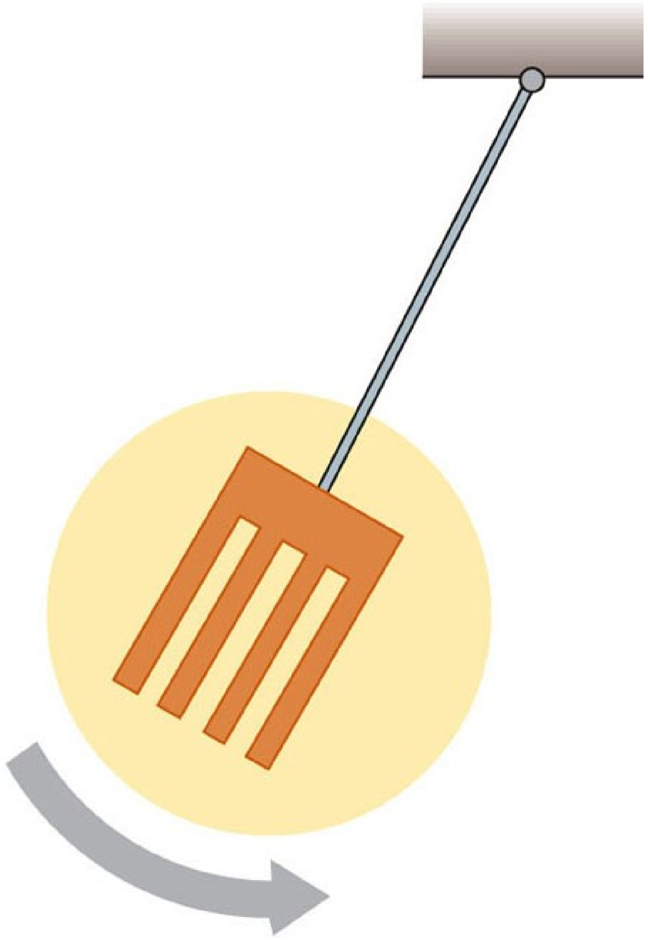
Eddy Currents, Final

- To reduce energy loses by the eddy currents, the conducting parts can
  - Be built up in thin layers separated by a nonconducting material
  - Have slots cut in the conducting plate
- Both prevent large current loops and increase the efficiency of the device



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