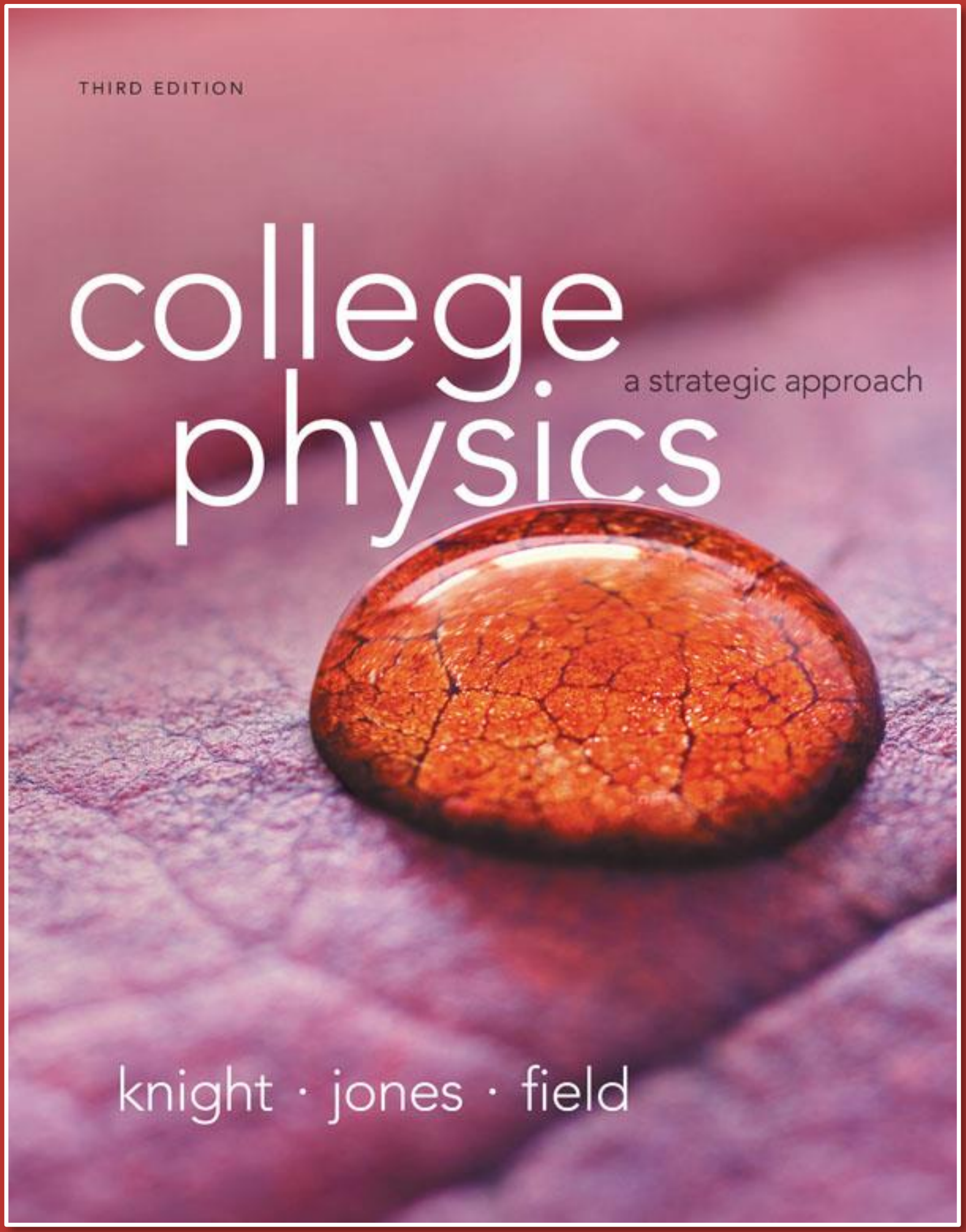


Lecture Presentation

Chapter 25

EM Induction and EM Waves

Suggested Videos for Chapter 25

- **Prelecture Videos**
  - *Electromagnetic Induction*
  - *Faraday's Law and Lenz's Law*
  - *Electromagnetic Waves*
- **Class Videos**
  - *Faraday's Law*
  - *Eddy Currents*
  - *Making Music with Magnetism*
  - *Microwaves*
- **Video Tutor Solutions**
  - *Electromagnetic Fields and Electromagnetic Waves*
- **Video Tutor Demos**
  - *Eddy Currents in Different Metals*
  - *Point of Equal Brightness between Two Light Sources*
  - *Parallel-Wire Polarizer for Microwaves*

Suggested Simulations for Chapter 25

- **ActivPhysics**
  - *13.9, 13.10*
  - *16.9*

- **PhETs**
  - *Faraday's Law*
  - *Faraday's Electromagnetic Lab*
  - *Generator*
  - *Radio Waves & Electromagnetic Fields*

Chapter 25 EM Induction and EM Waves

Chapter Goal: To understand the nature of electromagnetic induction and electromagnetic waves.

Chapter 25 Preview

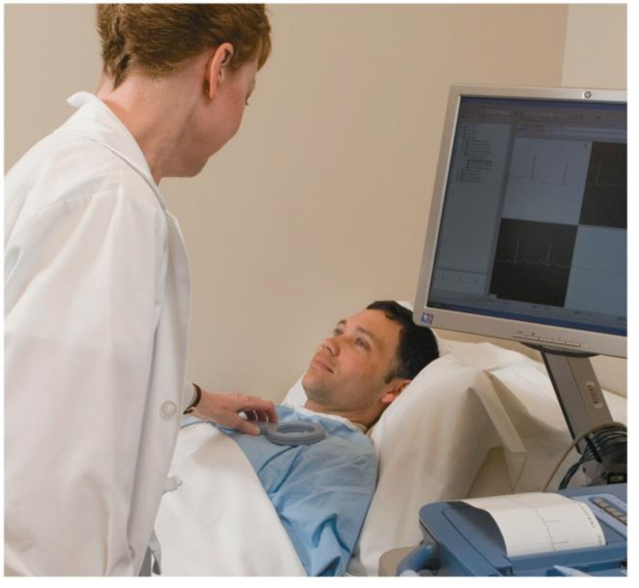
Looking Ahead: Magnetism and Electricity

- The turning windmill blades rotate a wire coil in a *magnetic* field, producing an *electric* current.

- You'll continue to explore the deep connections between magnetism and electricity.

Chapter 25 Preview
Looking Ahead: Induction

- A physician programs a pacemaker by using a rapidly changing magnetic field to **induce** a voltage in the implanted device.



- You'll learn to analyze **electromagnetic induction** qualitatively and quantitatively.

Chapter 25 Preview
Looking Ahead: Electromagnetic Waves

- This antenna detects **electromagnetic waves**, waves of electric and magnetic fields.

- You’ll learn the properties of different electromagnetic waves, from radio waves to light waves.

Chapter 25 Preview
Looking Ahead

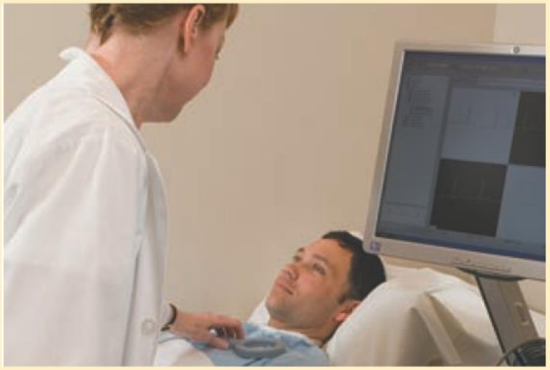
Magnetism and Electricity

The turning windmill blades rotate a wire coil in a *magnetic* field, producing an *electric* current.

You'll continue to explore the deep connections between magnetism and electricity.

Induction

A physician programs a pacemaker by using a rapidly changing magnetic field to **induce** a voltage in the implanted device.



You'll learn to analyze **electromagnetic induction** qualitatively and quantitatively.

Electromagnetic Waves

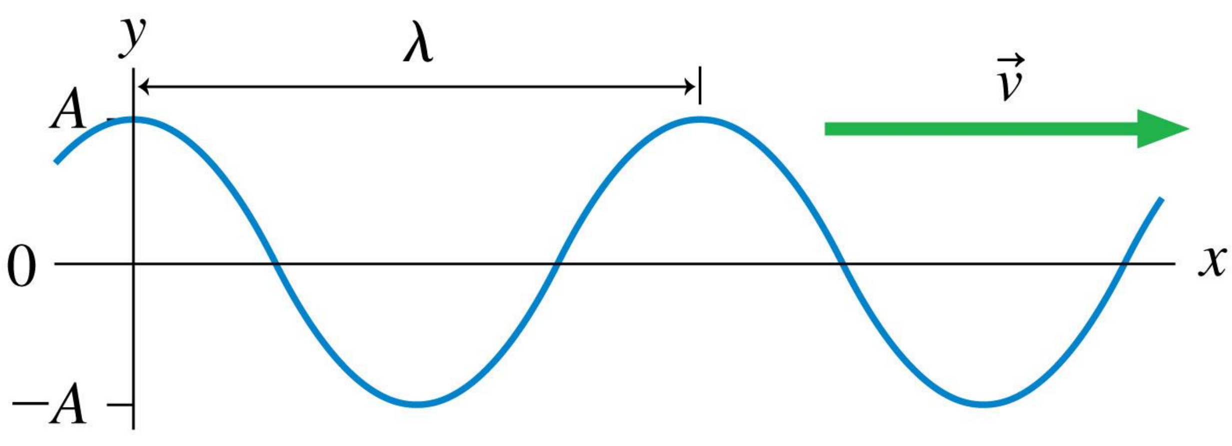
This antenna detects **electromagnetic waves**, waves of electric and magnetic fields.

You'll learn the properties of different electromagnetic waves, from radio waves to light waves.

Text: p. 804

Chapter 25 Preview
Looking Back: Traveling Waves

- In Chapter 15 you learned the properties of traveling waves. For sinusoidal waves, the wave speed is the product of the wave's frequency and wavelength.
- In this chapter, you'll see how the properties of traveling waves are used to describe electromagnetic waves.



$$v = \lambda f$$

Chapter 25 Preview
Stop to Think

A microwave oven uses 2.4 GHz electromagnetic waves. A cell phone uses electromagnetic waves at a slightly lower 1.9 GHz frequency. What can you say about the wavelengths of the two?

A. The waves from the oven have a longer wavelength.
B. The waves from the phone have a longer wavelength.
C. The waves from the oven and the phone have the same wavelength.

Reading Question 25.1

Which of the following will cause an induced current in a coil of wire?

A. A magnet resting near the coil
B. The constant field of the earth passing through the coil
C. A magnet being moved into or out of the coil
D. A wire carrying a constant current near the coil

Reading Question 25.1

Which of the following will cause an induced current in a coil of wire?

A. A magnet resting near the coil
B. The constant field of the earth passing through the coil
✔ C. A magnet being moved into or out of the coil
D. A wire carrying a constant current near the coil

Reading Question 25.2

A metallic conductor moving at a constant speed in a magnetic field may develop a voltage across it. This is an example of _______________.

A. Faraday's Law
B. Lenz's Law
C. Motional emf
D. Induced emf

Reading Question 25.2

A metallic conductor moving at a constant speed in a magnetic field may develop a voltage across it. This is an example of ________________.

A. Faraday's Law
B. Lenz's Law
✔ C. Motional emf
D. Induced emf

Reading Question 25.3

An emf is induced in response to a change in magnetic field inside a loop of wire. Which of the following changes would increase the magnitude of the induced emf?

A. Reducing the diameter of the loop
B. Turning the plane of the loop to be parallel to the magnetic field
C. Changing the magnetic field more rapidly
D. Reducing the resistance of the wire of which the loop is made

Reading Question 25.3

An emf is induced in response to a change in magnetic field inside a loop of wire. Which of the following changes would increase the magnitude of the induced emf?

A. Reducing the diameter of the loop
B. Turning the plane of the loop to be parallel to the magnetic field
✔ C. Changing the magnetic field more rapidly
D. Reducing the resistance of the wire of which the loop is made

Reading Question 25.4

The speed of electromagnetic waves

A. Depends upon the wavelength in a vacuum.
B. Depends on the photon energy.
C. Is the same as the speed of sound.
D. Is the same for all waves regardless of wavelength.

Reading Question 25.4

The speed of electromagnetic waves

A. Depends upon the wavelength in a vacuum.
B. Depends on the photon energy.
C. Is the same as the speed of sound.
✔ D. Is the same for all waves regardless of wavelength.

Reading Question 25.5

Comparing infrared and ultraviolet, we can say that

A. Infrared has longer wavelength and higher photon energy.
B. Infrared has longer wavelength and lower photon energy.
C. Ultraviolet has longer wavelength and higher photon energy.
D. Ultraviolet has longer wavelength and lower photon energy.

Reading Question 25.5

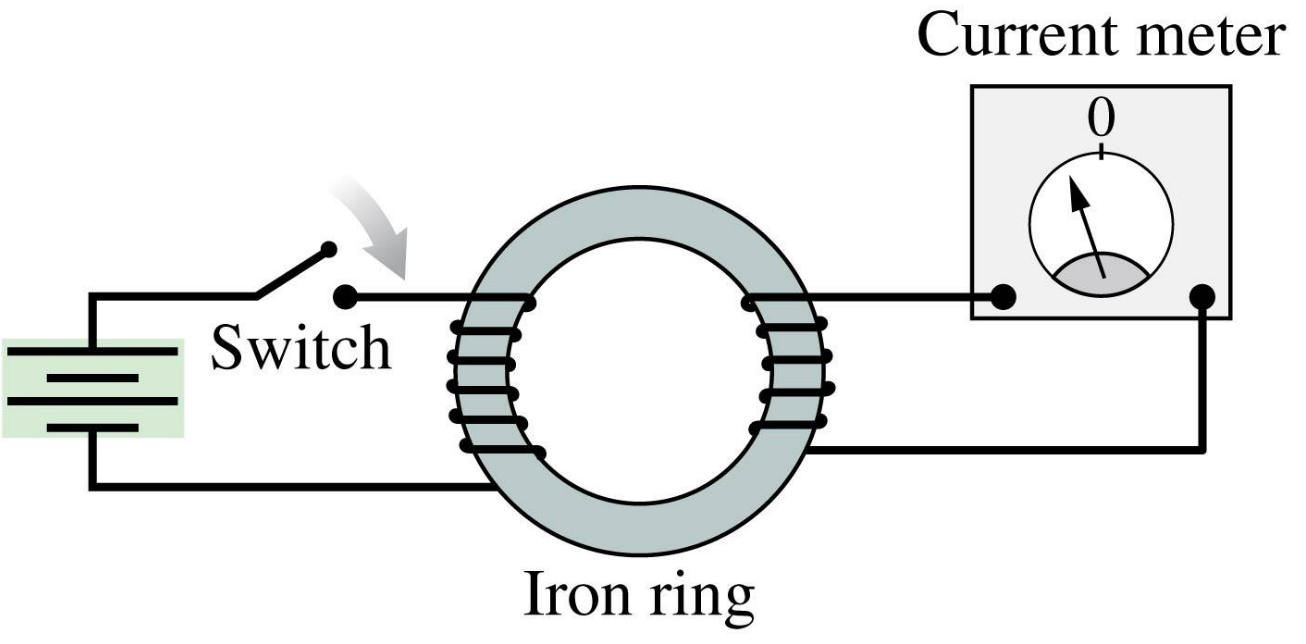
Comparing infrared and ultraviolet, we can say that

A. Infrared has longer wavelength and higher photon energy.
✔ B. Infrared has longer wavelength and lower photon energy.
C. Ultraviolet has longer wavelength and higher photon energy.
D. Ultraviolet has longer wavelength and lower photon energy.

Section 25.1 Induced Currents

Induced Currents

- We now know that a current can create a magnetic field. Can a magnetic field create a current?
- Michael Faraday experimented with two coils of wire wrapped around an iron ring in an attempt to generate a current from a magnetic field.

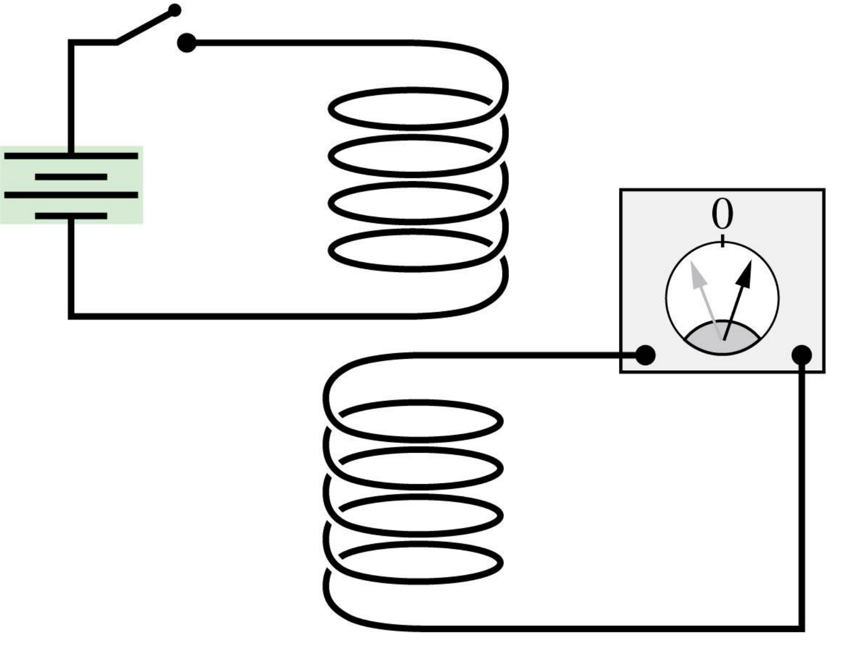


Induced Currents

- Faraday's experiment did not generate a steady current; however, in the instant he closed the switch in the circuit, there was a brief indication of a current.
- He realized that a current was generated only if the magnetic field was *changing* as it passed through the coil.
- Faraday then set up a series of experiments to test this hypothesis.

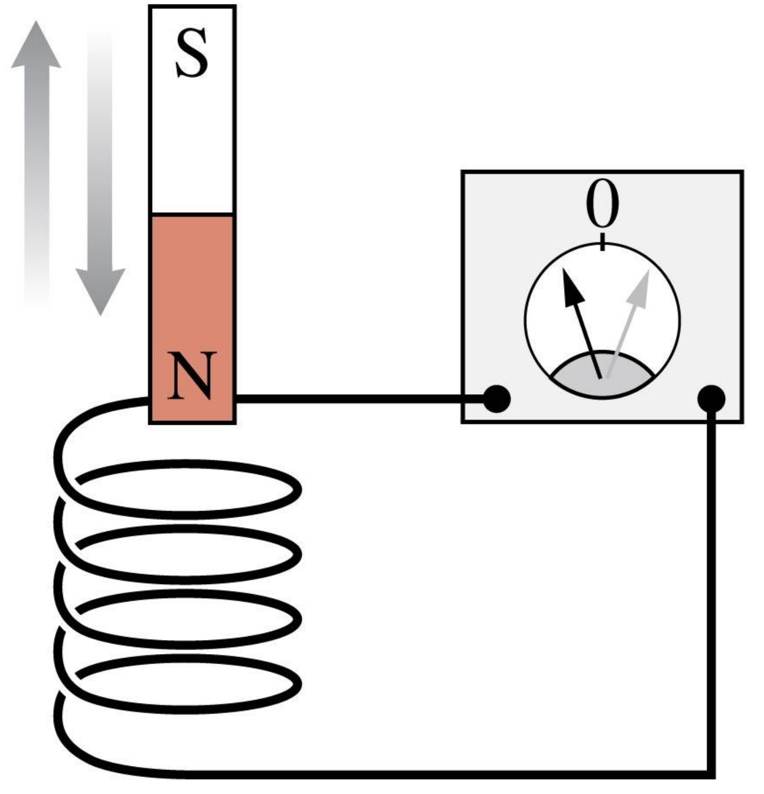
Induced Currents

- Faraday placed one coil directly above the other, without the iron ring.
- There was no current in the lower circuit while the switch was in the closed position, but a momentary current appeared whenever the switch was opened or closed.



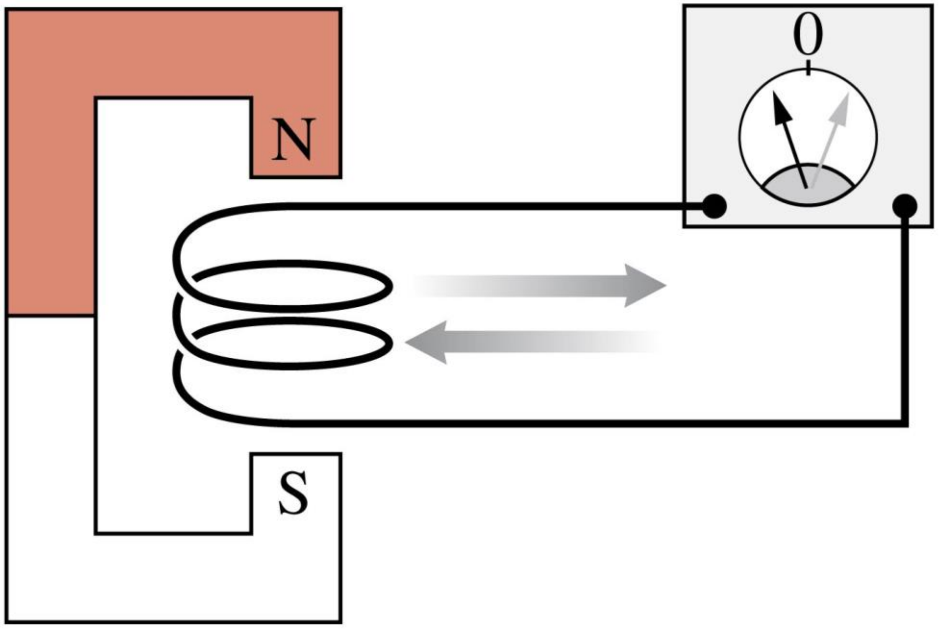
Induced Currents

- Faraday pushed a bar magnet into a coil of wire. This action caused a momentary deflection of the needle in the current meter, although *holding* the magnet inside the coil had no effect.
- A quick withdrawal of the magnet deflected the needle in the other direction.



Induced Currents

- Faraday created a momentary current by rapidly pulling a coil of wire out of a magnetic field. There was no current if the coil was stationary in the magnetic field.
- Pushing the coil *into* the magnet caused the needle to deflect in the opposite direction.

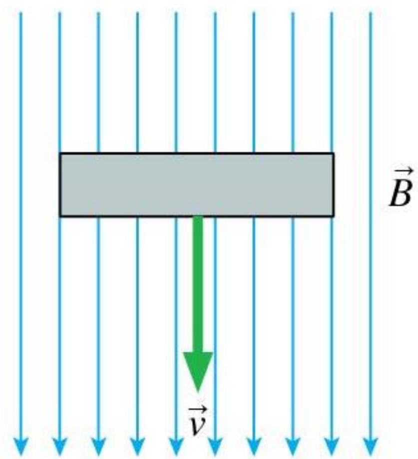


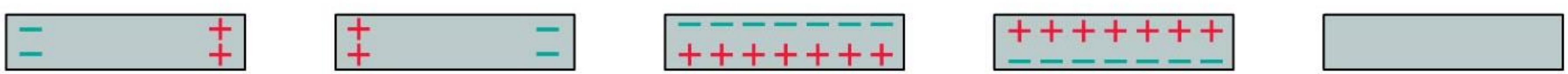
Induced Currents

- **Faraday found that there is a current in a coil of wire if and only if the magnetic field passing through the coil is *changing*.**
- The current in a circuit due to a changing magnetic field is called an **induced current.**
- The creation of an electric current by a changing magnetic field is an example of **electromagnetic induction.**

QuickCheck 25.1

A metal bar moves through a magnetic field. The induced charges on the bar are



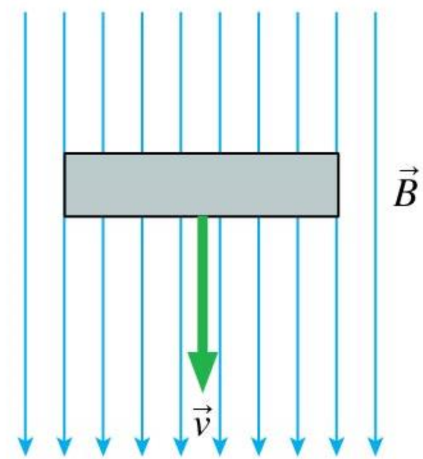


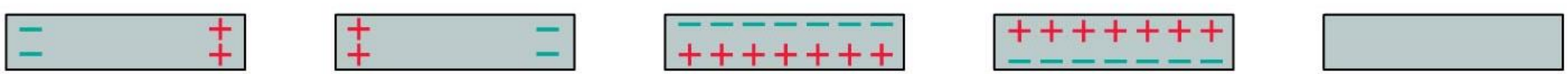
A. B. C. D. E.

Slide 25-28

QuickCheck 25.1

A metal bar moves through a magnetic field. The induced charges on the bar are



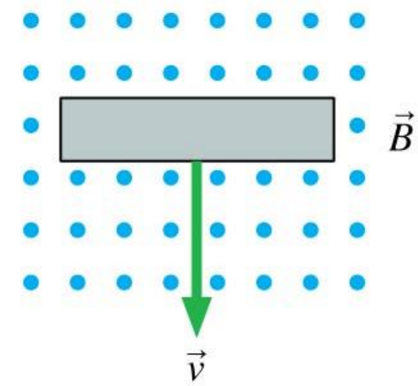


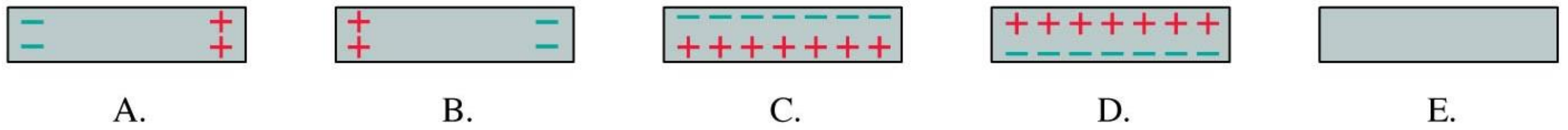
A. B. C. D. E.

Slide 25-29

QuickCheck 25.2

A metal bar moves through a magnetic field. The induced charges on the bar are

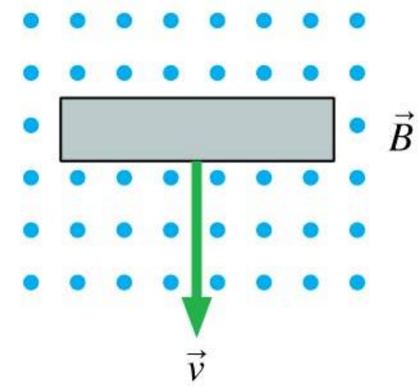


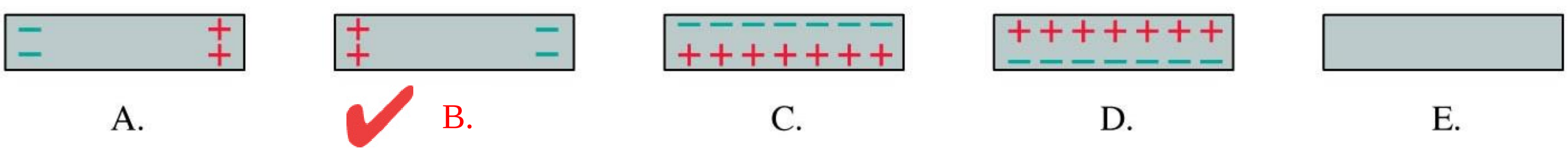


Slide 25-30

QuickCheck 25.2

A metal bar moves through a magnetic field. The induced charges on the bar are



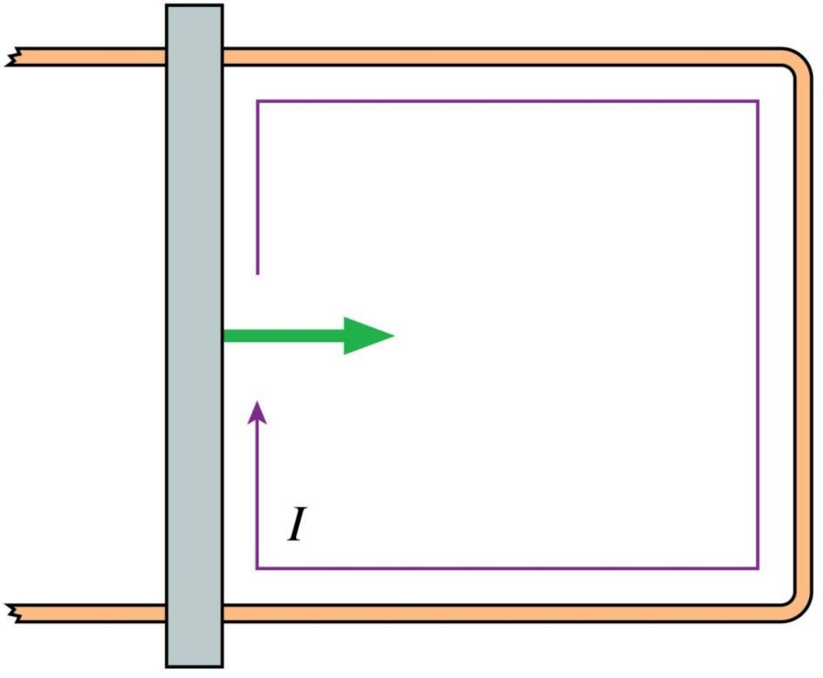


Slide 25-31

QuickCheck 25.3

An induced current flows clockwise as the metal bar is pushed to the right. The magnetic field points

A. Up.
B. Down.
C. Into the screen.
D. Out of the screen.
E. To the right.

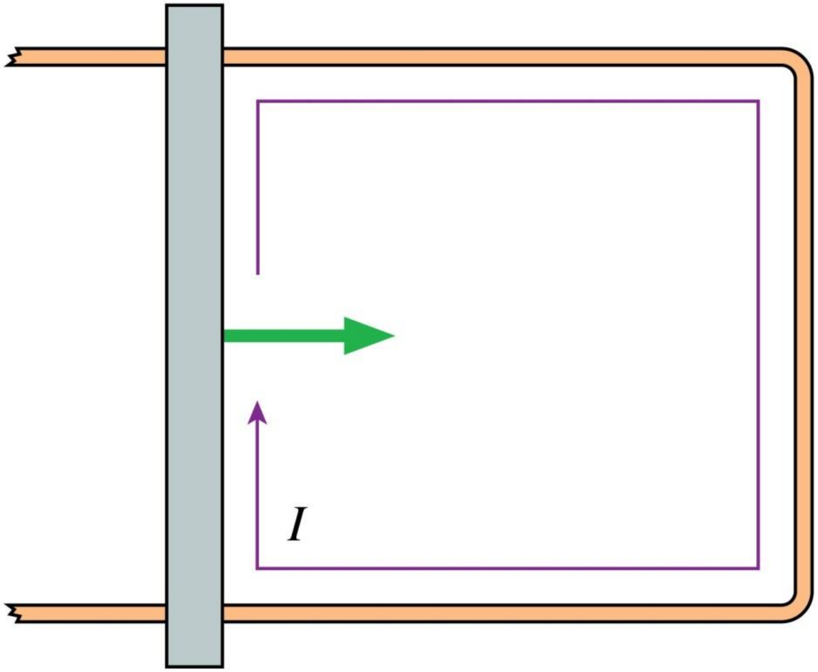


Slide 25-32

QuickCheck 25.3

An induced current flows clockwise as the metal bar is pushed to the right. The magnetic field points

A. Up.
B. Down.
✔ C. Into the screen.
D. Out of the screen.
E. To the right.



Slide 25-33

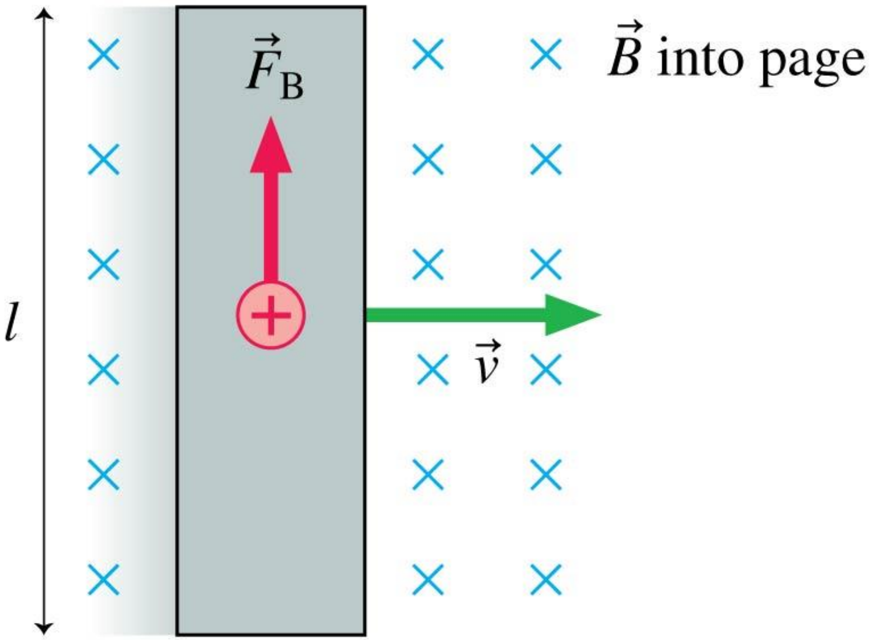
Section 25.2 Motional emf

Motional emf

- *Motional emf* is the voltage produced by the motion of a conductor in a magnetic field.

Motional emf

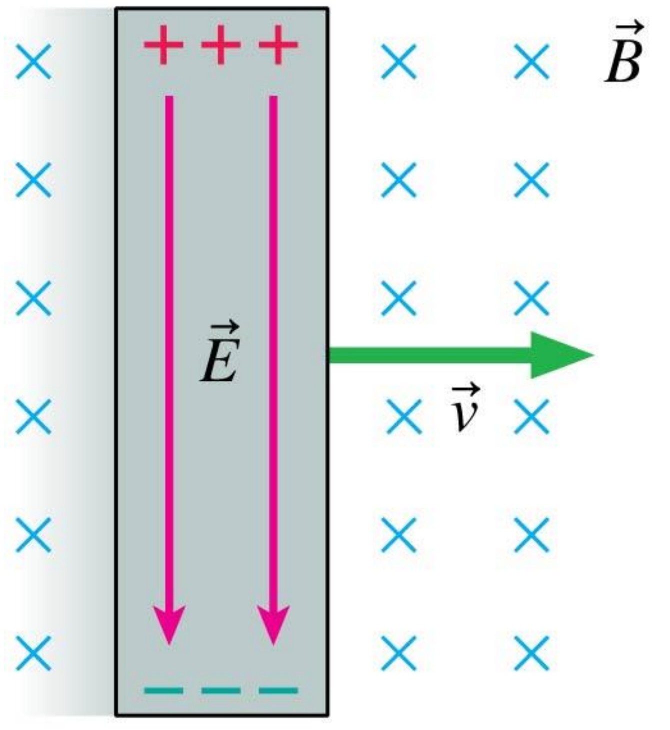
- As a conductor moves through a uniform magnetic field, the charge carriers inside the conductor also move with the same velocity.
- In a simple case where the velocity is perpendicular to the field, the charge carriers experience a force $F_B = qvB$.
- Positive charges are free to move and drift upward.



Motional emf

- Forces on the charge carriers in a moving conductor cause a charge separation that creates an electric field in the conductor.
- The charge separation continues until the electric force balances the magnetic force:

$$F_{\mathrm{E}} = qE = F_{\mathrm{B}} = qvB$$

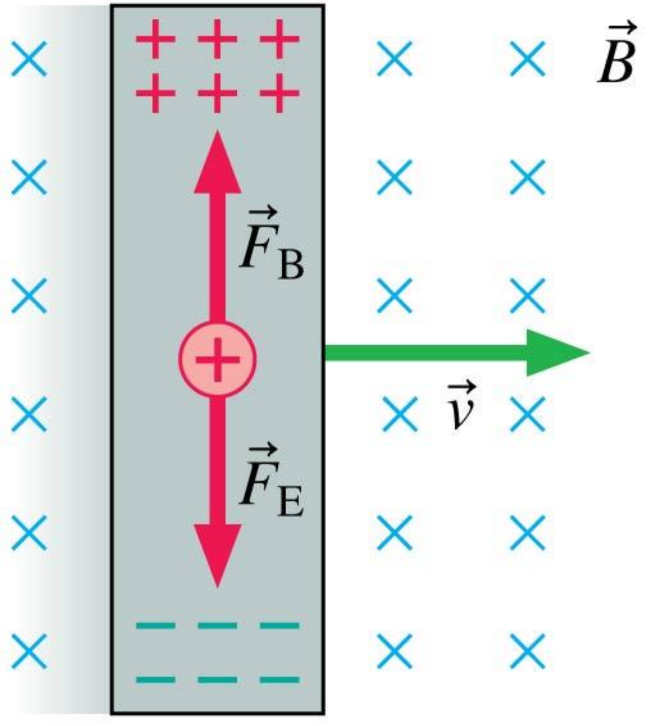


Motional emf

- When the electric force balances the magnetic force, the carriers experience no net force and therefore no motion. The electric field strength at equilibrium is

$$E = vB$$

- **The magnetic force on the charge carriers in a moving conductor creates an electric field $E = vB$ inside the conductor.**



Motional emf

- The motion of the wire through a magnetic field *induces* a potential difference between the ends of the conductor:

$$\Delta V = vlB$$

- The potential difference depends on the strength of the magnetic field and the wire's speed through the field.

Motional emf

- The **motional emf** of a conductor moving perpendicular to the magnetic field is

$$\mathcal{E} = vlB$$

emf due to motion of conductor (V)

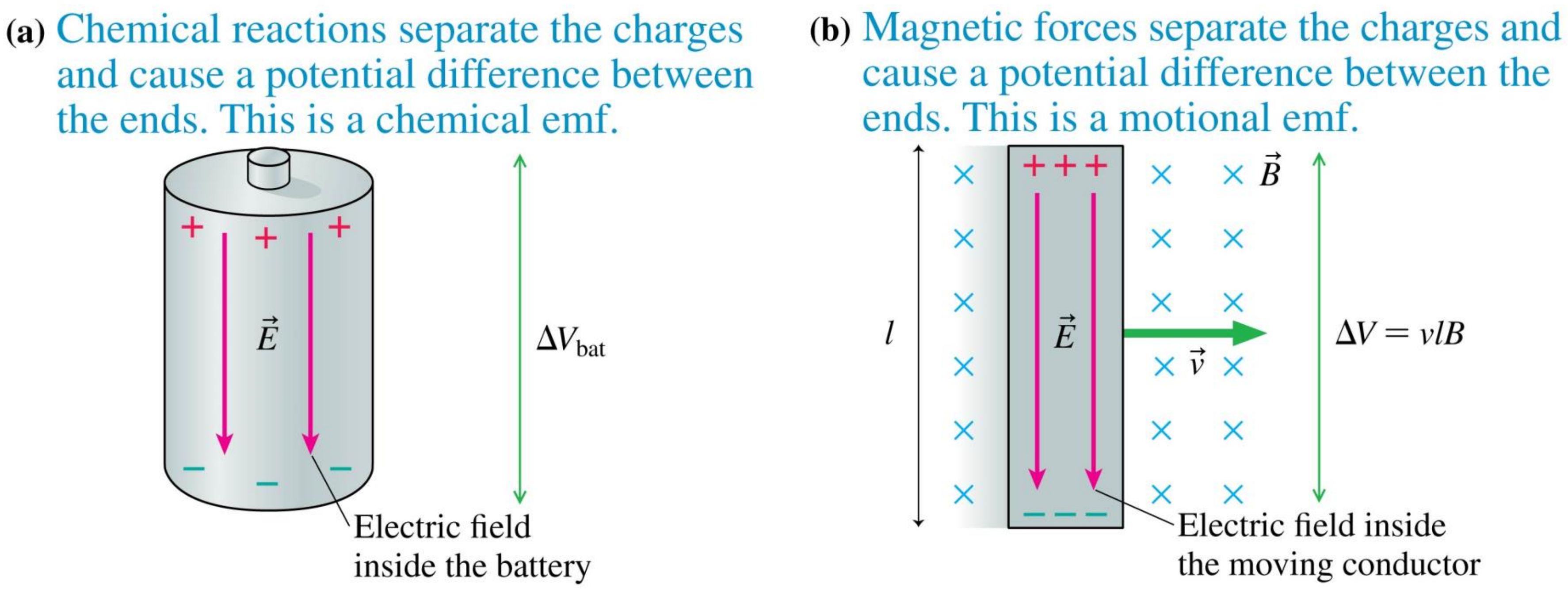
Speed of conductor perpendicular to magnetic field (m/s)

Magnetic field strength (T)

Length of conductor (m)

Motional emf

- There are two ways to generate an emf:



Example 25.1 Finding the motional emf for an airplane

A Boeing 747 aircraft with a wingspan of 65 m is cruising at 260 m/s over northern Canada, where the magnetic field of the earth (magnitude 5.0×10^{-5} T) is directed straight down. What is the potential difference between the tips of the wings?

PREPARE The wing is a conductor moving through a magnetic field, so there will be a motional emf. We can visualize a top view of this situation exactly as in Figure 25.3b, with the wing as the moving conductor.

Example 25.1 Finding the motional emf for an airplane (cont.)

SOLVE The magnetic field is perpendicular to the velocity, so we can compute the potential difference using Equation 25.3:

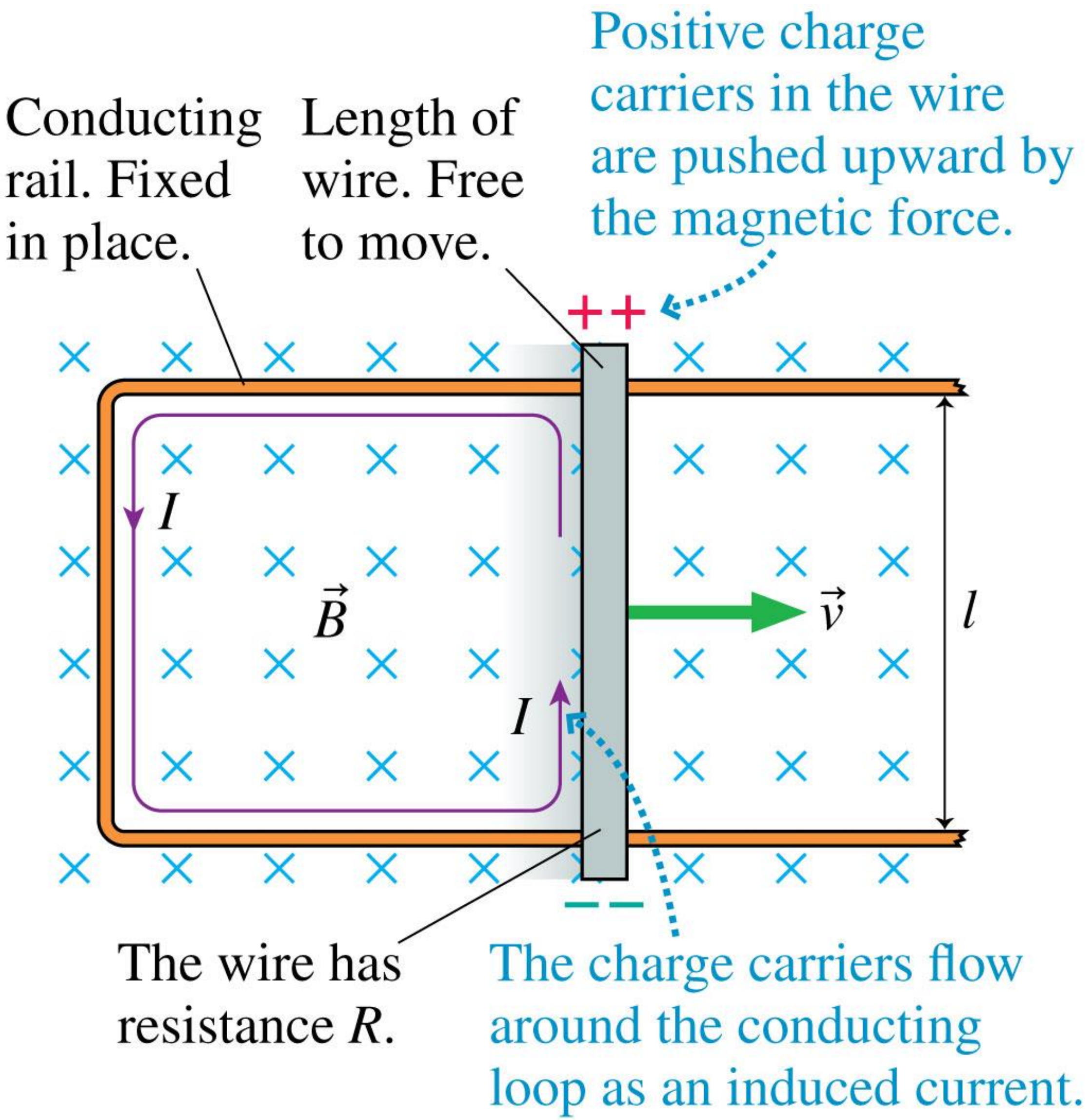
$$\Delta V = vlB = (260\text{ m/s})(65\text{ m})(5.0 \times 10^{-5}\text{ T}) = 0.85\text{ V}$$

ASSESS The earth's magnetic field is small, so the motional emf will be small as well unless the speed and the length are quite large. The tethered satellite generated a much higher voltage due to its much greater speed and the great length of the tether, the moving conductor.

Induced Current in a Circuit

- A moving conductor could have an emf, but it could not sustain a current because the charges had no where to go.
- If we include the moving conductor in a circuit, we can sustain a current.
- One way to create the circuit is to add a fixed U-shaped conducting rail along which the wire slides.

Induced Current in a Circuit



Induced Current in a Circuit

- In a circuit, the charges that are pushed toward the ends of a moving conductor in a magnetic field can continue to flow around the circuit.
- The moving wire acts like a battery in a circuit.
- **The current in the circuit is an induced current.**
- The induced current for a circuit including a wire with resistance *R* is given by Ohm's Law:

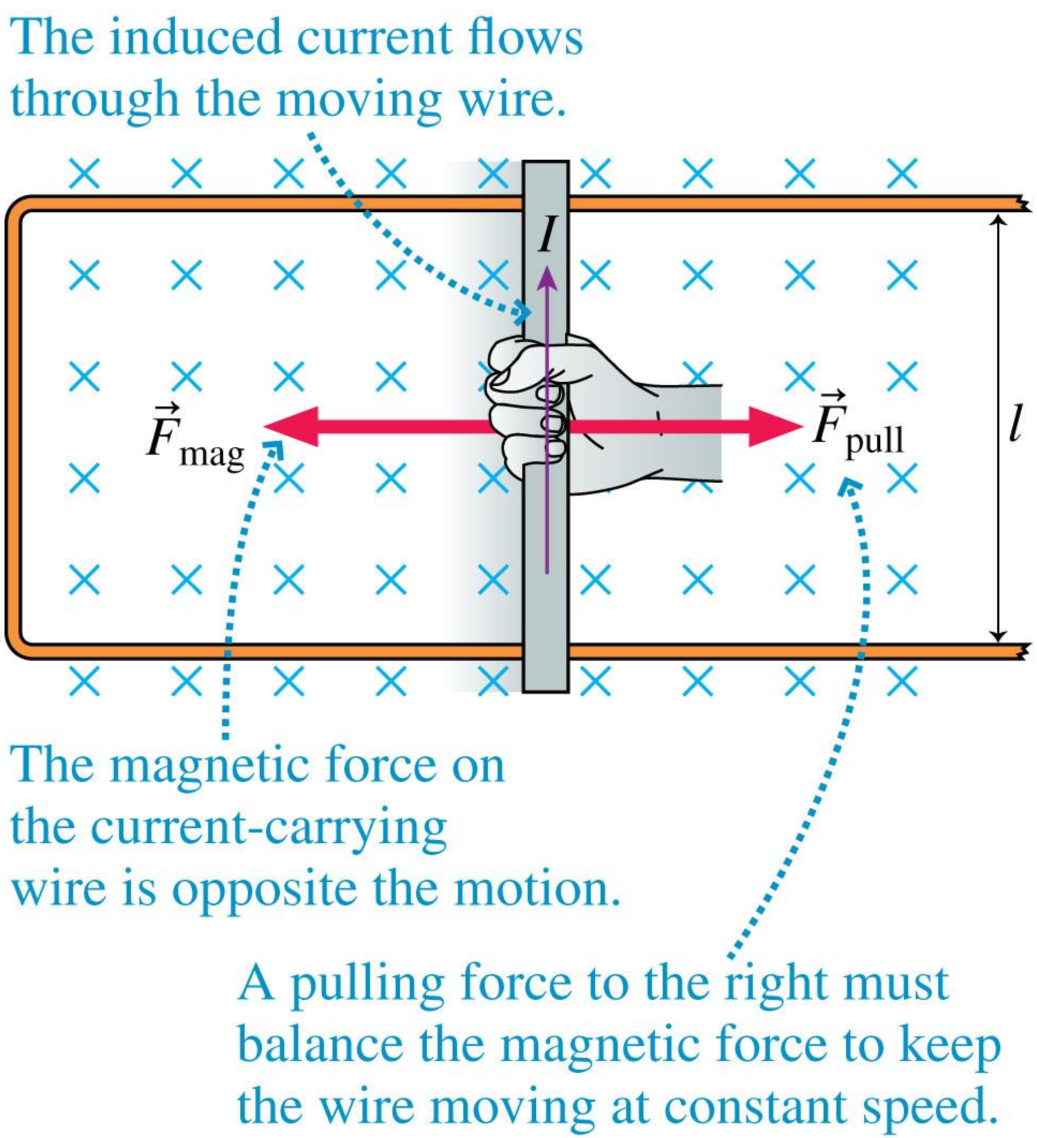
$$I = \frac{\mathcal{E}}{R} = \frac{vlB}{R}$$

Induced Current in a Circuit

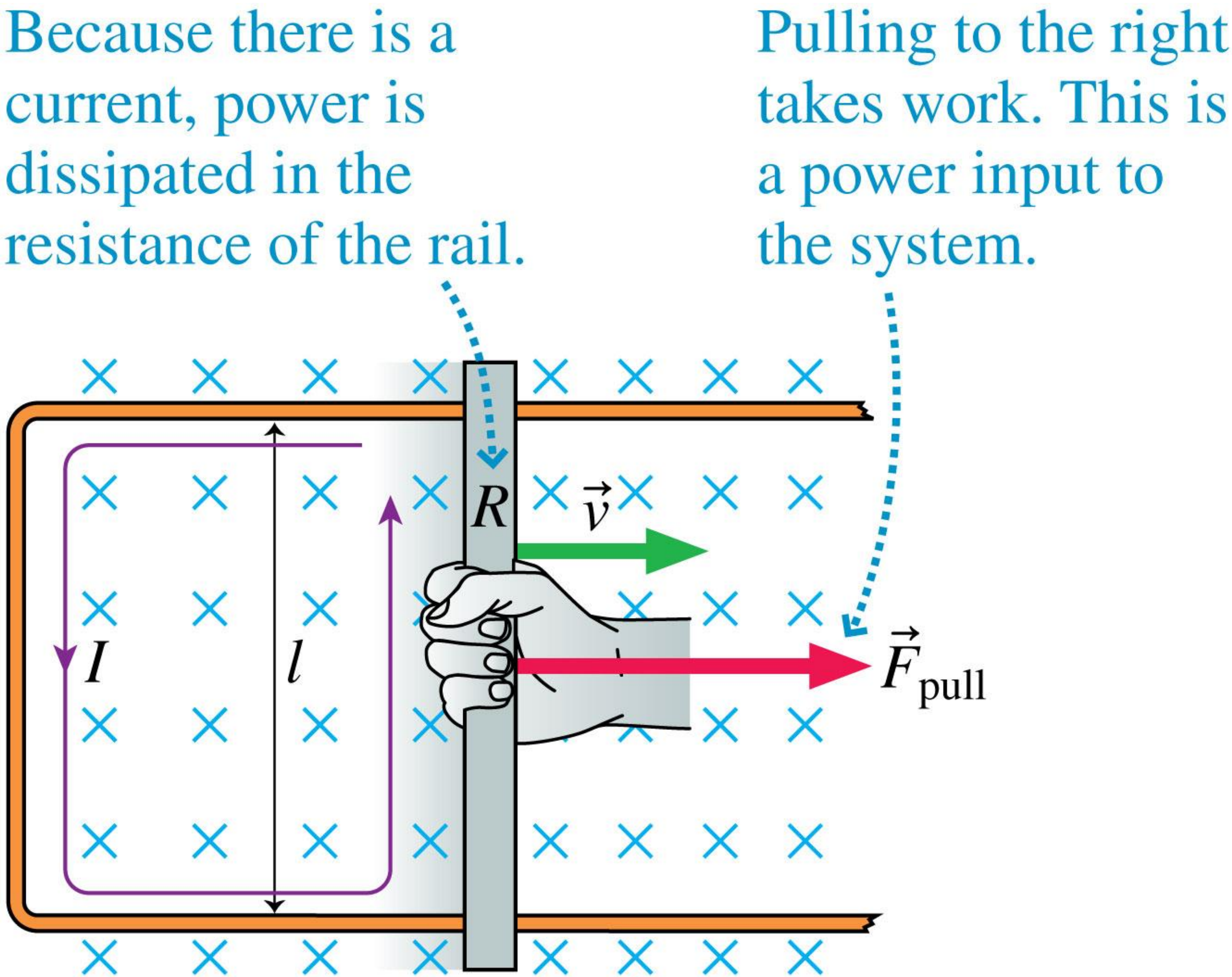
- In a circuit, a moving wire connected to rails in a magnetic field will carry an induced current *I*.
- The magnetic field will exert a force on the current in the direction opposite the wire's motion.
- This magnetic drag will cause the wire to slow down and stop unless an equal and opposite force pulls the wire.

$$F_{\text{pull}} = F_{\text{mag}} = IlB = \left(\frac{vlB}{R}\right)lB = \frac{vl^2B^2}{R}$$

Induced Current in a Circuit



Energy Considerations



Energy Considerations

- In Chapter 10 we learned that the power exerted by a force pushing or pulling an object with velocity v is $P = Fv$.
- The power provided to a circuit by a force pulling on the wire is

$$P_{\text{input}} = F_{\text{pull}}v = \frac{v^2 l^2 B^2}{R}$$

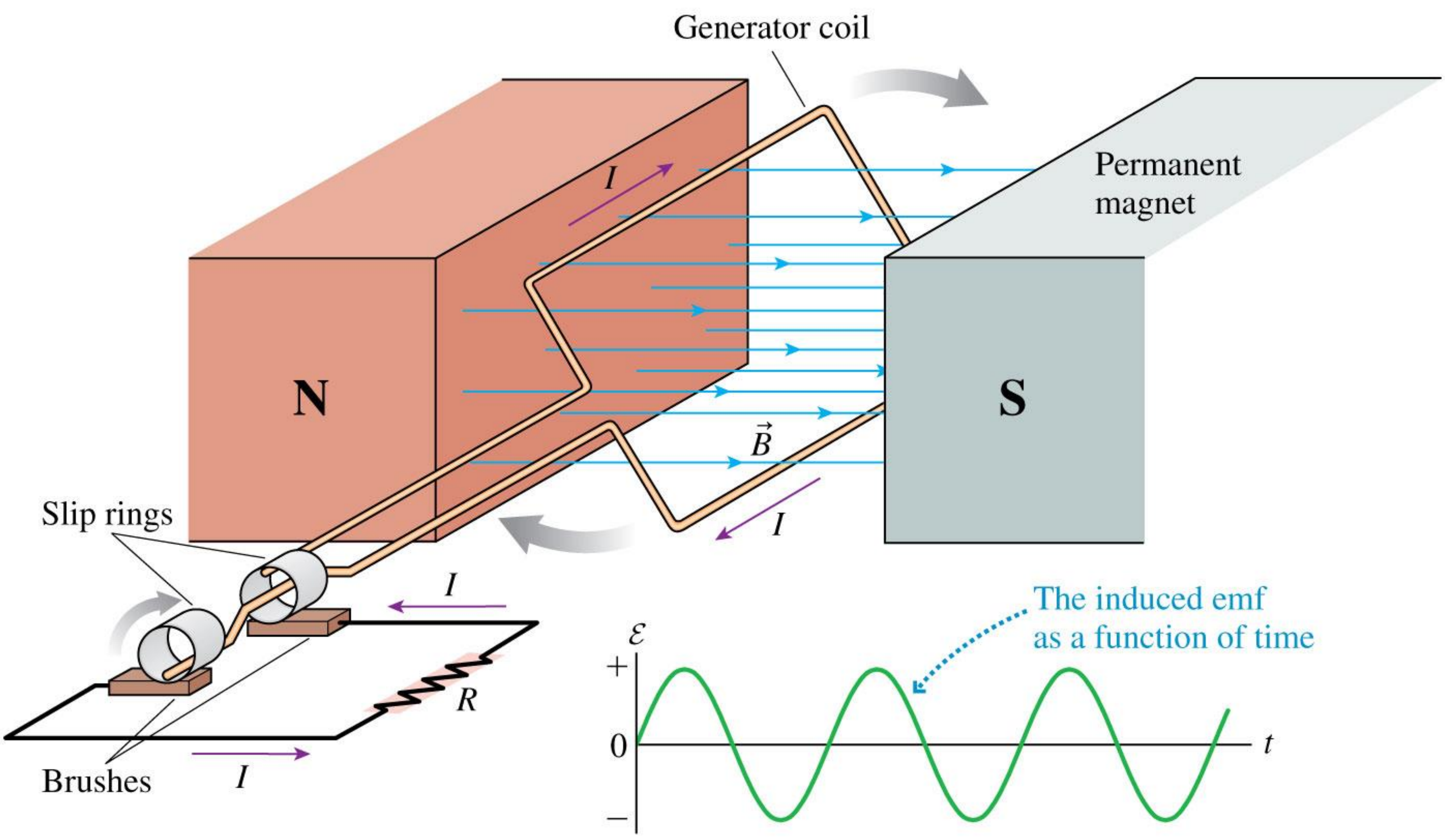
- The resistance in the circuit causes the power in the circuit to dissipate:

$$P_{\text{dissipated}} = I^2 R = \frac{v^2 l^2 B^2}{R}$$

Generators

- A **generator** is a device that converts mechanical energy to electric energy.
- Rather than move a straight wire through a magnetic field, it is more practical to rotate a coil of wire. As the coil rotates, one edge always moves upward through the electric field while the other edge moves downward.
- The motion of the wire induces a current, which is then removed by *brushes* that press up against rotating *slip rings*.

Generators



Generator coil
Permanent magnet
N
S
I
I
$\vec{B}$
Slip rings
I
R
Brushes
I
The induced emf as a function of time
$\mathcal{E}$
+
0
–
t

Generators

- As the coil in a generator rotates, the sense of emf changes, giving a sinusoidal variation of emf as a function of time.
- The alternating sign of the voltage produces an *alternating current*, AC.

Try It Yourself: No Work, No Light

Turning the crank on a generator flashlight rotates a coil of wire in the magnetic field of a permanent magnet. With the switch off, there is no current and no drag force; it's easy to turn the crank. Closing the switch allows an induced current to flow through the coil, so the bulb lights. But the current in the wire experiences a drag force in the magnetic field, so you must do work to keep the crank turning. This is the source of the output power of the circuit, the light of the bulb.

Section 25.3 Magnetic Flux

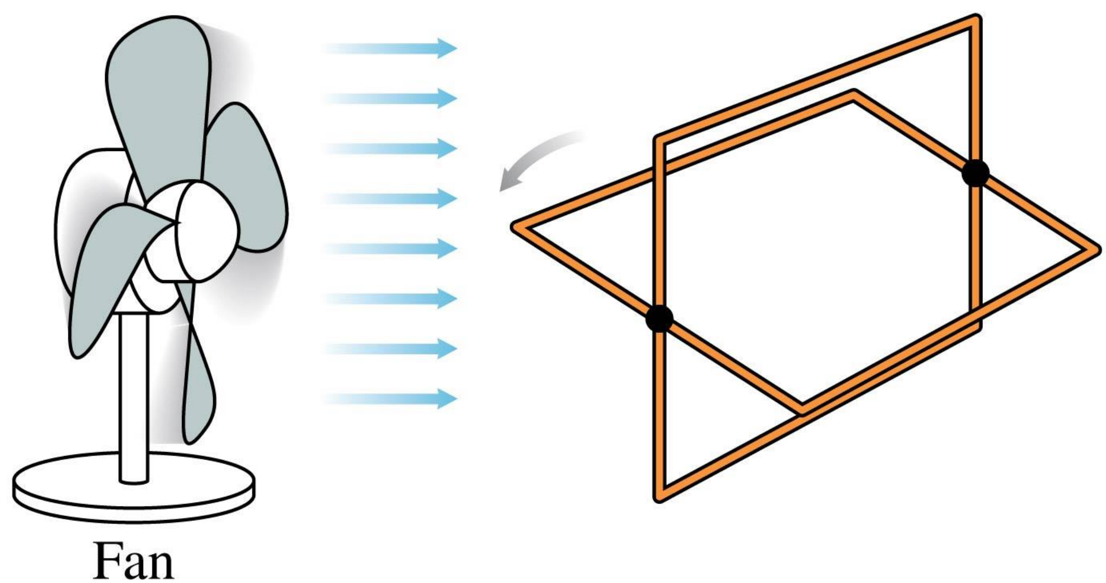
Magnetic Flux

- Faraday found that a current was induced when the amount of magnetic field passing through a coil or loop changes.
- This is what happens when we slide a wire along a rail; the circuit expands and so more magnetic field passes through the larger loop.

Magnetic Flux

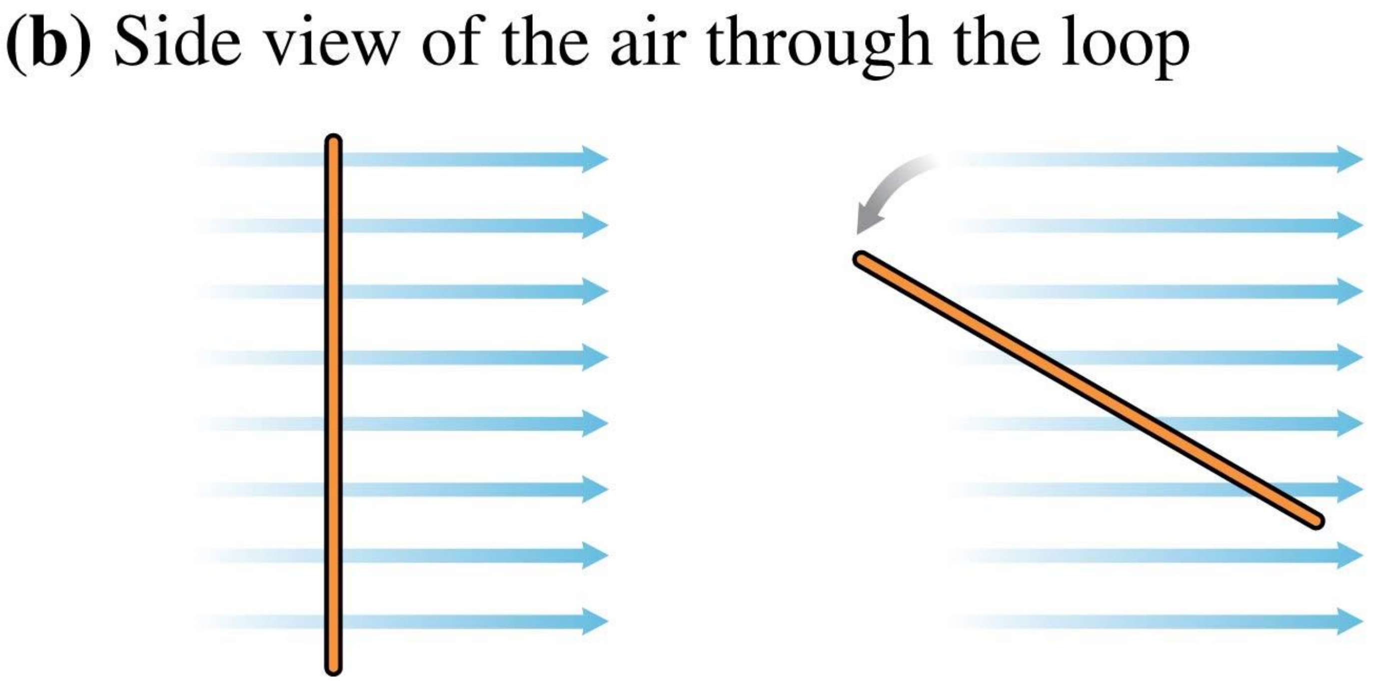
- We can think about the amount of magnetic flux passing through a loop in the same way we think about the amount of air a fan blows through a loop.
- The amount of air flowing through a loop depends on the angle.
- Tipping the loop changes the amount of air through the loop.

(a) A fan blows air through a loop



Magnetic Flux

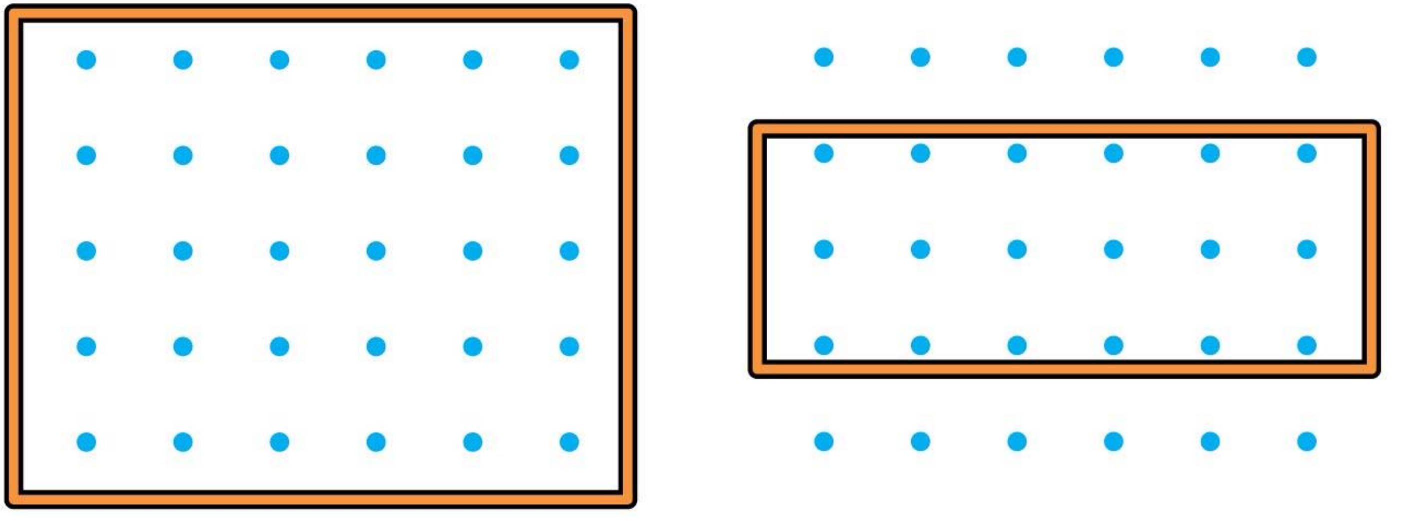
- We can look at a side-view of air being blown through a tipped loop.
- Tipping the loop reduces the amount of air that flows through the loop.



Magnetic Flux

- If we consider the front-end view of a fan blowing air through a loop, we can see that the tipping causes a reduction in air flow.
- Here, the dots represent the front of arrows, indicating the direction of the airflow.

(c) Front view of the air through the loop

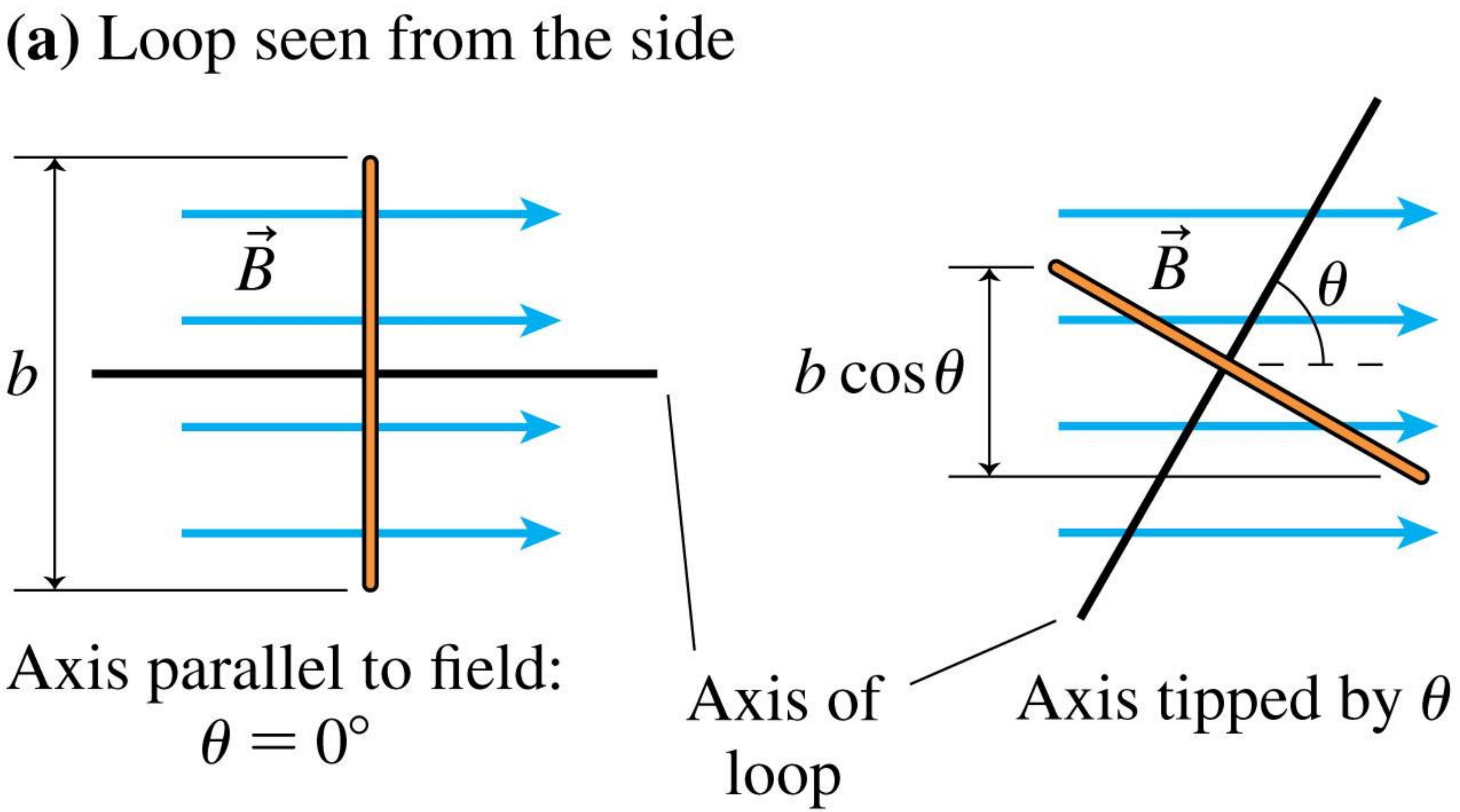


Magnetic Flux

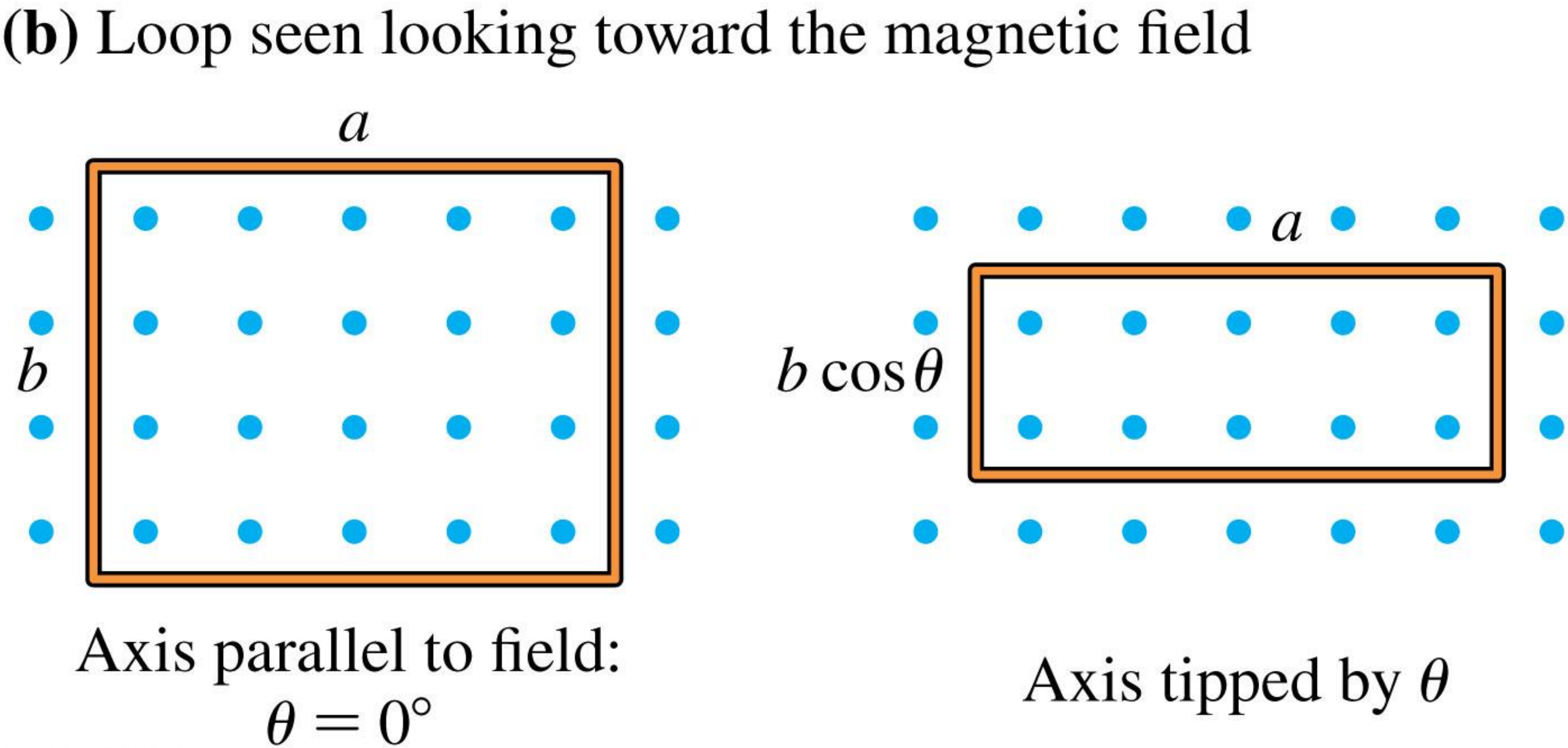
- The magnetic field passing through a loop is also affected by the tipping of the loop.
- The *axis* of the loop is a line through the center of the loop that is perpendicular to the plane of the loop.
- The *effective area* of the loop is reduced when the loop is tipped.
- The effective area is defined as

$$A_{\text{eff}} = ab \cos\theta = A \cos\theta$$

Magnetic Flux



Magnetic Flux



Magnetic Flux

- The **magnetic flux** depends on the strength of the field and the effective area of the loop:

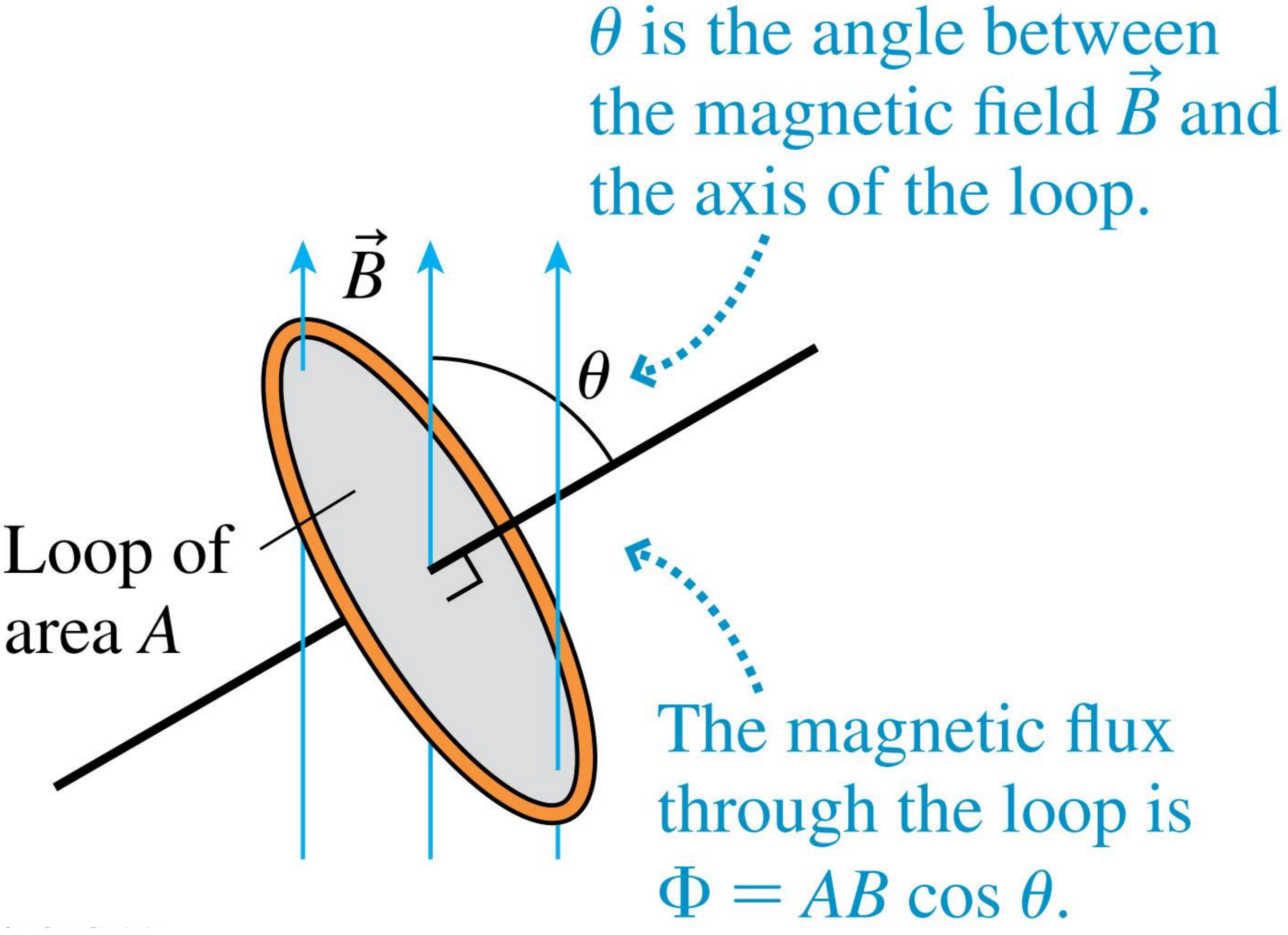
$$\Phi = A_{\text{eff}}B = AB\cos\theta$$

Magnetic flux through area A at angle θ to field B

- The SI unit of magnetic flux is the **weber**.
- 1 weber = 1 Wb = 1 T · m^2

Magnetic Flux

- The magnetic flux is

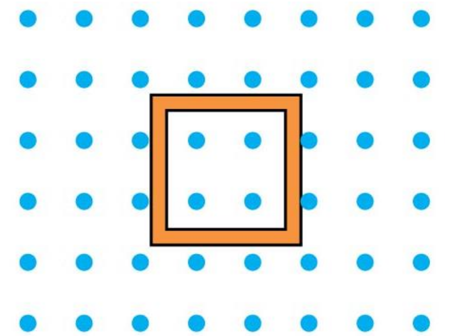


QuickCheck 25.4

Which loop has the larger magnetic flux through it?

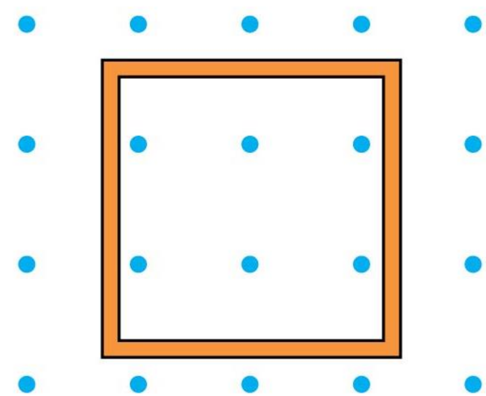
A. Loop A
B. Loop B
C. The fluxes are the same.
D. Not enough information to tell

A.



This field is twice as strong.

B.



This square is twice as wide.

Slide 25-65

QuickCheck 25.4

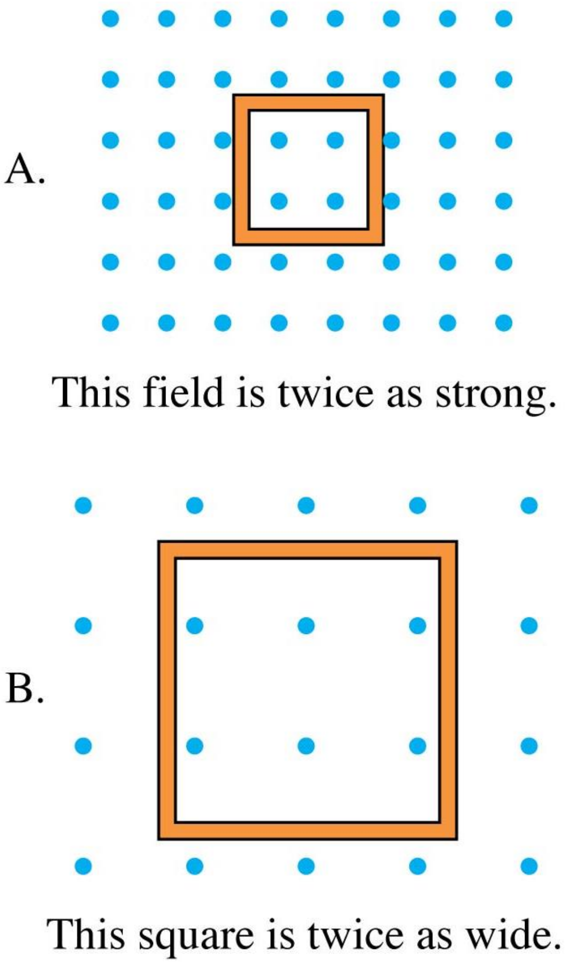
Which loop has the larger magnetic flux through it?

A. Loop A

✔ B. Loop B $\Phi_m = L^2B$

C. The fluxes are the same.

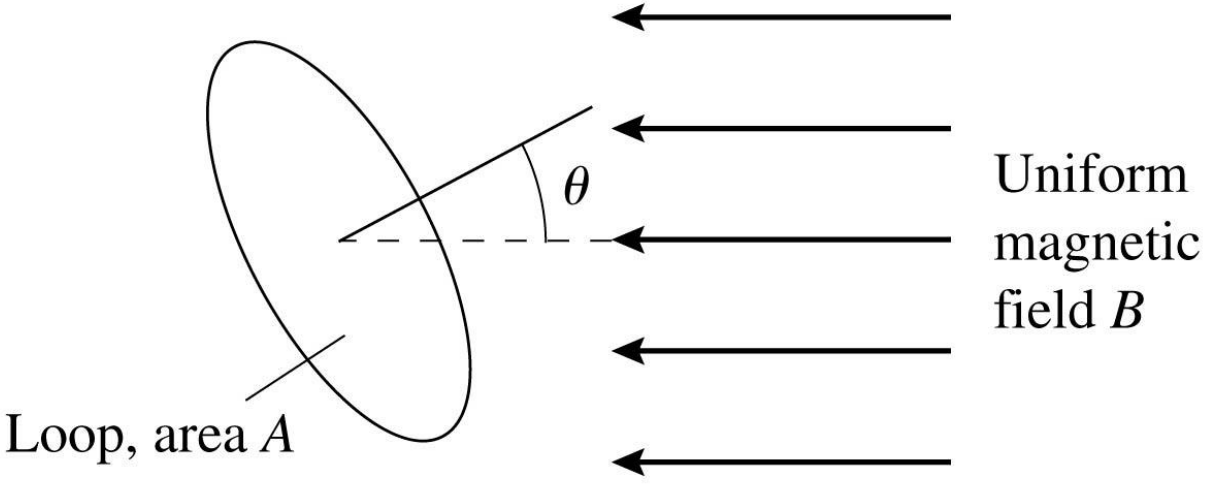
D. Not enough information to tell



QuickCheck 25.5

A loop of wire of area *A* is tipped at an angle θ to uniform magnetic field *B*. The maximum flux occurs for an angle $\theta = 0$. What angle θ will give a flux that is ½ of this maximum value?

A. $\theta = 30°$
B. $\theta = 45°$
C. $\theta = 60°$
D. $\theta = 90°$

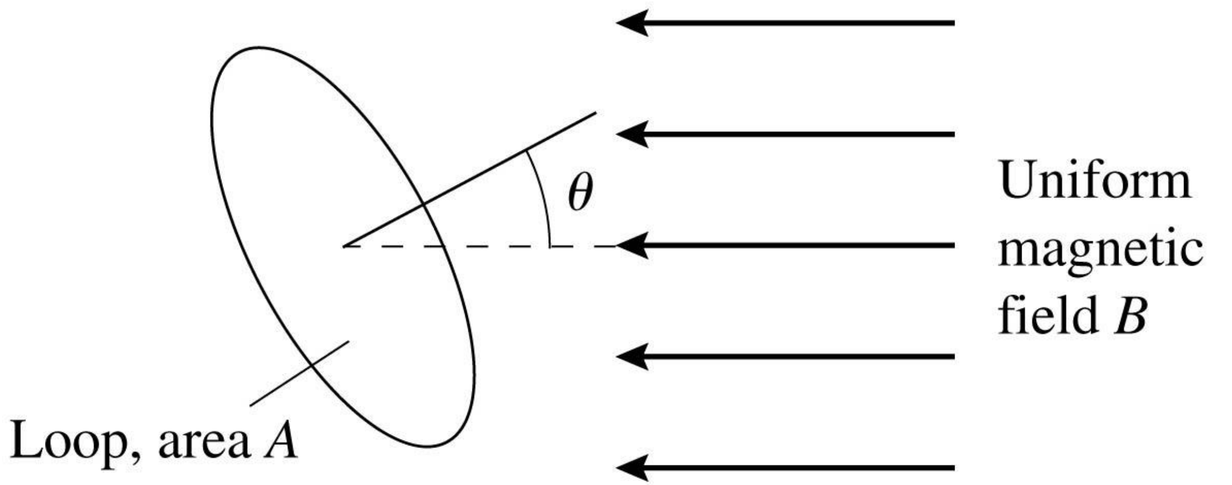


Slide 25-67

QuickCheck 25.5

A loop of wire of area *A* is tipped at an angle θ to uniform magnetic field *B*. The maximum flux occurs for an angle $\theta = 0$. What angle θ will give a flux that is ½ of this maximum value?

A. $\theta = 30°$
B. $\theta = 45°$
✔ C. $\theta = 60°$
D. $\theta = 90°$

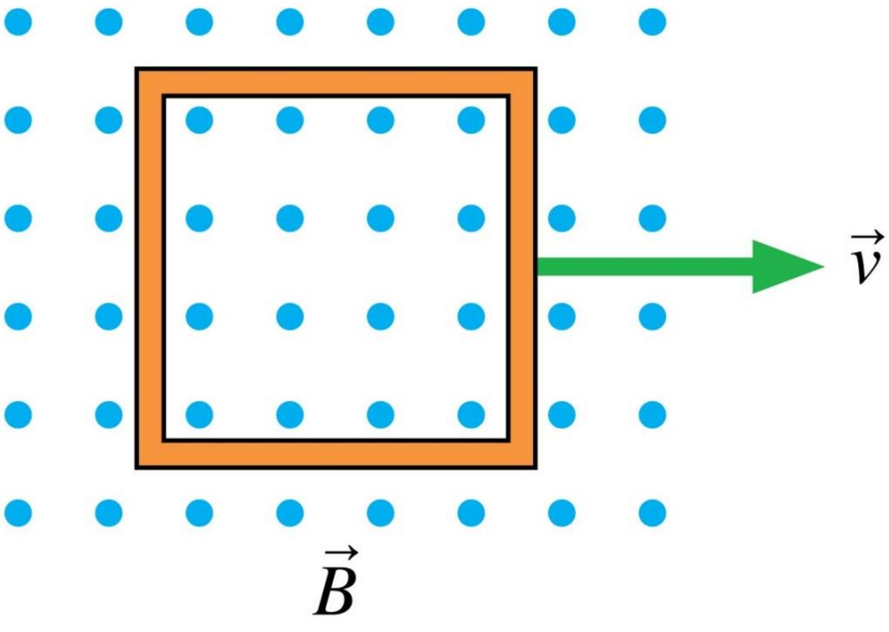


Slide 25-68

QuickCheck 25.6

The metal loop is being pulled through a uniform magnetic field. Is the magnetic flux through the loop changing?

A. Yes
B. No



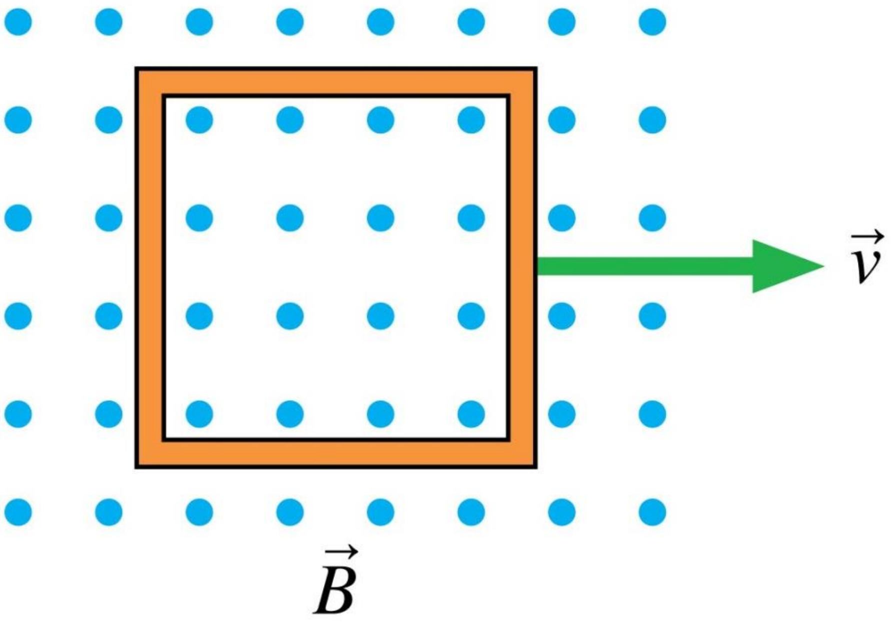
Slide 25-69

QuickCheck 25.6

The metal loop is being pulled through a uniform magnetic field. Is the magnetic flux through the loop changing?

A. Yes

✔ B. No

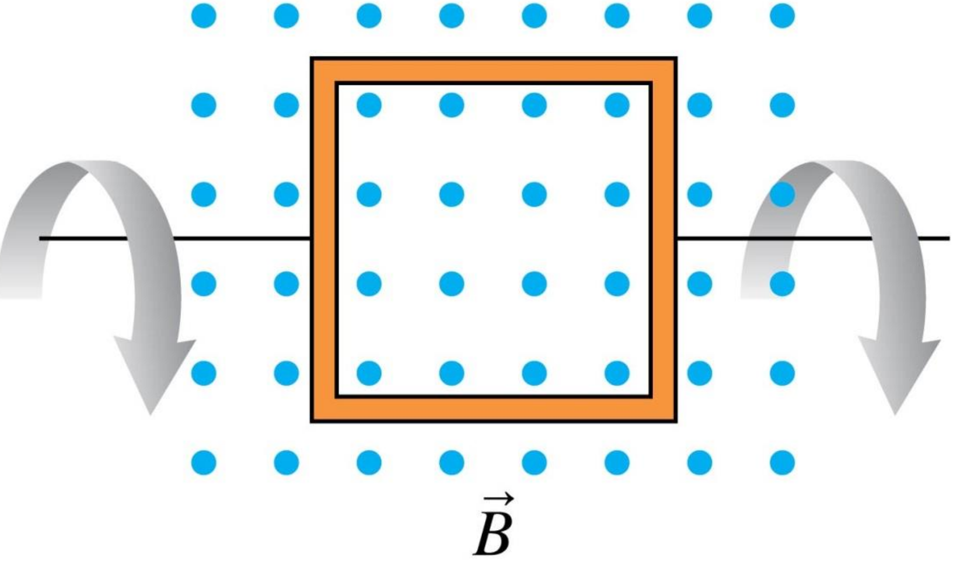


Slide 25-70

QuickCheck 25.7

The metal loop is rotating in a uniform magnetic field. Is the magnetic flux through the loop changing?

A. Yes
B. No



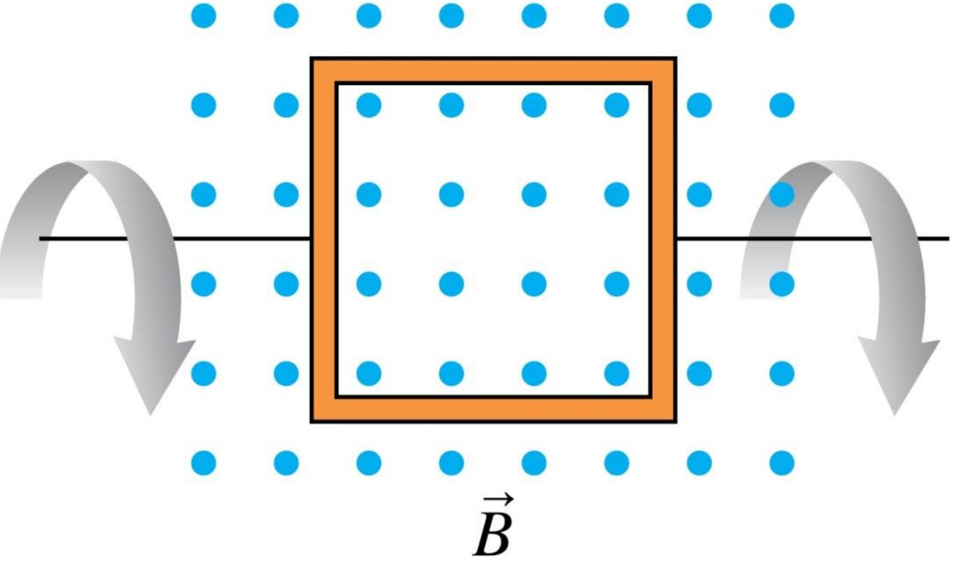
Slide 25-71

QuickCheck 25.7

The metal loop is rotating in a uniform magnetic field. Is the magnetic flux through the loop changing?

✔ A. Yes

B. No



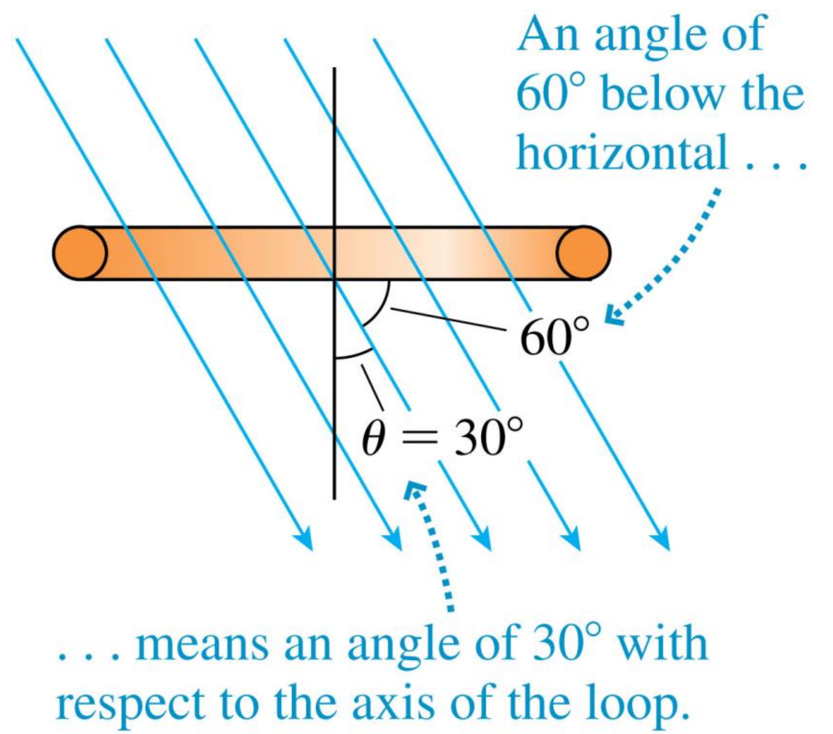
Slide 25-72

Example 25.2 Finding the flux of the earth's field through a vertical loop

At a particular location, the earth's magnetic field is 50 μT tipped at an angle of 60° below horizontal. A 10-cm-diameter circular loop of wire sits flat on a table. What is the magnetic flux through the loop?

Example 25.2 Finding the flux of the earth's field through a vertical loop (cont.)

PREPARE **FIGURE 25.11** shows the loop and the field of the earth. The field is tipped by 60°, so the angle of the field with respect to the axis of the loop is $\theta = 30°$. The radius of the loop is 5.0 cm, so the area of the loop is $A = \pi r^2 = \pi\,(0.050\text{ m})^2 = 0.0079\text{ m}^2$.



Example 25.2 Finding the flux of the earth's field through a vertical loop (cont.)

SOLVE The flux through the loop is given by Equation 25.9, with the angle and area as above:

$$\Phi = AB\cos\theta = (0.0079\,\text{m}^2)(50 \times 10^{-6}\,\text{T})\cos 30^\circ$$
$$= 3.4 \times 10^{-7}\,\text{Wb}$$

ASSESS It's a small loop and a small field, so a very small flux seems reasonable.

Lenz's Law

- **Current is induced in a loop of wire when the magnetic flux through the loop changes.**
- Motion is not required to induce a current.

Lenz's Law

- The German physicist Heinrich Lenz developed a rule for determining the direction of an induced current, now called **Lenz's law:**

Lenz's law There is an induced current in a closed, conducting loop if and only if the magnetic flux through the loop is changing. The direction of the induced current is such that the induced magnetic field opposes the *change* in the flux.

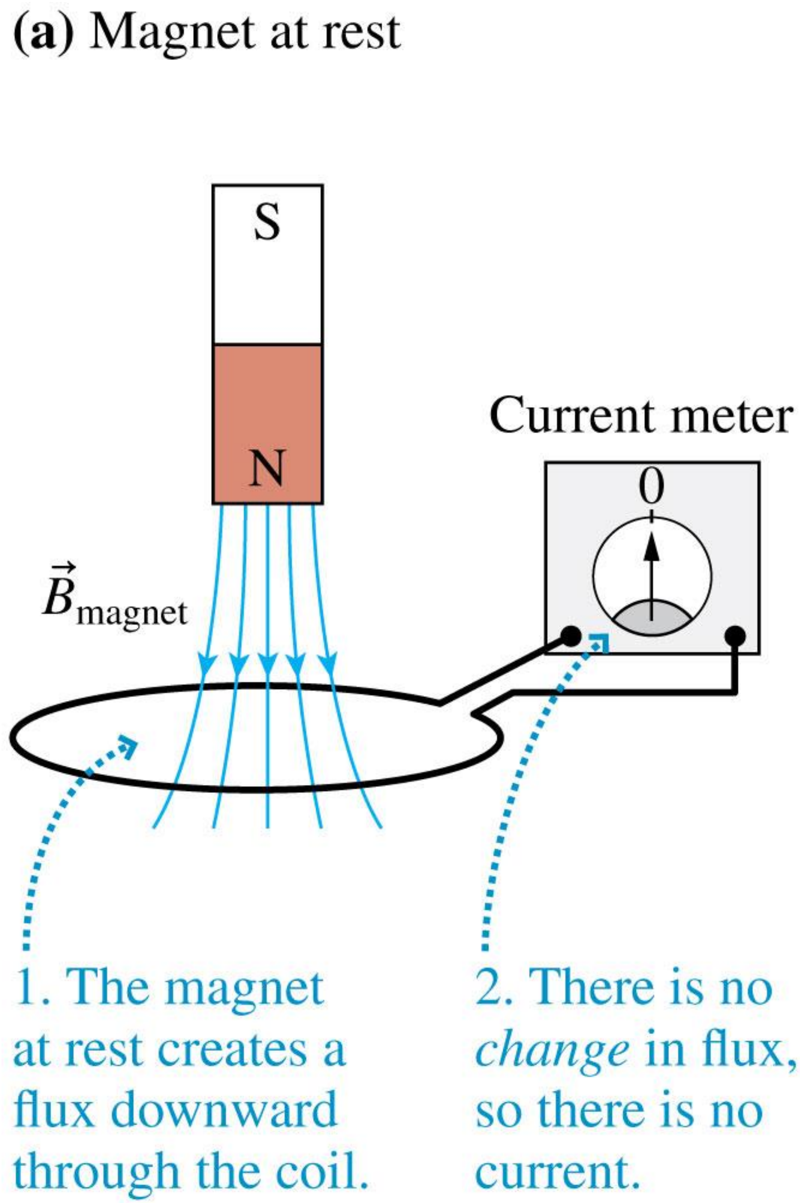
Lenz's Law

- The magnetic flux can change in three ways:

  1. The magnetic field through the loop changes.
  2. The loop changes in area or angle.
  3. The loop moves into or out of a magnetic field.

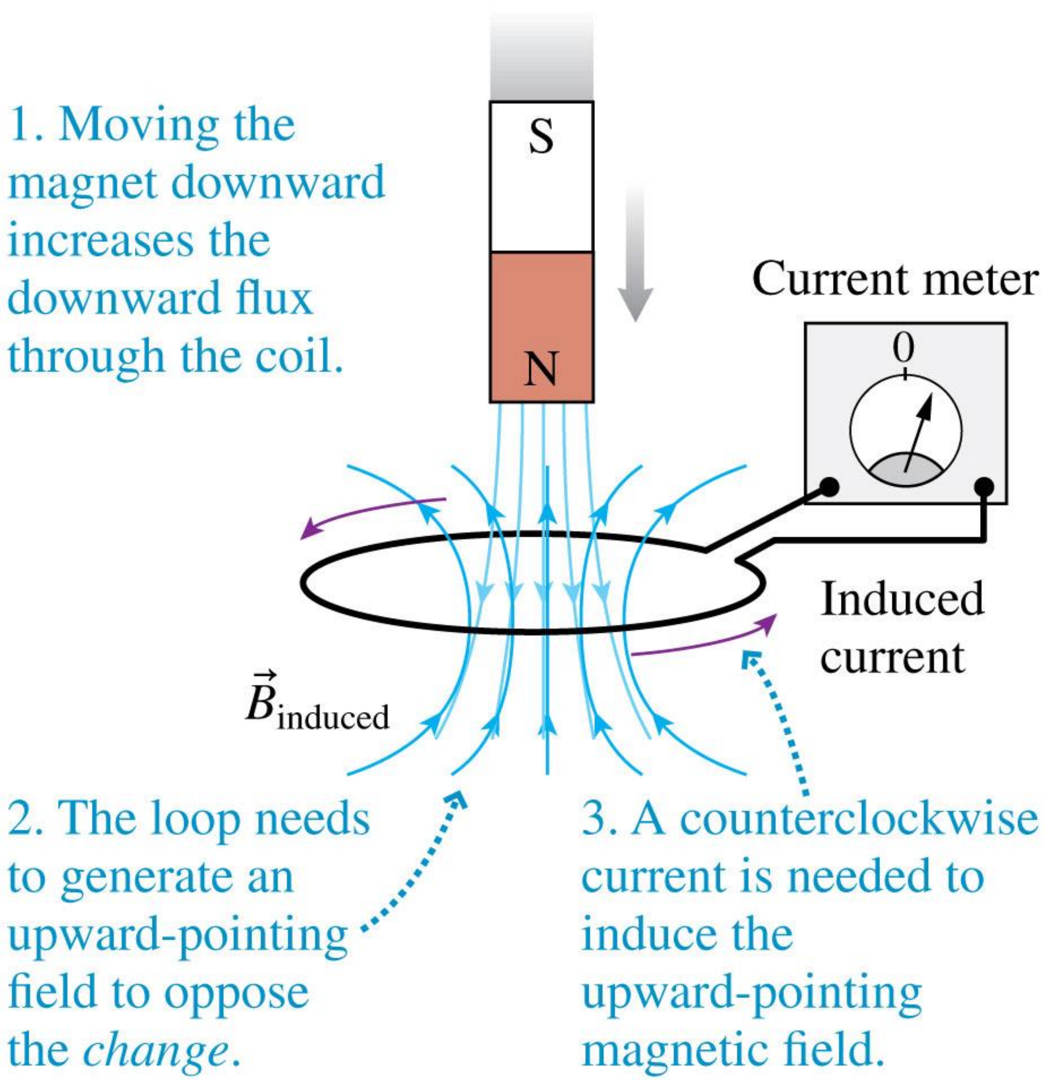
- The induced current generates its own magnetic field. **It is this induced field that opposes the flux change**.

Lenz's Law

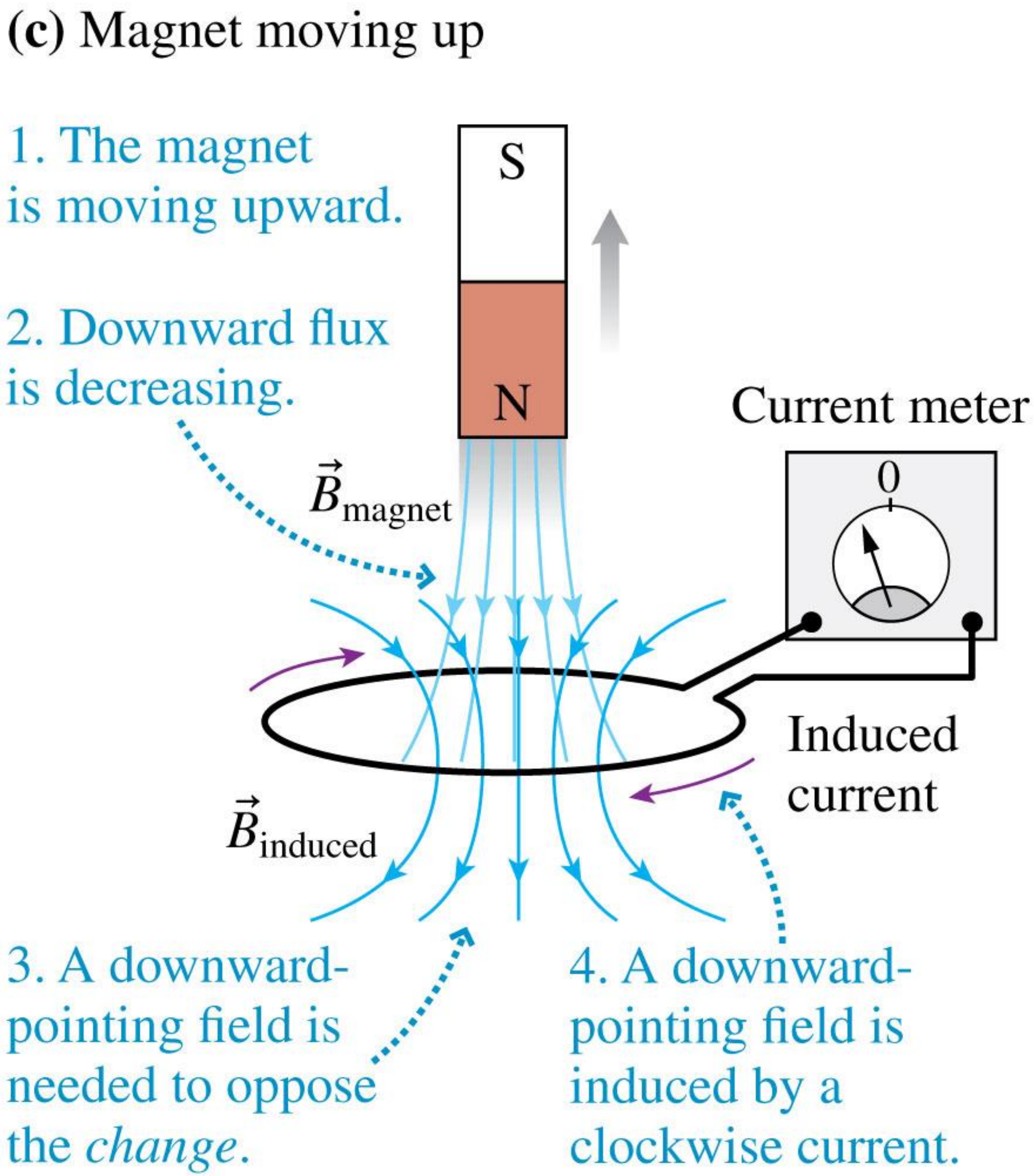

(a) Magnet at rest
S
N
Current meter
0
$\vec{B}_{magnet}$
1. The magnet at rest creates a flux downward through the coil.
2. There is no *change* in flux, so there is no current.

Lenz's Law

(b) Magnet moving down



Lenz's Law


(c) Magnet moving up
1. The magnet is moving upward.
S
N
2. Downward flux is decreasing.
Current meter
0
$\vec{B}_{magnet}$
Induced current
$\vec{B}_{induced}$
3. A downward-pointing field is needed to oppose the *change*.
4. A downward-pointing field is induced by a clockwise current.

Lenz's Law

TACTICS BOX 25.1 **Using Lenz's law**

1. Determine the direction of the applied magnetic field. The field must pass through the loop.
2. Determine how the flux is changing. Is it increasing, decreasing, or staying the same?

Text: p. 813

Lenz's Law

TACTICS BOX 25.1 **Using Lenz's law**

❸ Determine the direction of an induced magnetic field that will oppose the *change* in the flux:

- Increasing flux: The induced magnetic field points opposite the applied magnetic field.
- Decreasing flux: The induced magnetic field points in the same direction as the applied magnetic field.
- Steady flux: There is no induced magnetic field.

Text: p. 813

Lenz's Law

TACTICS BOX 25.1 **Using Lenz's law**

❹ Determine the direction of the induced current. Use the right-hand rule to determine the current direction in the loop that generates the induced magnetic field you found in step 3.

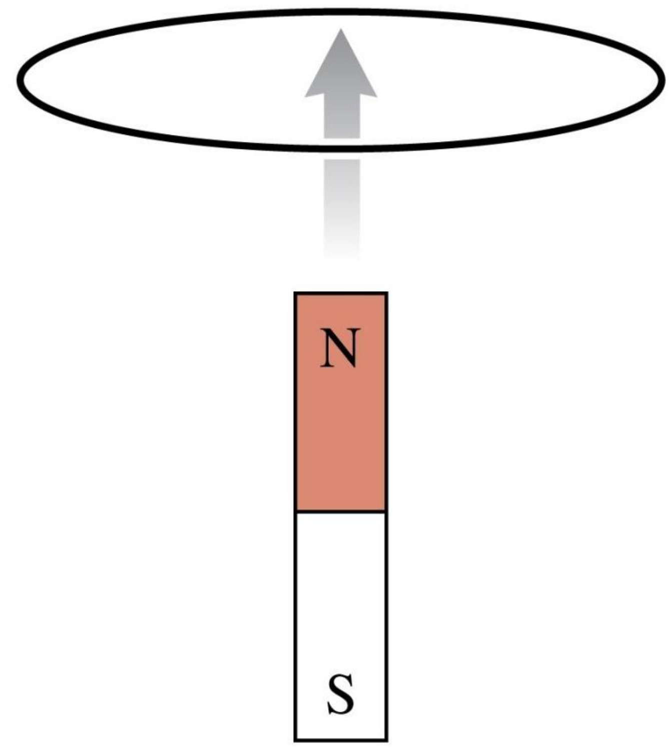
Exercises 9–11

Text: p. 813

QuickCheck 25.8

The bar magnet is pushed toward the center of a wire loop. Which is true?

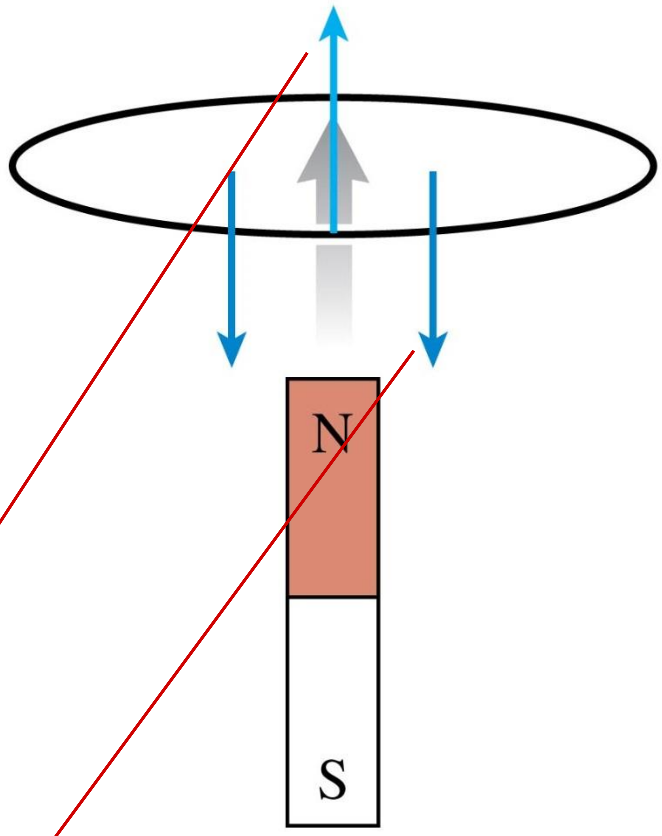
A. There is a clockwise induced current in the loop.
B. There is a counterclockwise induced current in the loop.
C. There is no induced current in the loop.



Slide 25-85

QuickCheck 25.8

The bar magnet is pushed toward the center of a wire loop. Which is true?



✔ A. There is a clockwise induced current in the loop.

B. There is a counterclockwise induced current in the loop.

C. There is no induced current in the loop.

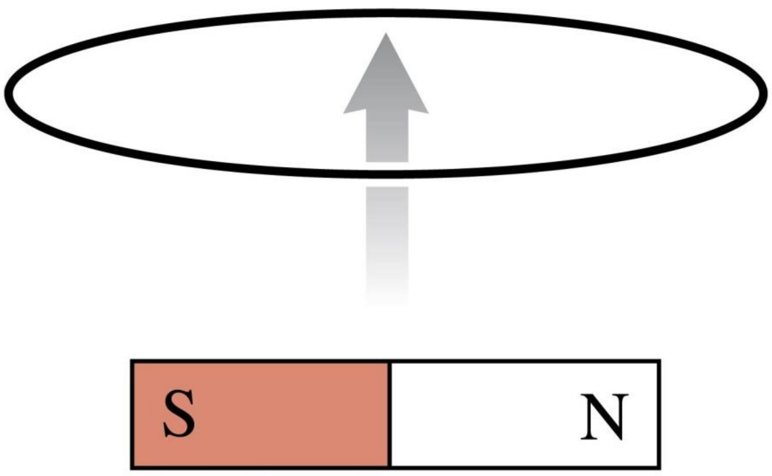
1. Upward flux from magnet is <u>increasing</u>.
2. To oppose the <u>increase</u>, the field of the induced current points down.
3. From the right-hand rule, a downward field needs a cw current.

Slide 25-86

QuickCheck 25.9

The bar magnet is pushed toward the center of a wire loop. Which is true?

A. There is a clockwise induced current in the loop.
B. There is a counterclockwise induced current in the loop.
C. There is no induced current in the loop.



Slide 25-87

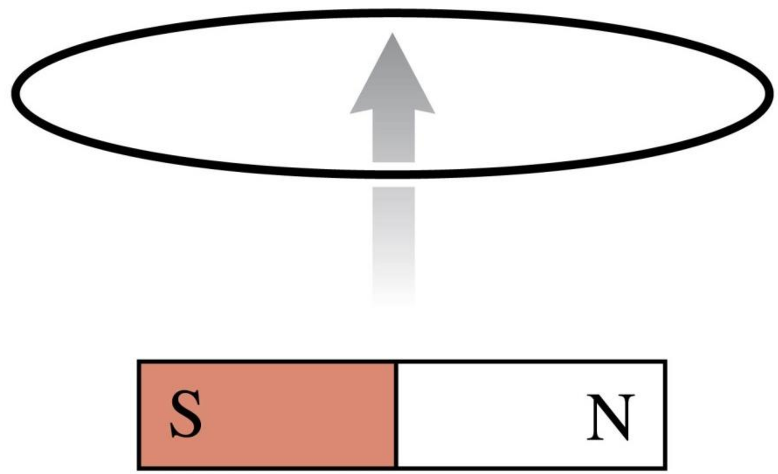
QuickCheck 25.9

The bar magnet is pushed toward the center of a wire loop. Which is true?

A. There is a clockwise induced current in the loop.

B. There is a counterclockwise induced current in the loop.

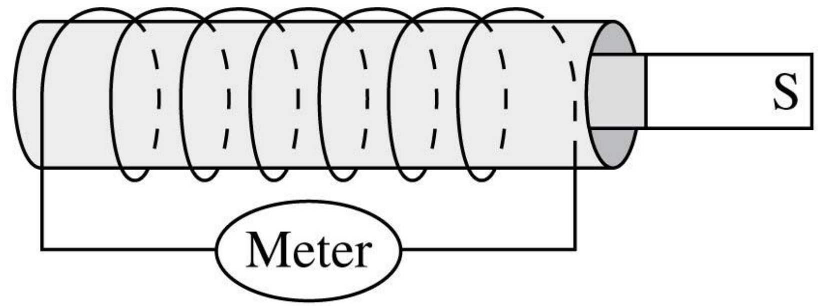
✔ C. There is no induced current in the loop.



Magnetic flux is zero, so there's no change of flux.

QuickCheck 25.10

A bar magnet sits inside a coil of wire that is connected to a meter. For each of the following circumstances



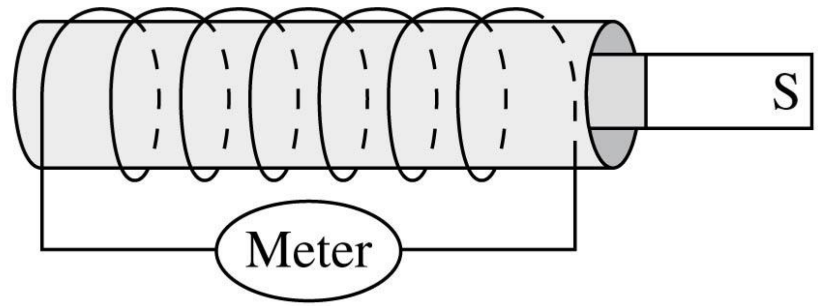
1. The bar magnet is at rest in the coil,
2. The bar magnet is pulled out of the coil,
3. The bar magnet is completely out of the coil and at rest,
4. The bar magnet is reinserted into the coil,

What can we say about the current in the meter?

A. The current goes from right to left.
B. The current goes from left to right.
C. There is no current in the meter.

QuickCheck 25.10

A bar magnet sits inside a coil of wire that is connected to a meter. For each of the following circumstances



1. The bar magnet is at rest in the coil, C
2. The bar magnet is pulled out of the coil, A
3. The bar magnet is completely out of the coil and at rest, C
4. The bar magnet is reinserted into the coil, B

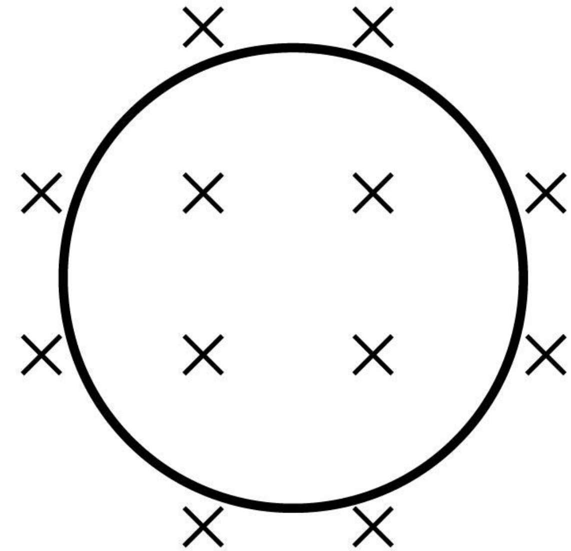
What can we say about the current in the meter?

A. The current goes from right to left.
B. The current goes from left to right.
C. There is no current in the meter.

QuickCheck 25.11

A magnetic field goes through a loop of wire, as at right. If the magnitude of the magnetic field is

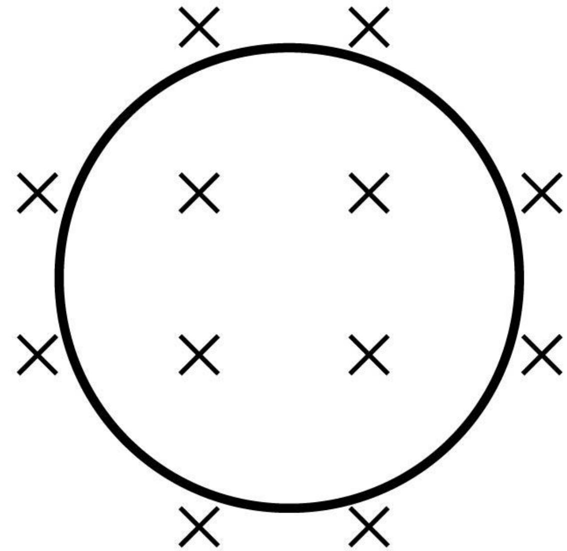
1. Increasing,
2. Decreasing,
3. Constant,



What can we say about the current in the loop? Answer for each of the stated conditions.

A. The loop has a clockwise current.
B. The loop has a counterclockwise current.
C. The loop has no current.

QuickCheck 25.11



A magnetic field goes through a loop of wire, as at right. If the magnitude of the magnetic field is

1. Increasing, B
2. Decreasing, A
3. Constant, C

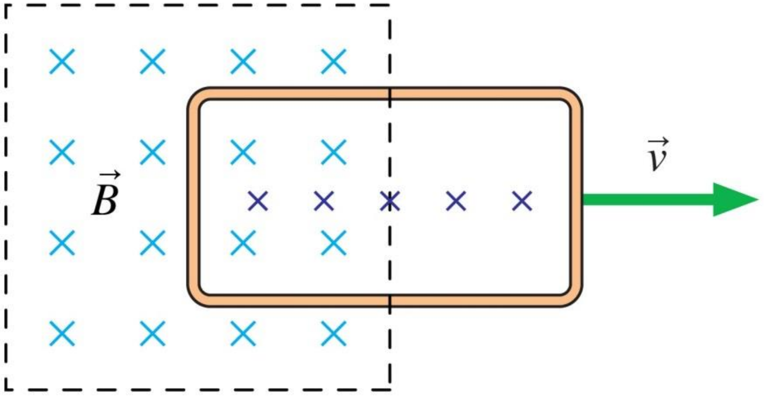
What can we say about the current in the loop? Answer for each of the stated conditions.

A. The loop has a clockwise current.
B. The loop has a counterclockwise current.
C. The loop has no current.

QuickCheck 25.12

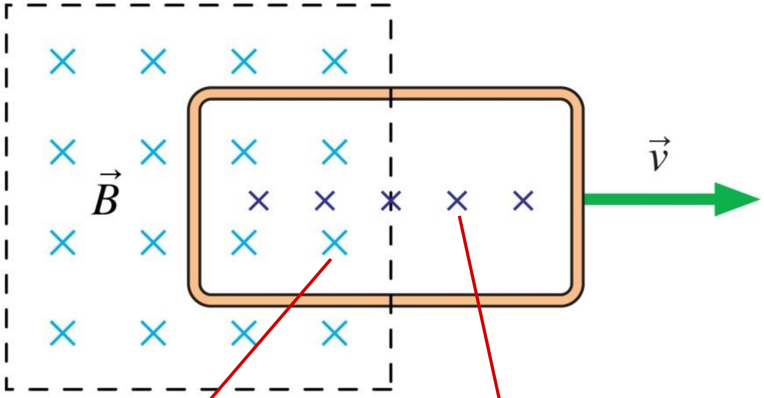
The magnetic field is confined to the region inside the dashed lines; it is zero outside. The metal loop is being pulled out of the magnetic field. Which is true?

A. There is a clockwise induced current in the loop.
B. There is a counterclockwise induced current in the loop.
C. There is no induced current in the loop.



QuickCheck 25.12

The magnetic field is confined to the region inside the dashed lines; it is zero outside. The metal loop is being pulled out of the magnetic field. Which is true?



✔ A. There is a clockwise induced current in the loop.

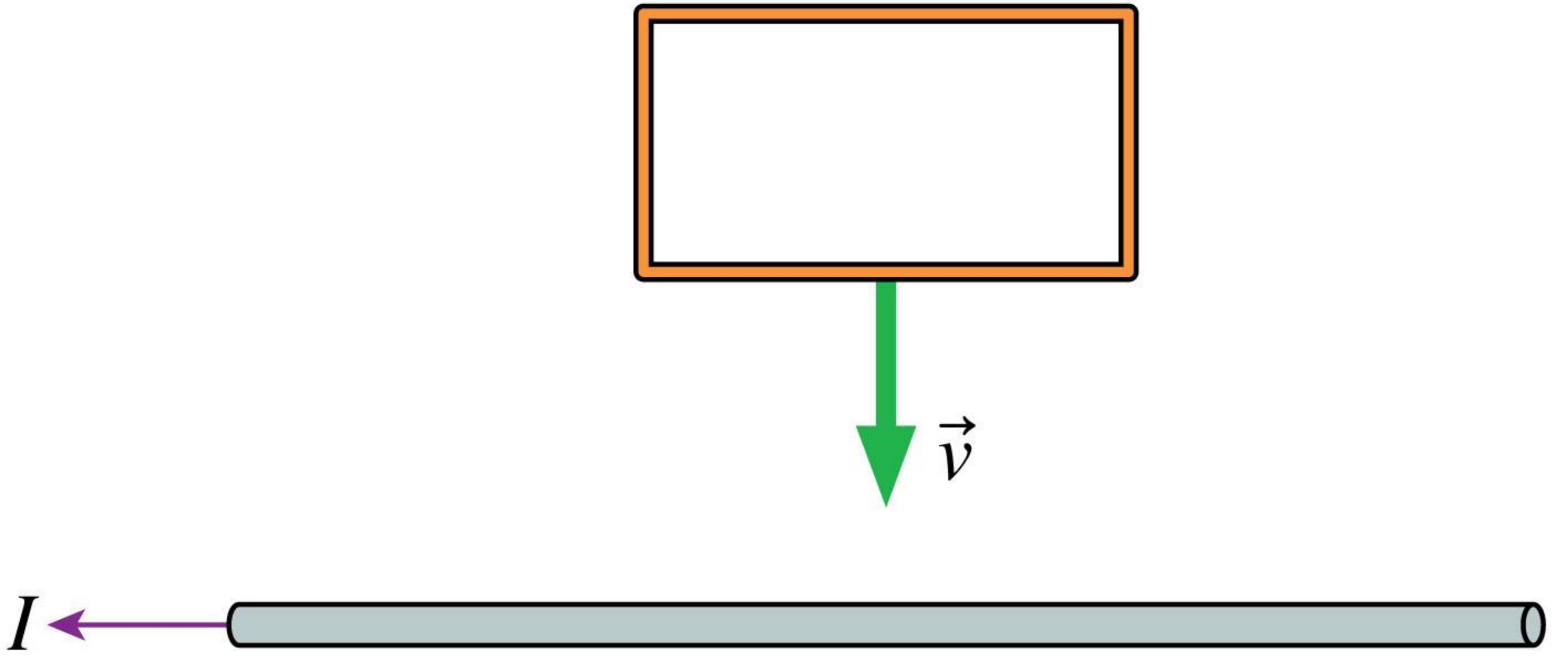
B. There is a counterclockwise induced current in the loop.

C. There is no induced current in the loop.

1. The flux through the loop is <u>into</u> the screen and <u>decreasing</u>.
2. To oppose the <u>decrease</u>, the field of the induced current must point <u>into</u> the screen.
3. From the right-hand rule, an inward field needs a cw current.

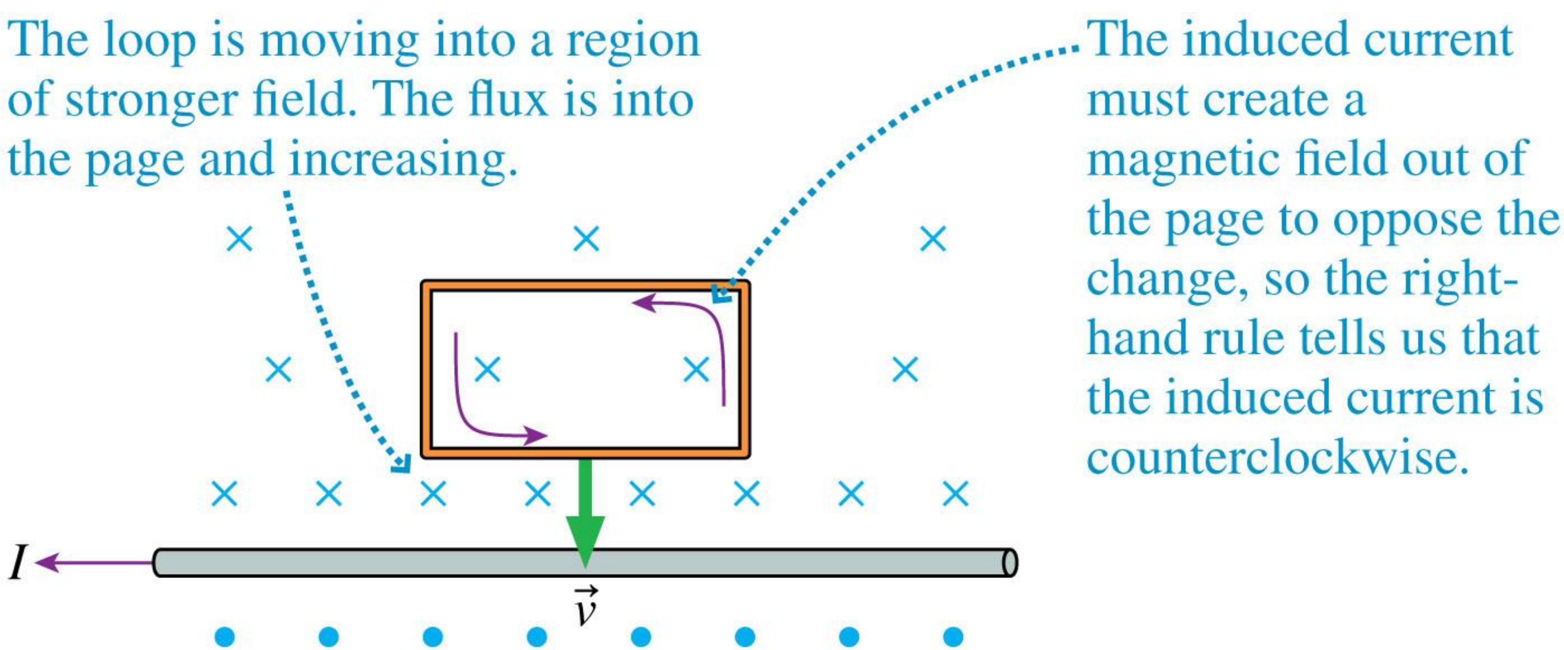
Example 25.4 Applying Lenz's law 2

A loop is moved toward a current-carrying wire as shown in **FIGURE 25.16**. As the wire is moving, is there a clockwise current around the loop, a counterclockwise current, or no current?



Example 25.4 Applying Lenz's law 2 (cont).

PREPARE **FIGURE 25.17** shows that the magnetic field above the wire points into the page. We learned in Chapter 24 that the magnetic field of a straight, current-carrying wire is proportional to $1/r$, where r is the distance away from the wire, so the field is stronger closer to the wire.



Example 25.4 Applying Lenz's law 2 (cont).

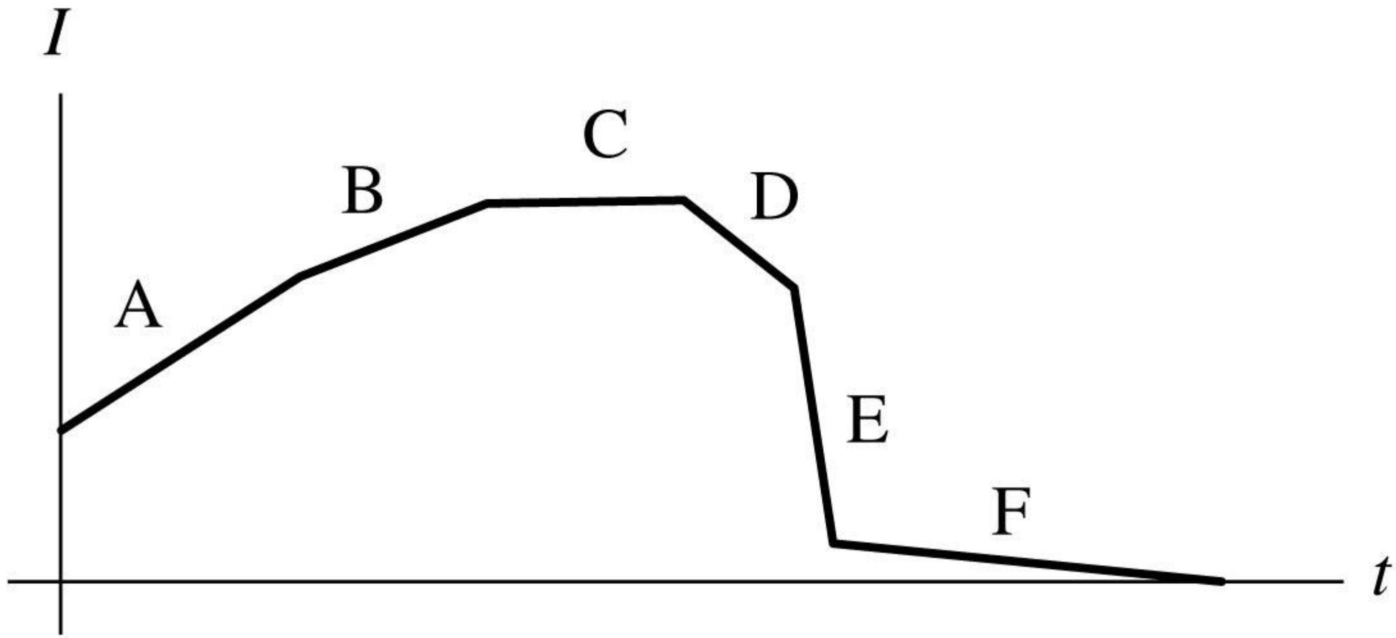
SOLVE As the loop moves toward the wire, the flux through the loop increases. To oppose the change in the flux—the increase into the page—the magnetic field of the induced current must point out of the page. Thus, according to the right-hand rule, a counterclockwise current is induced, as shown in Figure 25.17.

ASSESS The loop moves into a region of stronger field. To oppose the increasing flux, the induced field should be opposite the existing field, so our answer makes sense.

QuickCheck 25.13

A long conductor carrying a current runs next to a loop of wire. The current in the wire varies as shown in the graph.

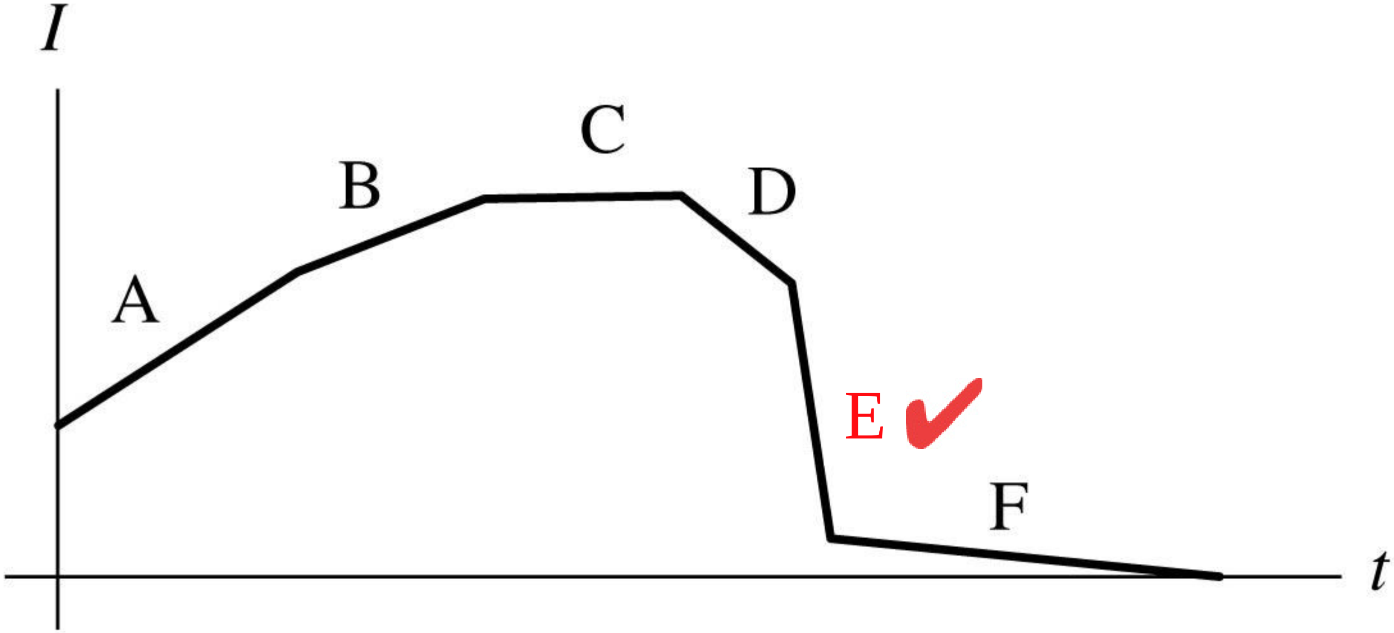
Which segment of the graph corresponds to the largest induced current in the loop?



QuickCheck 25.13

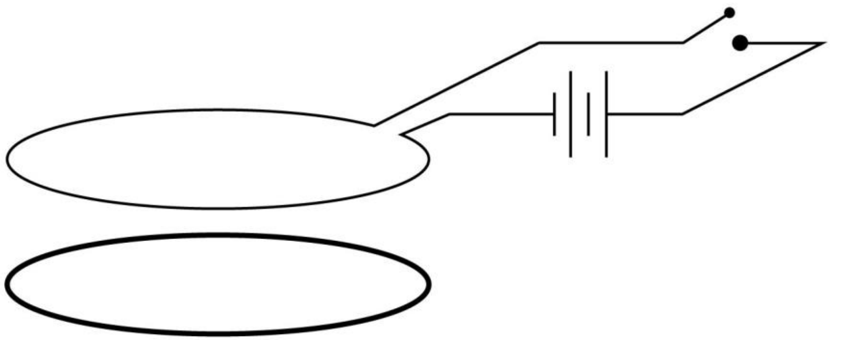
A long conductor carrying a current runs next to a loop of wire. The current in the wire varies as shown in the graph.

Which segment of the graph corresponds to the largest induced current in the loop?



Slide 25-99

QuickCheck 25.14



A battery, a loop of wire, and a switch make a circuit as shown. A second loop of wire sits directly below. At the following times,

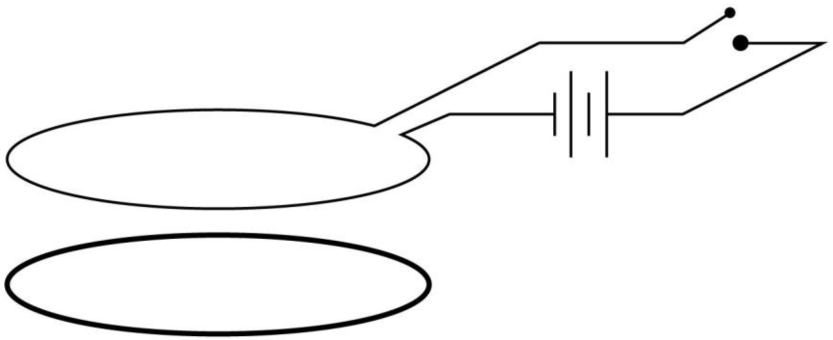
1. Just before the switch is closed,
2. Immediately after the switch is closed,
3. Long after the switch is closed,
4. Immediately after the switch is reopened,

What can we say about the current in the lower loop? Answer for each of the stated conditions.

A. The loop has a clockwise current.
B. The loop has a counterclockwise current.
C. The loop has no current.

QuickCheck 25.14

A battery, a loop of wire, and a switch make a circuit as shown. A second loop of wire sits directly below. At the following times,



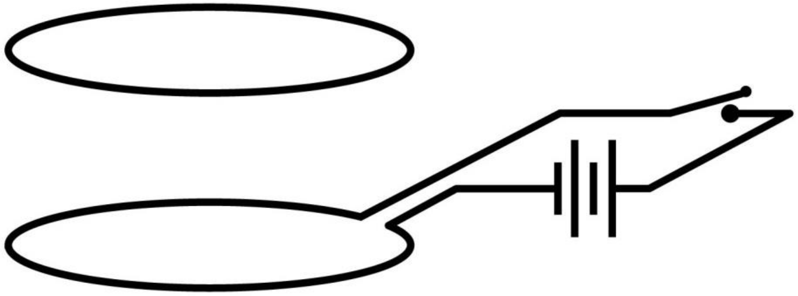
1. Just before the switch is closed, C
2. Immediately after the switch is closed, A
3. Long after the switch is closed, C
4. Immediately after the switch is reopened, B

What can we say about the current in the lower loop? Answer for each of the stated conditions.

A. The loop has a clockwise current.
B. The loop has a counterclockwise current.
C. The loop has no current.

QuickCheck 25.15

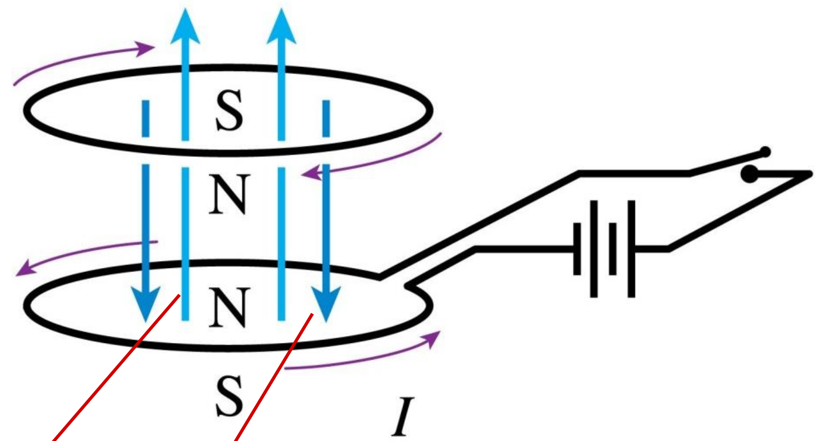
Immediately after the switch is closed, the lower loop exerts _________ on the upper loop.



A. A torque
B. An upward force
C. A downward force
D. No force or torque

QuickCheck 25.15

Immediately after the switch is closed, the lower loop exerts _________ on the upper loop.



A. A torque

✔ B. An upward force

C. A downward force

D. No force or torque

1. The battery drives a ccw current that, briefly, increases rapidly.
2. The flux through the top loop is upward and increasing.
3. To oppose the increase, the field of the induced current must point downward.
4. From the right-hand rule, a downward field needs a cw current.
5. The ccw current in the lower loop makes the upper face a north pole. The cw induced current in the upper loop makes the lower face a north pole.
6. Facing north poles exert repulsive forces on each other.

Section 25.4 Faraday's Law

Faraday's Law

- An **induced emf** $\mathcal{E}$ is the emf associated with a changing magnetic flux.

$$I_{\text{induced}} = \frac{\mathcal{E}}{R}$$

- The direction of the current is determined by Lenz's law. The size of the induced emf is determined by Faraday's law.

Faraday's Law

- **Faraday's law** is a basic law of electromagnetic induction. It says that the magnitude of the induced emf is the *rate of change* of the magnetic flux through the loop:

Faraday's law An emf $\mathcal{E}$ is induced in a conducting loop if the magnetic flux through the loop changes. If the flux changes by $\Delta\Phi$ during time interval Δt, the magnitude of the emf is

$$\mathcal{E} = \left|\frac{\Delta\Phi}{\Delta t}\right|$$

and the direction of the emf is such as to drive an induced current in the direction given by Lenz's law.

Faraday's Law

- A coil wire consisting of *N* turns acts like *N* batteries in series, so the induced emf in the coil is

$$\mathcal{E}_{\text{coil}} = N \left| \frac{\Delta \Phi_{\text{per coil}}}{\Delta t} \right|$$

Faraday's Laws

- There are two fundamentally different ways to change the magnetic flux through a conducting loop:
  1. The loop can move or expand or rotate, creating a motional emf.
  2. The magnetic field can change.
- The induced emf is the rate of change of the magnetic flux through the loop, regardless of what causes the flux to change.

Faraday’s Laws

PROBLEM-SOLVING STRATEGY 25.1 **Electromagnetic induction**

Faraday’s law allows us to find the *magnitude* of induced emfs and currents; Lenz’s law allows us to determine the *direction.*

PREPARE Make simplifying assumptions about wires and magnetic fields. Draw a picture or a circuit diagram. Use Lenz’s law to determine the direction of the induced current.

Text: p. 815

Faraday's Laws

PROBLEM-SOLVING STRATEGY 25.1 **Electromagnetic induction**

SOLVE The mathematical representation is based on Faraday's law

$$\mathcal{E} = \left|\frac{\Delta\Phi}{\Delta t}\right|$$

For an N-turn coil, multiply by N. The size of the induced current is $I = \mathcal{E}/R$.

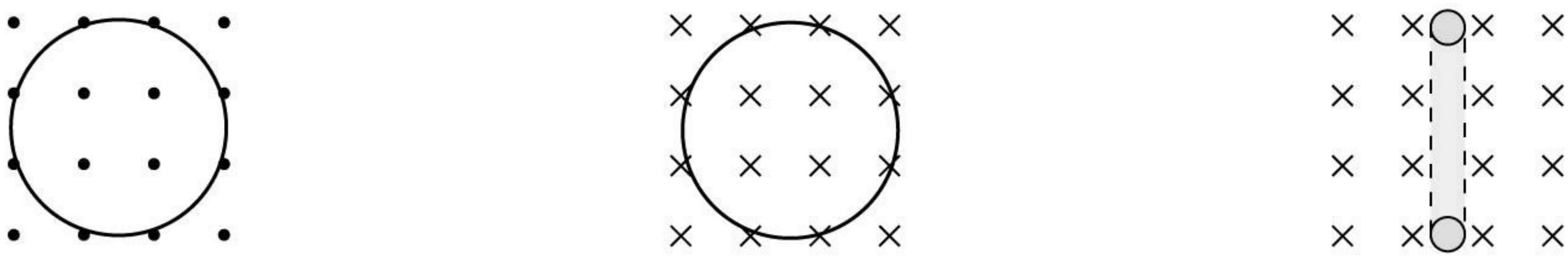
ASSESS Check that your result has the correct units, is reasonable, and answers the question.

Exercise 16

Text: p. 815

Example Problem

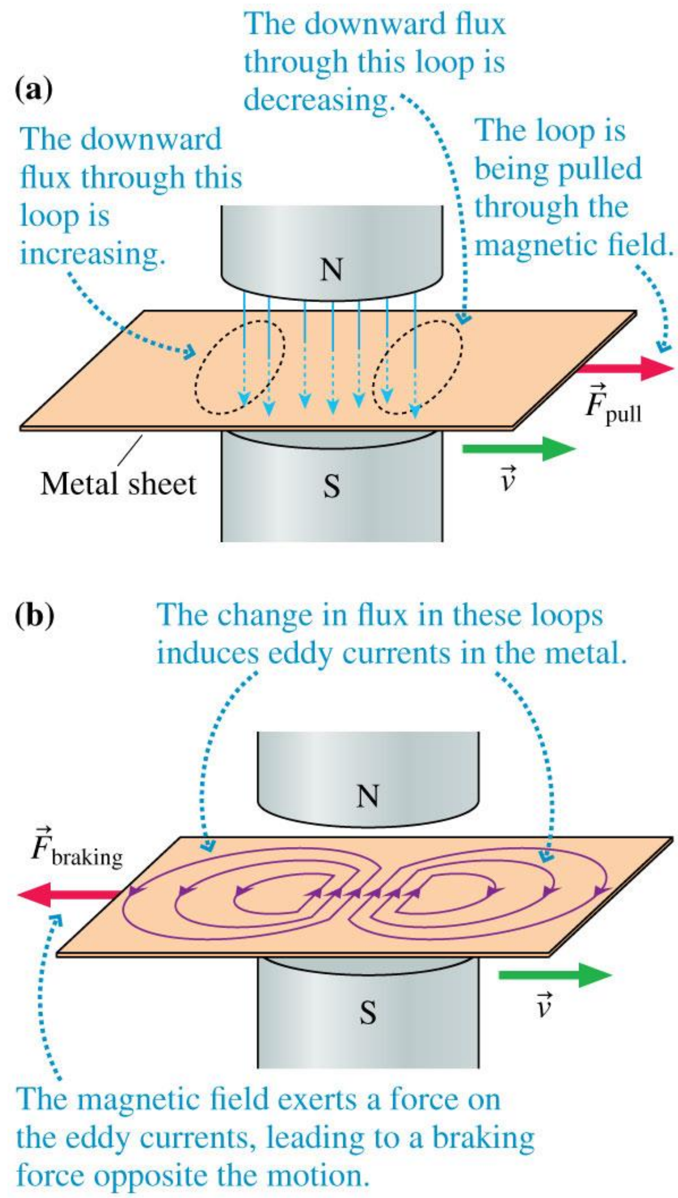
The following figure shows a 10-cm-diameter loop in three different magnetic fields. The loop's resistance is 0.1 Ohms. For each situation, determine the magnitude and direction of the induced current.



a) Increasing at 0.5 T/s b) Decreasing at 0.5 T/s c) Decreasing at 0.5 T/s

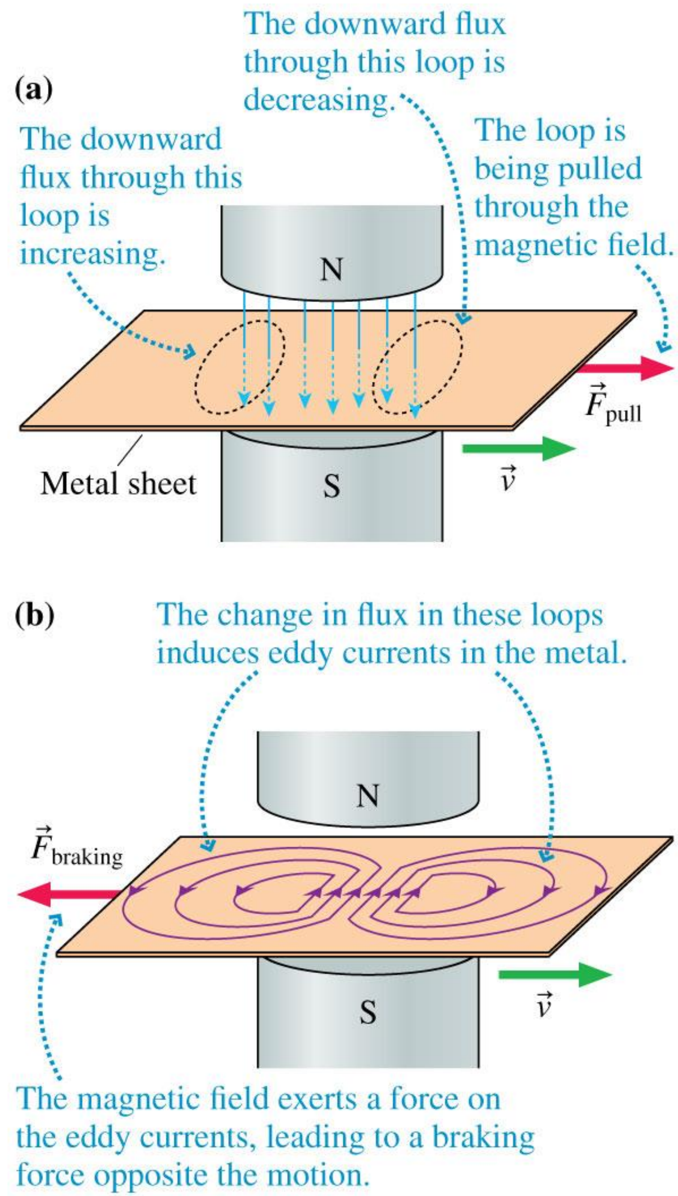
Eddy Currents

- There are two "loops" lying entirely in a metal sheet between two magnets.
- As the sheet is pulled, the loop on the right is leaving the magnetic field, and the flux is decreasing.
- According to Faraday's law, the flux change induces a current to flow around the loop. Lenz's law says the current flows clockwise.



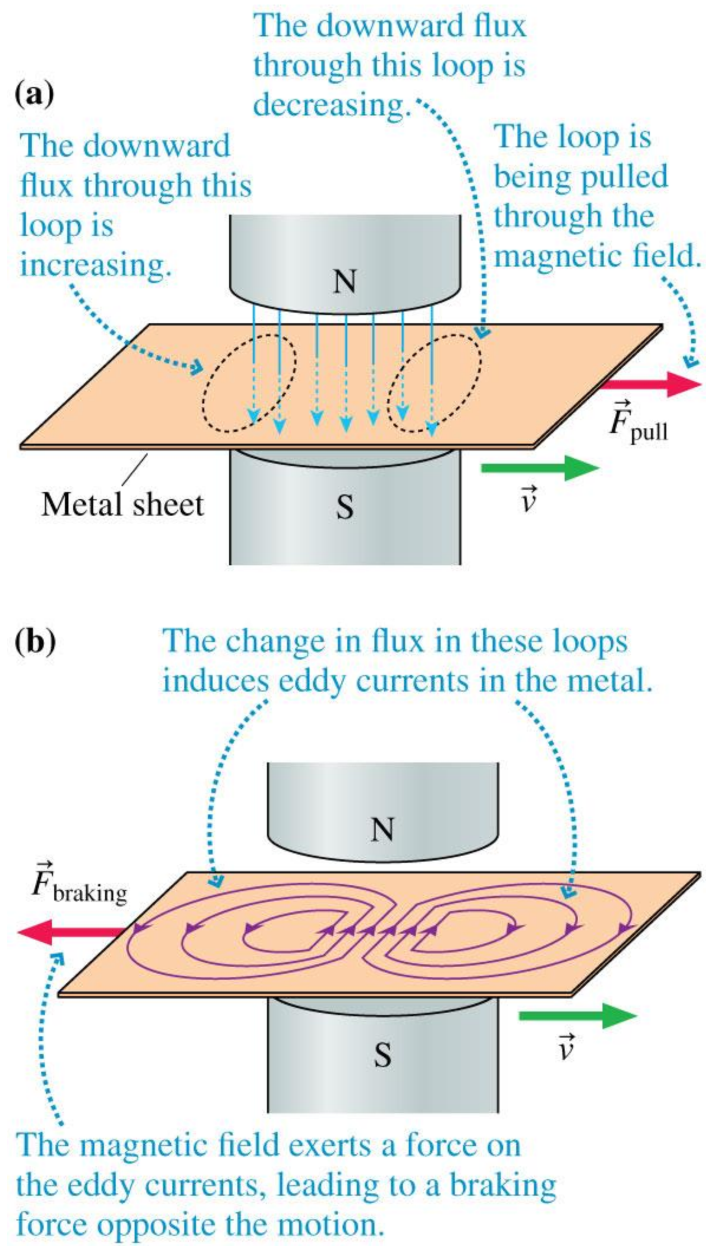
Eddy Currents

- The loop on the left side of the metal enters the field and so the flux through it is increasing.
- Lenz's law requires the induced "whirlpool" current on the left loop to be counterclockwise.



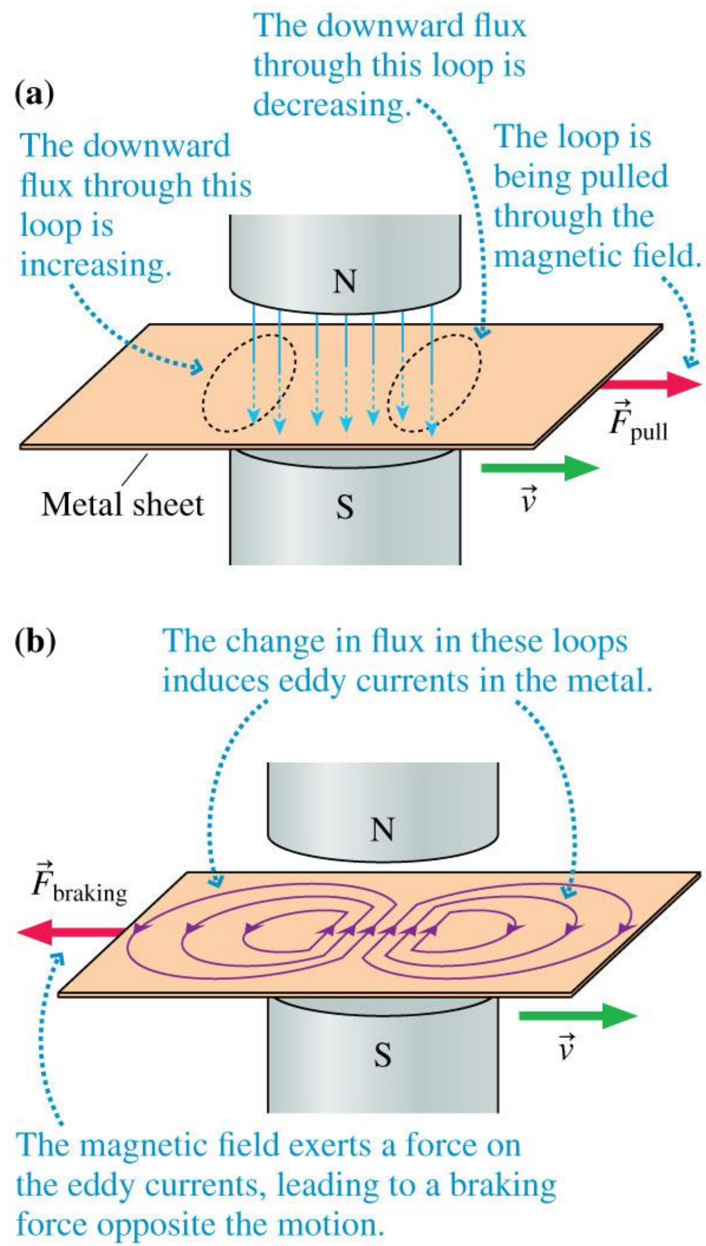
Eddy Currents

- **Eddy currents** are the spread-out whirlpools of an induced current in a solid conductor.
- Both whirlpools of current are moving in the same direction as they pass through the magnet. The magnetic field exerts a force on the current, opposite the direction of pull, acting as a *braking force*.



Eddy Currents

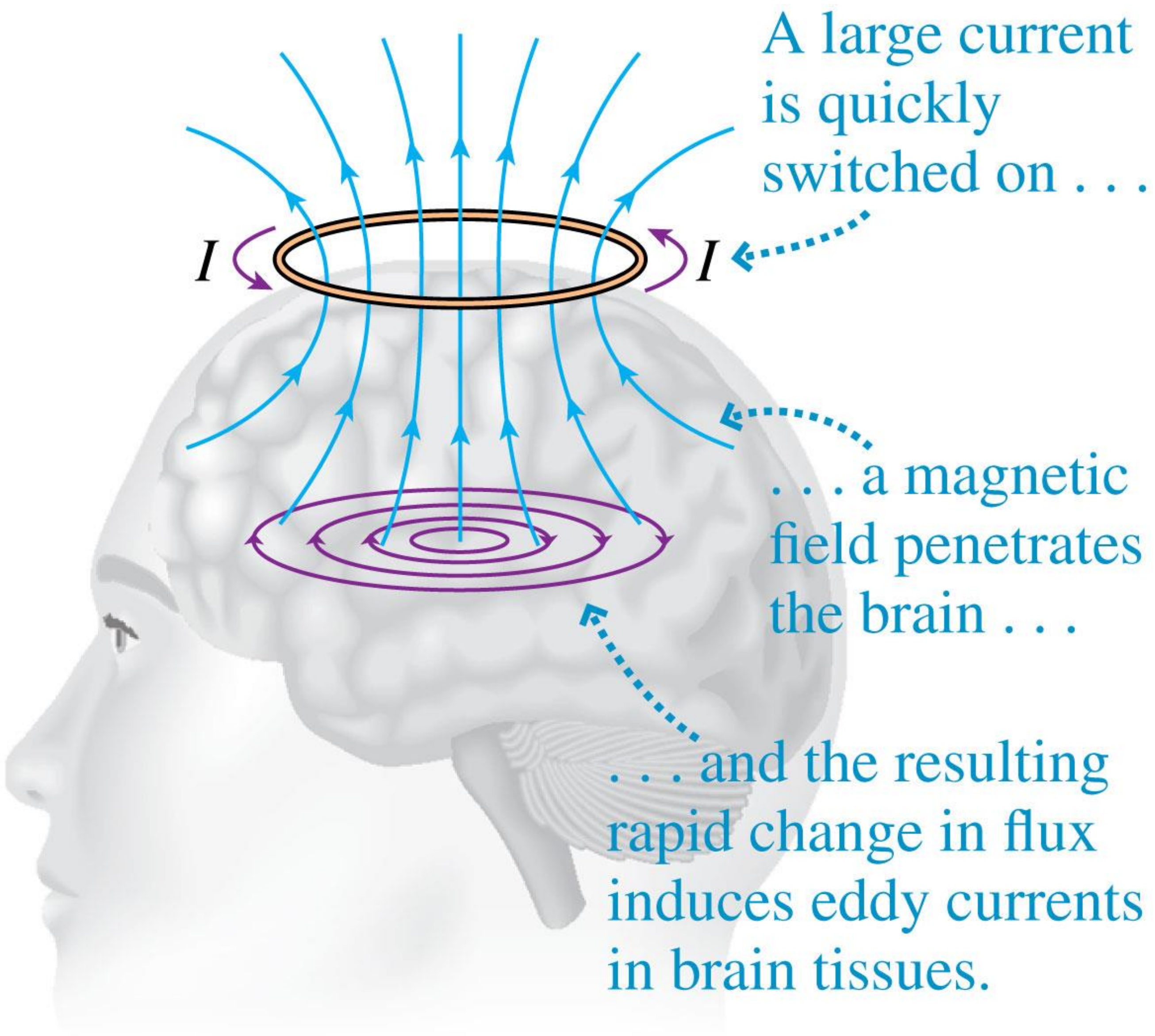
- Because of the braking force exerted by the magnetic field, **an external force is required to pull a metal through a magnetic field.**
- If the pulling force ceases, the magnetic braking force quickly causes the metal to decelerate until it stops.



Eddy Currents

- In a technique called *transcranial magnetic stimulation* (TMS), a large oscillating magnetic field is applied to the head via a current carrying-coil.
- The field produces small eddy currents on the brain, inhibiting the neurons in the stimulated region. This technique can be used to determine the importance of the stimulated region in certain perceptions or tasks.

Eddy Currents



Example Problem

A coil used to produce changing magnetic fields in a TMS device produces a magnetic field that increases from 0 T to 2.5 T in a time of 200 μs. Suppose this field extends throughout the entire head. Estimate the size of the brain and calculate the induced emf in a loop around the outside of the brain.

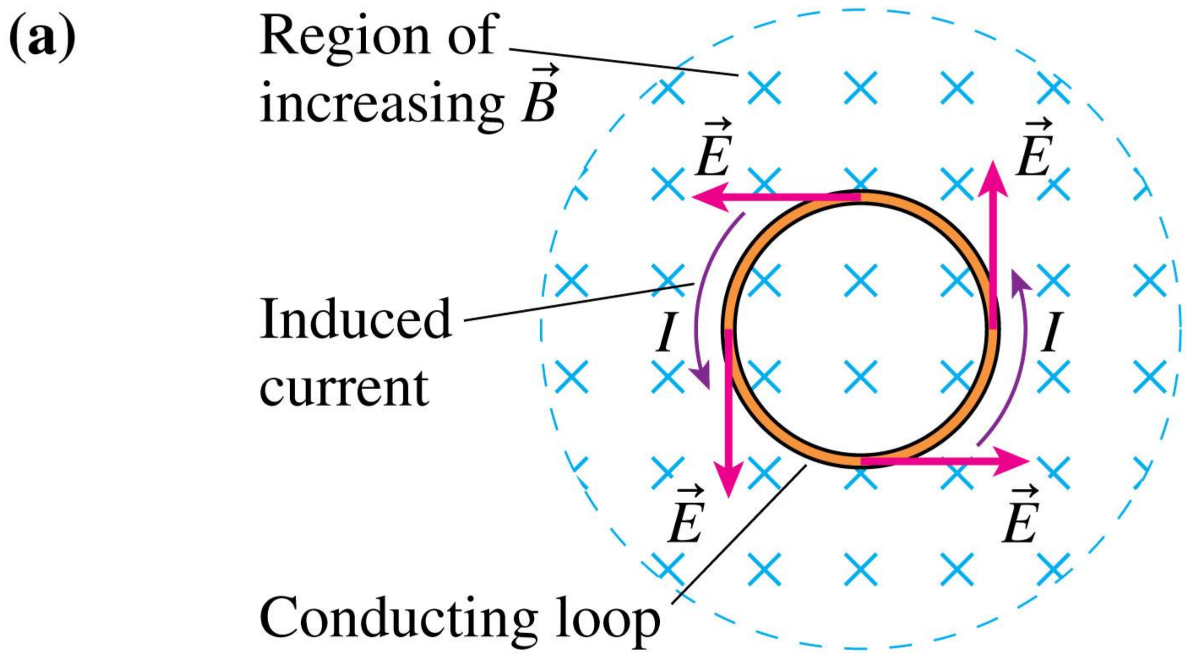
Section 25.5 Electromagnetic Waves

Induced Fields

- When a changing flux through a loop induces a current, what actually *causes* the current? What *force* pushes the charges around the loop?
- We know that an *electric field* can move charges through a conductor.
- A changing magnetic field creates an **induced electric field.**

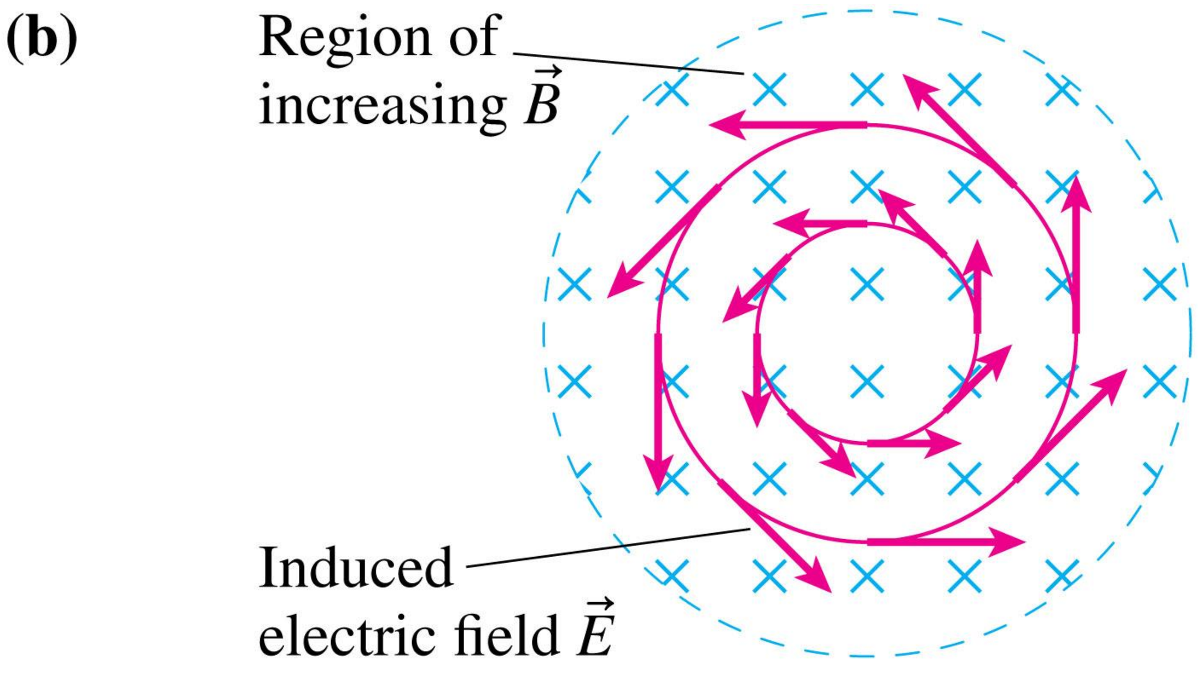
Induced Fields

- An increasing magnetic field directed into the screen induces a current in a loop in the counterclockwise direction.
- The induced electric field must be tangent to the loop at all points to make the charges in the loop move.



Induced Fields

- An induced electric field is produced by a changing magnetic field whether there is a conducting loop or not.
- Just as a changing magnetic field produces an induced electric field, **a changing electric field creates an induced magnetic field.**

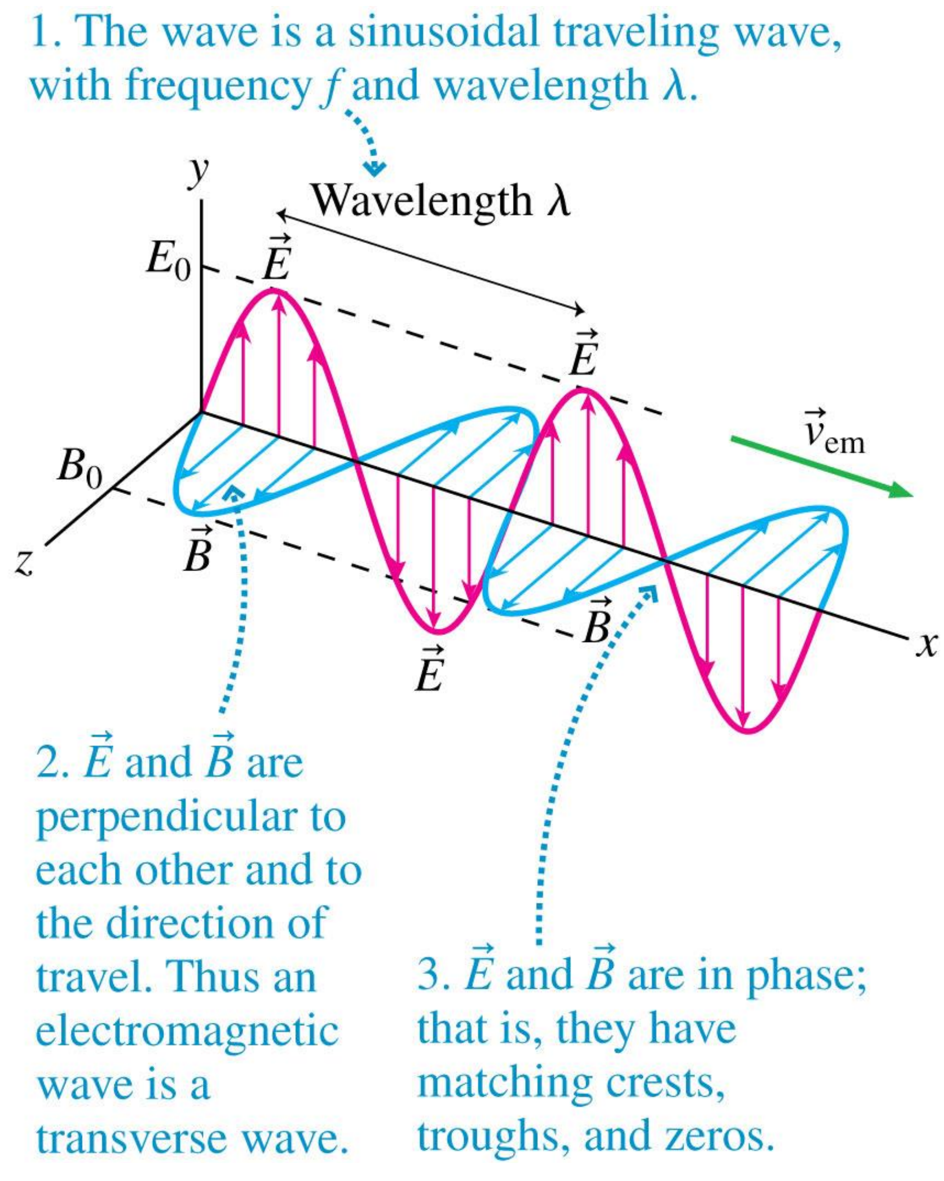


Induced Fields

- A changing magnetic field can induce an electric field in the absence of any charges, and a changing electric field can induce a magnetic field in the absence of any current.
- Therefore, it is possible to sustain a magnetic or electric field independent of charges or currents.
- A changing electric field can induce a magnetic field, which can change in just the right way to recreate the electric field, which can change to recreate the magnetic field. The fields are continuously recreated through electromagnetic induction.
- Electric and magnetic fields can sustain themselves free of charges and currents in the form of an **electromagnetic wave.**

Properties of Electromagnetic Waves

- **An electromagnetic wave is a transverse wave.**



Properties of Electromagnetic Waves

- An electromagnetic wave travels with the speed

$$v_{\text{em}} = \frac{1}{\sqrt{\epsilon_0 \mu_0}}$$

- ε_0 and μ_0 are the permittivity and permeability constants.
- If you insert the known values, we find that $v_{\text{em}} = 3.00 \times 10^8$ m/s – the speed of light *c*.
- James Clerk Maxwell, the first to complete this analysis concluded, that **light is an electromagnetic wave.**

Properties of Electromagnetic Waves

- At every point on an electromagnetic wave, the electric and magnetic field strengths are related by

$$\frac{E}{B} = c$$

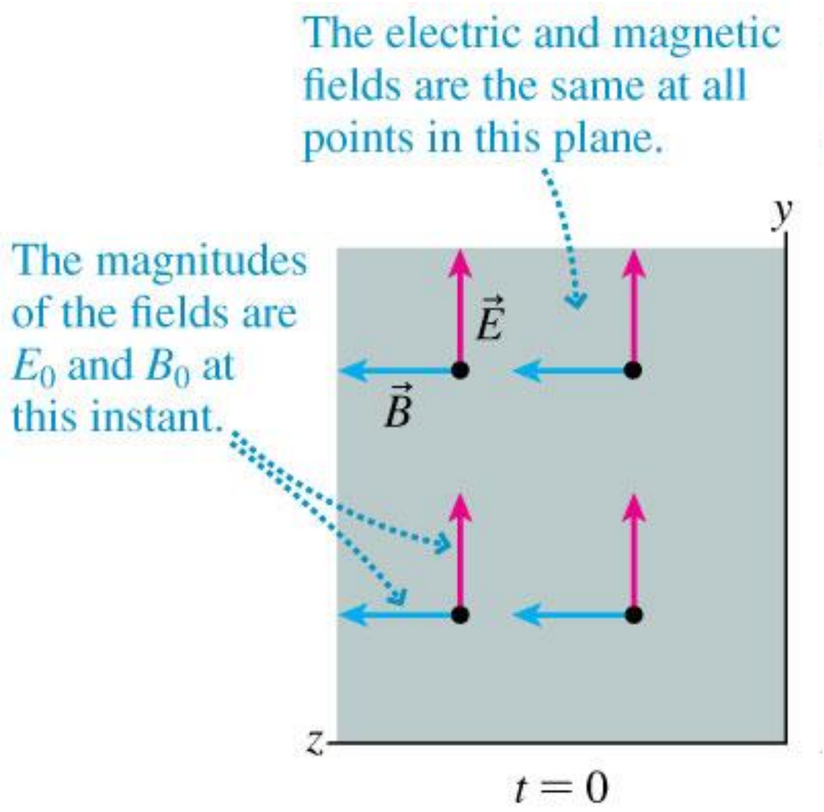
- We learned that we can relate the speed, frequency and wavelength of a sinusoidal wave as $v = \lambda f$. For electromagnetic waves, the relationship becomes

$$c = \lambda f$$

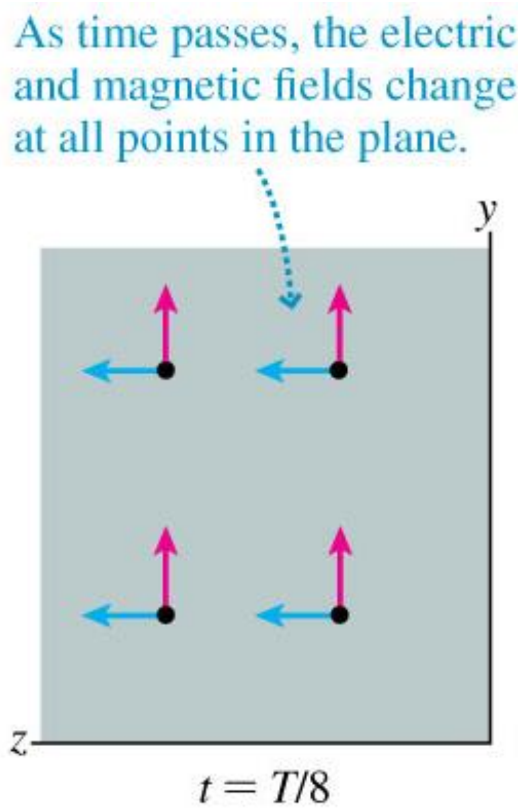
Properties of Electromagnetic Waves

- The displacement of a plane wave is the same at all points in any plane perpendicular to the direction of motion.
- If an electromagnetic wave were moving directly toward you, the electric and magnetic waves would vary in time but remain synchronized with all other points in the plane.
- As the plane wave passes you, you would see a uniform oscillation of the electric and magnetic fields of the wave.

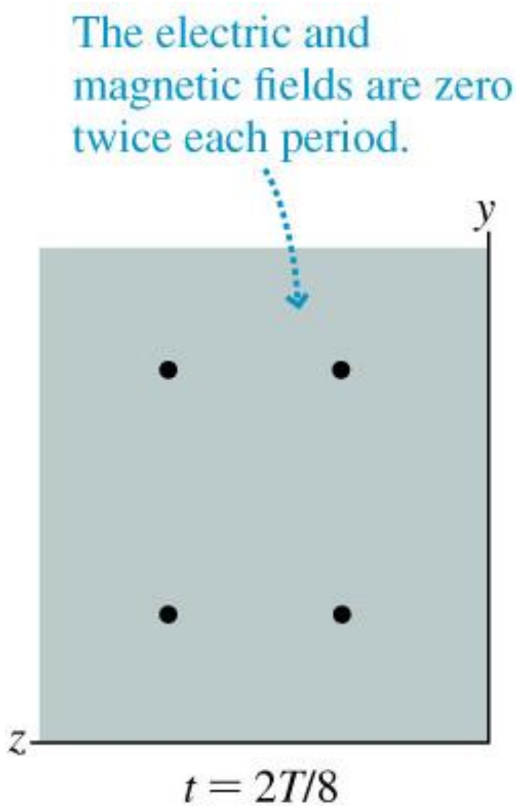
Properties of Electromagnetic Waves



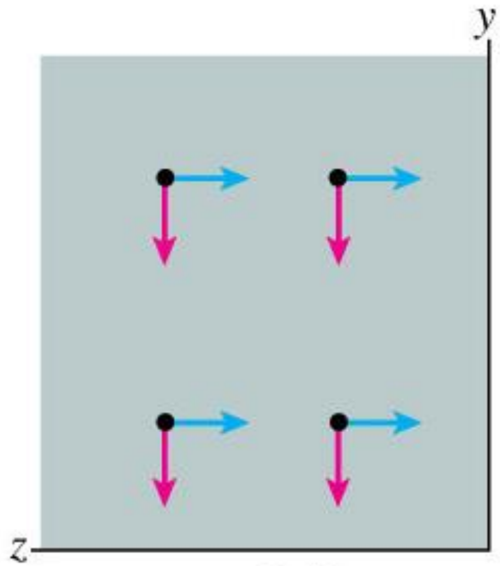
Properties of Electromagnetic Waves



Properties of Electromagnetic Waves

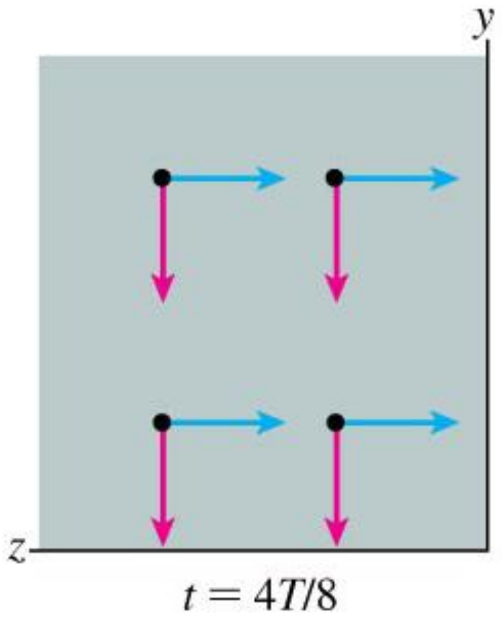


Properties of Electromagnetic Waves



$t = 3T/8$

Properties of Electromagnetic Waves



Properties of Electromagnetic Waves

- If a plane electromagnetic wave moves in the *x*-direction with the electric field along the *y*-axis, then the magnetic field is along the *z*-axis.
- The equations for the electric and magnetic fields of a wave with a period T and wavelength λ are:

$$E_y = E_0 \sin\left(2\pi\left(\frac{x}{\lambda} - \frac{t}{T}\right)\right) \qquad B_z = B_0 \sin\left(2\pi\left(\frac{x}{\lambda} - \frac{t}{T}\right)\right)$$

- E_0 and B_0 are the amplitudes of the oscillating fields.

Properties of Electromagnetic Waves

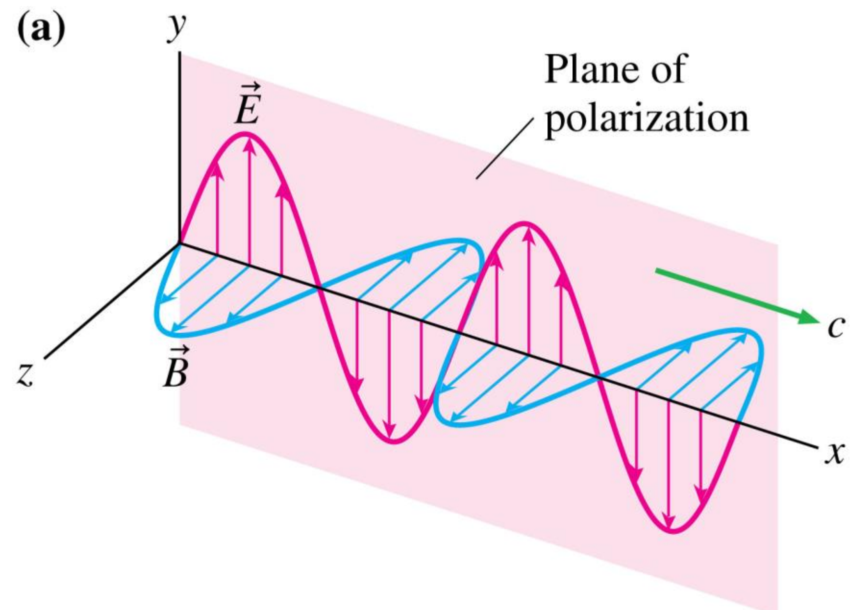
- The amplitudes of the fields in an electromagnetic wave must be related:

$$\frac{E_0}{B_0} = c$$

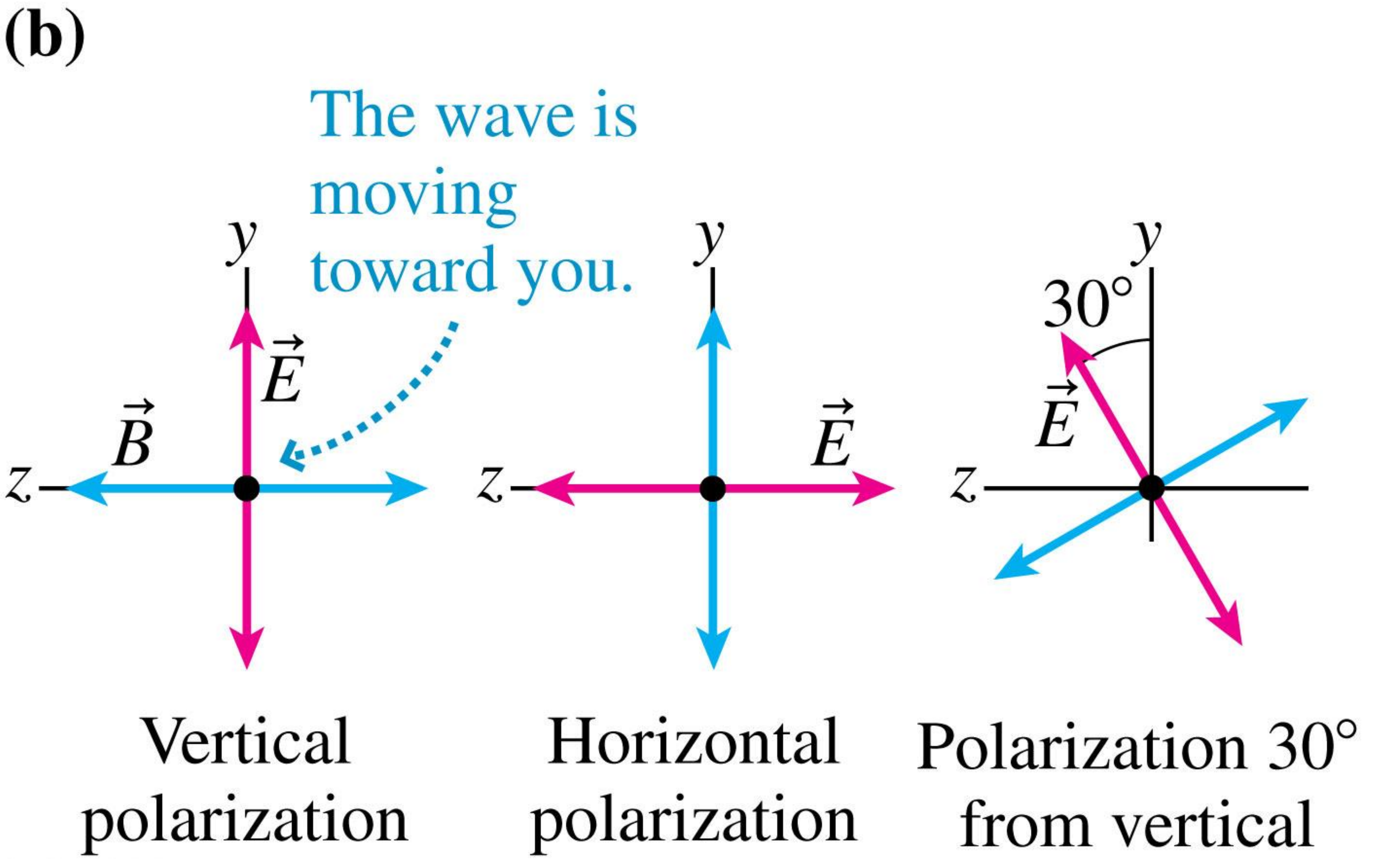
Relationship between field amplitudes for an electromagnetic wave

Polarization

- The plane containing the electric field vectors of an electromagnetic wave is called the **plane of polarization.**
- This figure shows a wave traveling along the *x*-axis, so the plane of polarization is the *xy*-plane.
- This wave is *vertically polarized* (the electric field is oscillating along the *y*-axis).



Polarization



Polarization

- Each atom in the sun emits light independently of all other atoms, so the polarization of each atom is in a random direction.
- The superposition of the waves from all of the different atoms results in an *unpolarized* wave.
- The radiation from most sources of electromagnetic radiation is unpolarized.

Energy of Electromagnetic Waves

- The energy of the electromagnetic wave depends on the amplitudes of the electric and magnetic fields.
- In Chapter 15 we defined *intensity* to be $I = P/A$, where P is the power, or energy transferred per second, of a wave that impinges on the area A.

$$I = \frac{P}{A} = \frac{1}{2}c\epsilon_0 E_0^2 = \frac{1}{2}\frac{c}{\mu_0}B_0^2$$

Intensity of an electromagnetic wave with field amplitudes E_0 and B_0

Energy of Electromagnetic Waves

- The intensity of a plane wave, like a laser beam, does not change with distance.
- The intensity of a spherical wave, which spreads out from a point, must decrease with the square of the distance in order to conserve energy.
- If a power source emits uniformly in all directions, the wave intensity at a distance *r* is

$$I = \frac{P_{\text{source}}}{4\pi r^2}$$

QuickCheck 25.16

To double the intensity of an electromagnetic wave, you should increase the amplitude of the electric field by a factor of

A. 0.5
B. 0.707
C. 1.414
D. 2
E. 4

Slide 25-140

QuickCheck 25.16

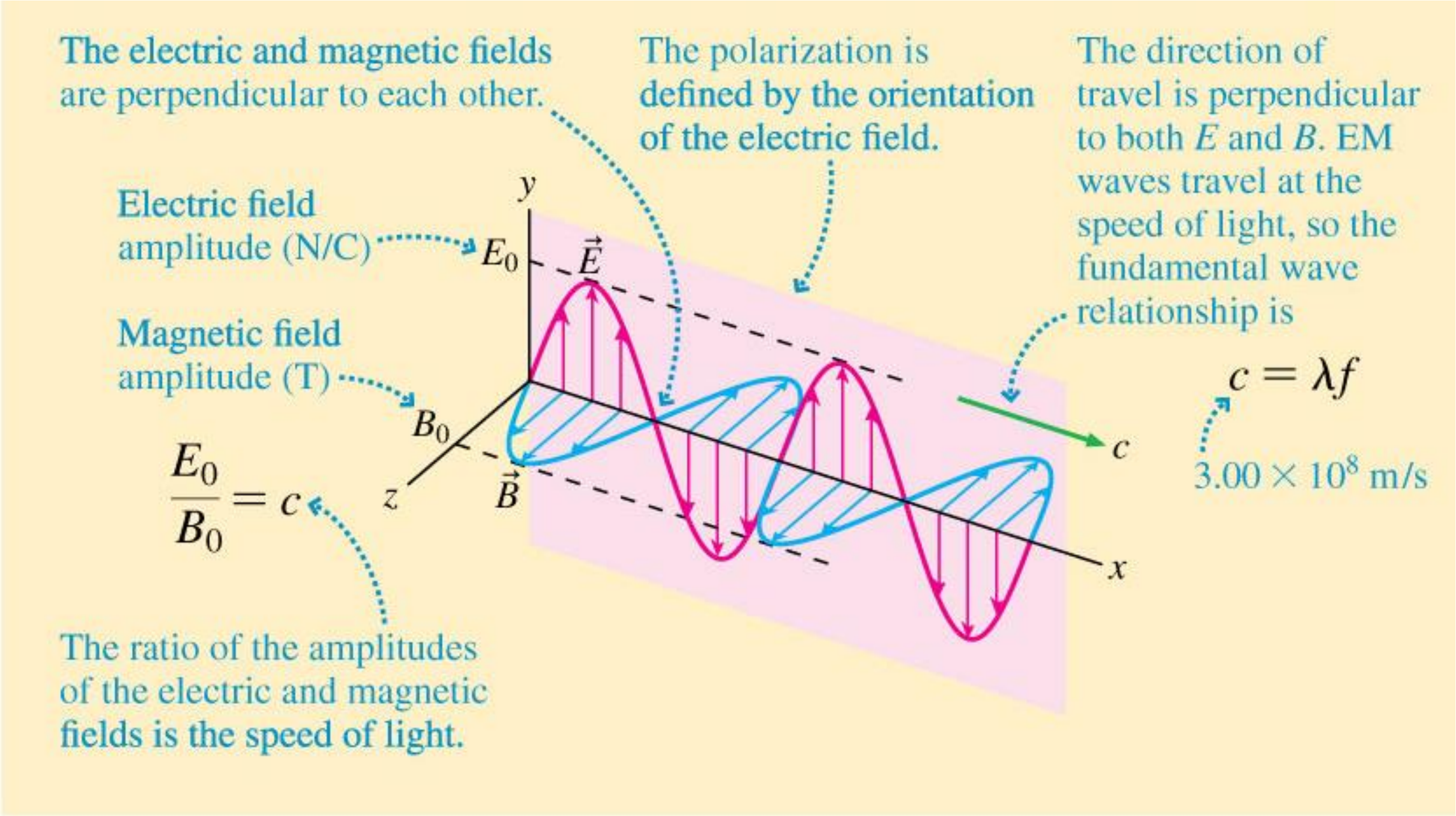
To double the intensity of an electromagnetic wave, you should increase the amplitude of the electric field by a factor of

A. 0.5
B. 0.707
✔ C. 1.414 $I \propto E_0^2$
D. 2
E. 4

Slide 25-141

SYNTHESIS 25.1 Electromagnetic waves

- An electromagnetic wave is a transverse wave of oscillating electric and magnetic fields.



Text: p. 820

SYNTHESIS 25.1 Electromagnetic waves

- An electromagnetic wave is a transverse wave of oscillating electric and magnetic fields.

The intensity of the EM wave depends on the field amplitudes:

Intensity (W/m²)

$$I = \frac{1}{2}c\epsilon_0 E_0^2 = \frac{1}{2}\frac{c}{\mu_0}B_0^2$$

Permittivity constant, $8.85 \times 10^{-12}\ \mathrm{C^2/N \cdot m^2}$

Permeability constant, $1.26 \times 10^{-6}\ \mathrm{T \cdot m/A}$

The intensity of an EM point source decreases with distance from the source:

$$I = \frac{P_{\text{source}}}{4\pi r^2}$$

Source power (W)

Distance from the source (m)

Text: p. 820

Example Problem

Inside the cavity of a microwave oven, the 2.4 GHz electromagnetic waves have an intensity of 5.0 kW/m^2. What is the strength of the electric field? The magnetic field?

Example 25.7 Electric and magnetic fields of a cell phone

A digital cell phone emits 0.60 W of 1.9 GHz radio waves. What are the amplitudes of the electric and magnetic fields at a distance of 10 cm?

PREPARE We can solve this problem using details from Synthesis 25.1. We can approximate the cell phone as a point source, so we can use the second intensity equation to find the intensity at 10 cm. Once we know the intensity, we can use the first intensity equation to compute the field amplitudes.

Example 25.7 Electric and magnetic fields of a cell phone (cont.)

SOLVE The intensity at a distance of 10 cm is

$$I = \frac{P_{\text{source}}}{4\pi r^2} = \frac{0.60 \text{ W}}{4\pi(0.10 \text{ m})^2} = 4.8 \text{ W/m}^2$$

Example 25.7 Electric and magnetic fields of a cell phone (cont.)

We can rearrange the first intensity equation to solve for the amplitude of the electric field:

$$E_0 = \sqrt{\frac{2I}{c\epsilon_0}} = \sqrt{\frac{2(4.8\ \text{W/m}^2)}{(3.0 \times 10^8\ \text{m/s})(8.85 \times 10^{-12}\ \text{C}^2/\text{N} \cdot \text{m}^2)}} = 60\ \text{V/m}$$

Example 25.7 Electric and magnetic fields of a cell phone (cont.)

We can then use the relationship between field amplitudes to find the amplitude of the magnetic field:

$$B_0 = \frac{E_0}{c} = 2.0 \times 10^{-7}\ \text{T}$$

Example 25.7 Electric and magnetic fields of a cell phone (cont.)

ASSESS The electric field amplitude is reasonably small. For comparison, the typical electric field due to atmospheric electricity is 100 V/m; the field near a charged Van de Graaff generator can be 1000 times larger than this. The scale of the result thus seems reasonable; we know that the electric fields near a cell phone's antenna aren't large enough to produce significant effects. The magnetic field is smaller yet, only 1/250th of the earth's field, which, as you know, is quite weak. This makes sense as well; you haven't noticed magnetic effects while making a phone call!

QuickCheck 25.18

A typical analog cell phone has a frequency of 850 MHz; a digital phone a frequency of 1950 MHz. Compared to the signal from an analog cell phone, the digital signal has

A. Longer wavelength and lower photon energy.
B. Longer wavelength and higher photon energy.
C. Shorter wavelength and lower photon energy.
D. Shorter wavelength and higher photon energy.

Slide 25-150

QuickCheck 25.18

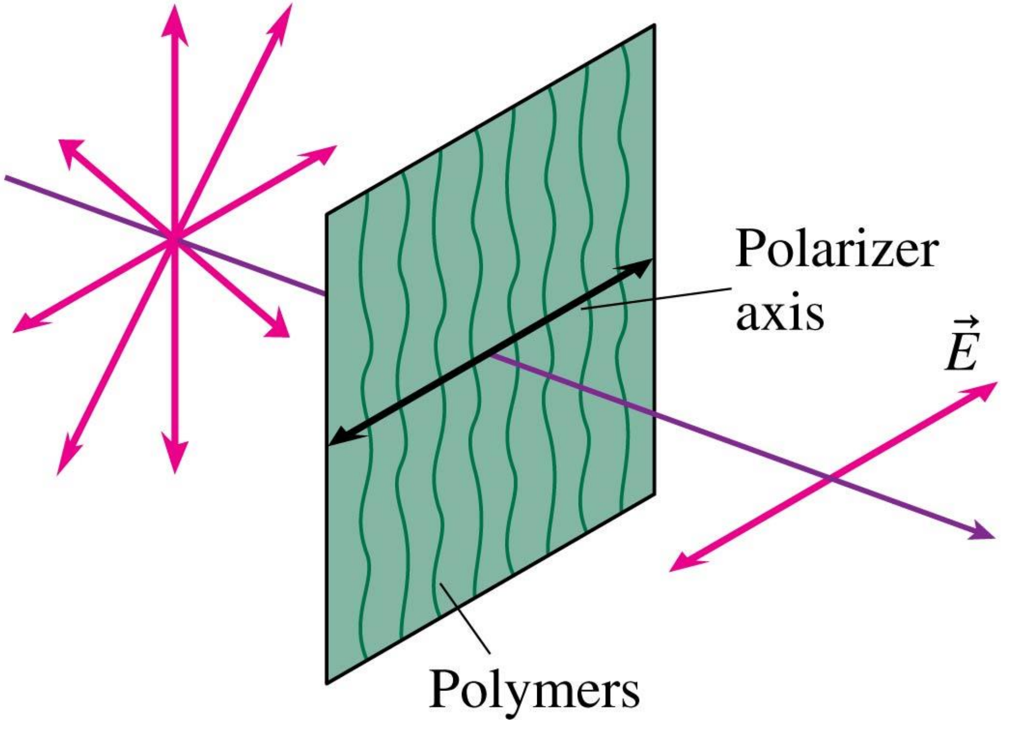
A typical analog cell phone has a frequency of 850 MHz; a digital phone a frequency of 1950 MHz. Compared to the signal from an analog cell phone, the digital signal has

A. Longer wavelength and lower photon energy.
B. Longer wavelength and higher photon energy.
C. Shorter wavelength and lower photon energy.
✔ D. Shorter wavelength and higher photon energy.

Slide 25-151

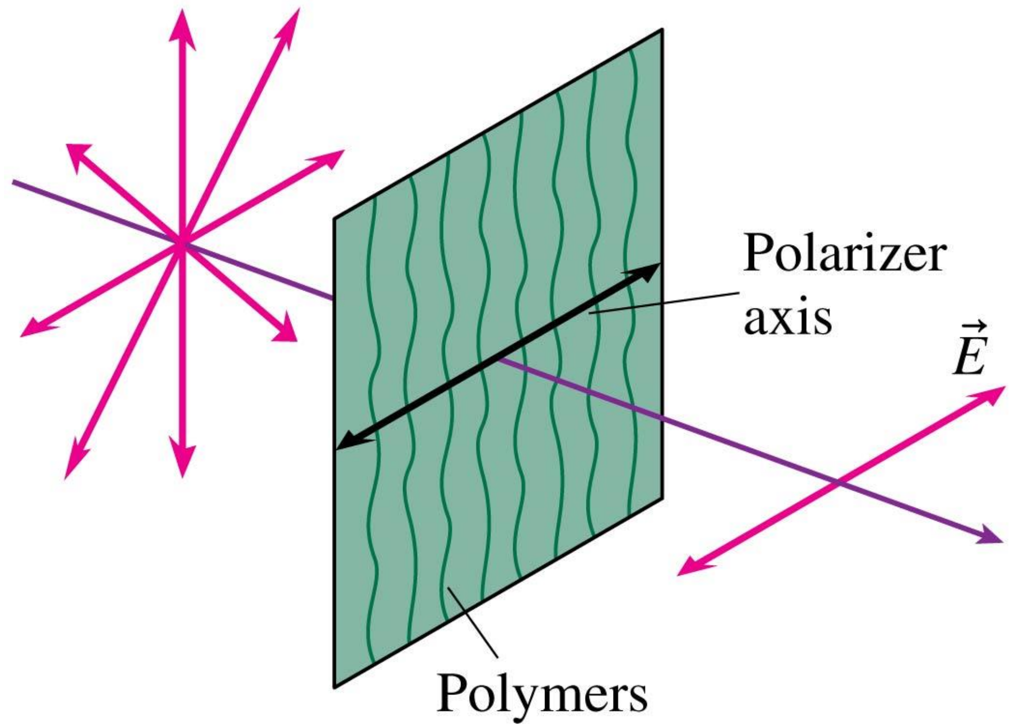
Polarizers and Changing Polarization

- We can transform unpolarized light into polarized light with a *polarizing filter*.
- A typical polarizing filter is a plastic sheet containing long organic molecules called polymers.



Polarizers and Changing Polarization

- As light enters a polarizing filter, the component of the electric field oscillating parallel to the polymers drives electrons up and down the molecules, which absorb the energy from the light.



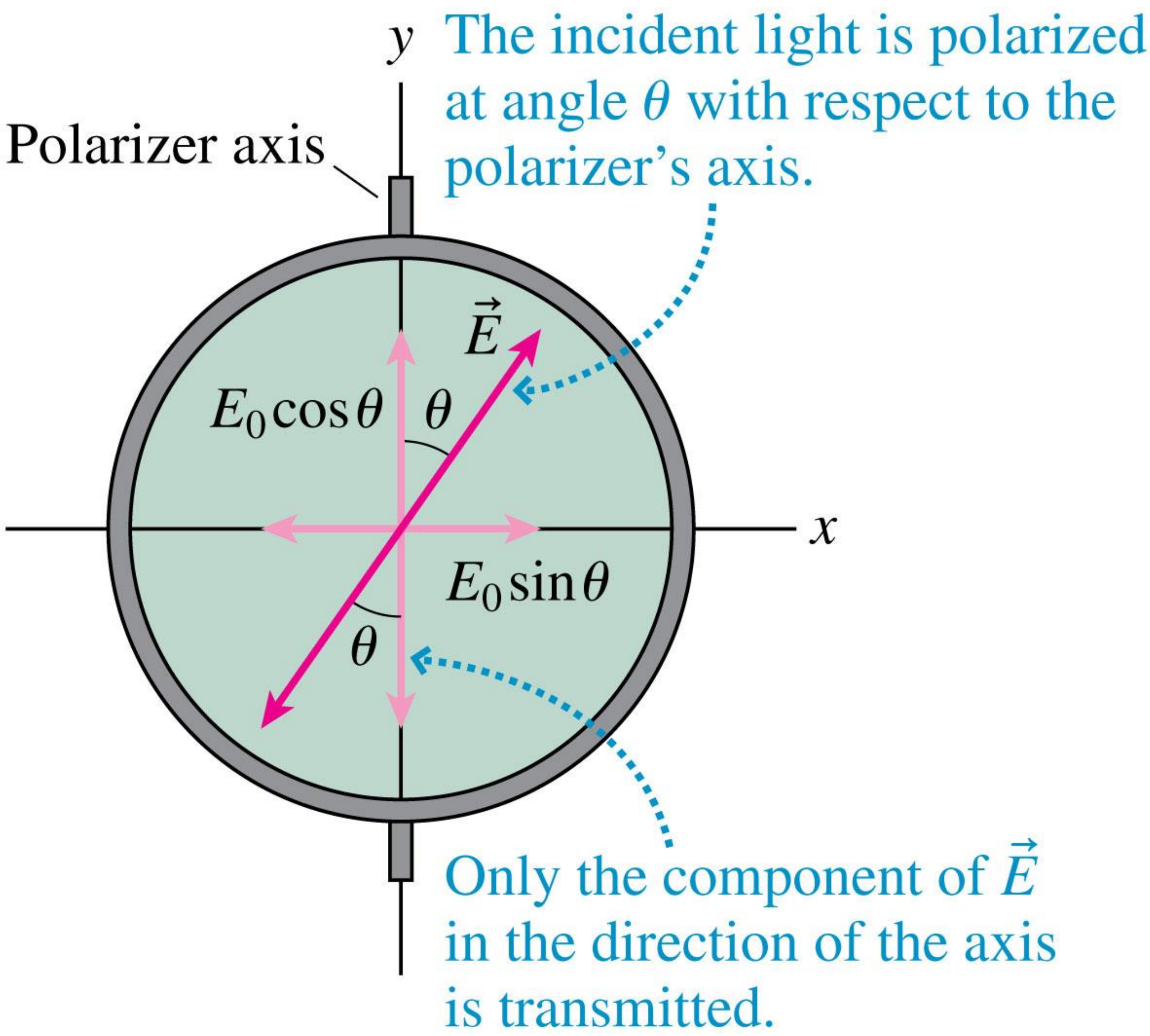
- Only the component of the light polarized perpendicular to the polymers emerges.
- The direction of the transmitted polarization is the axis of the polarizer.

Polarizers and Changing Polarization

- When polarized light approaches a polarizer, the magnitude of the electric field of light transmitted is

$$E_{\text{transmitted}} = E_{\text{incident}} \cos \theta$$

Polarizers and Changing Polarization



Polarizers and Changing Polarization

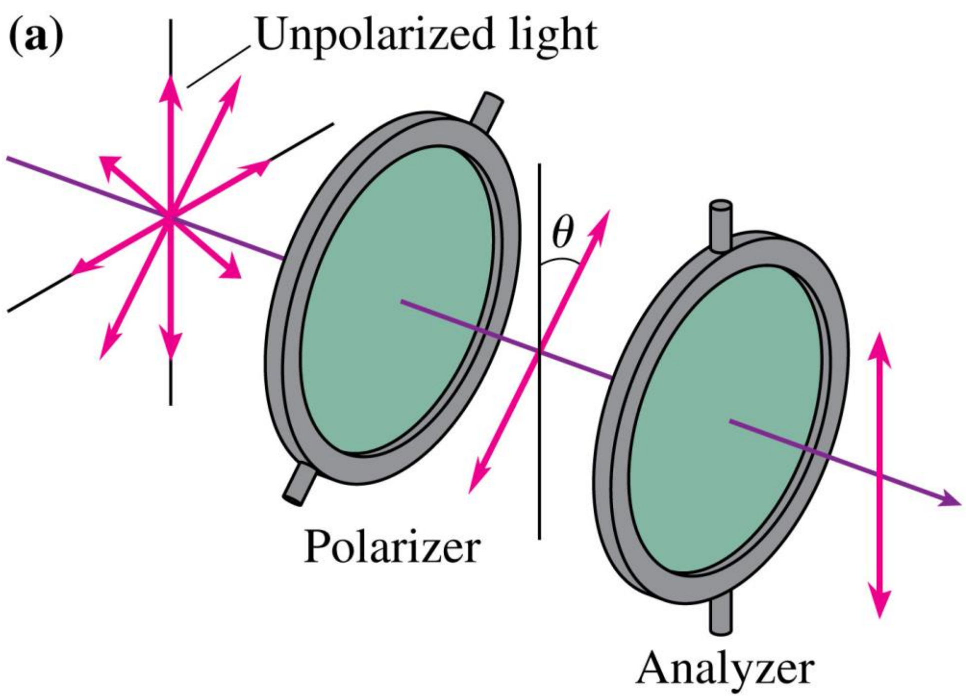
- The intensity depends on the square of the electric field amplitude, so the transmitted intensity of light from a filter is related to the intensity of the incident light by **Malus's law**:

$$I_{\text{transmitted}} = I_{\text{incident}}(\cos\theta)^2$$

Malus's law for transmission of polarized light by a polarizing filter

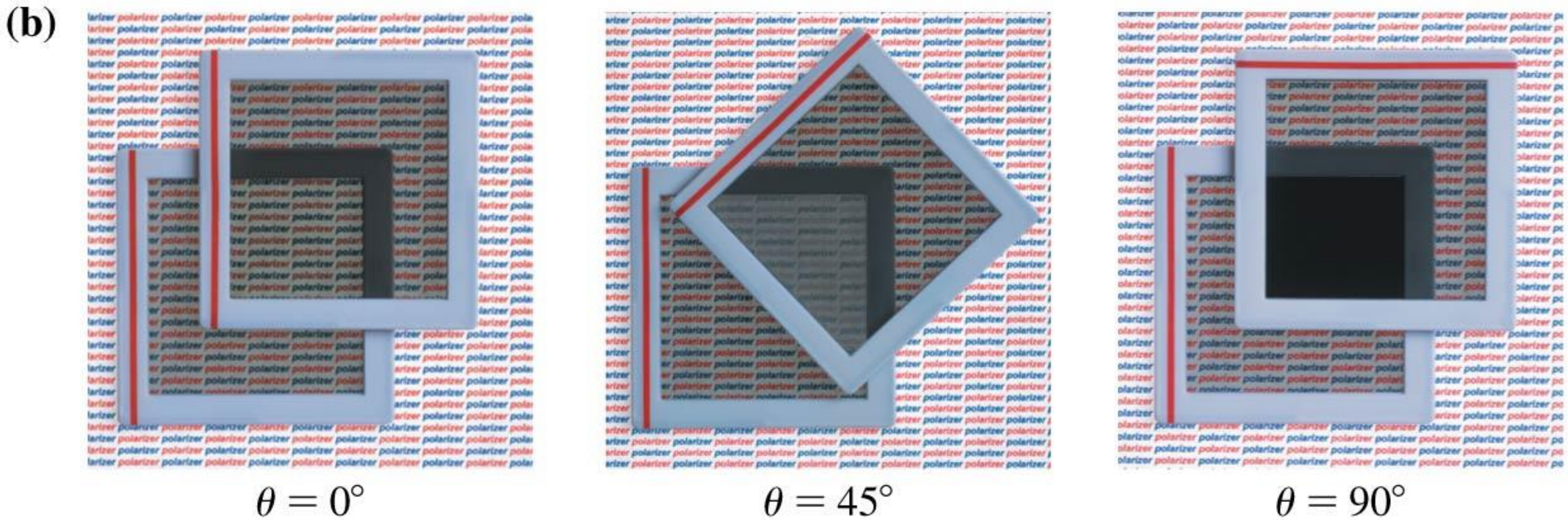
Polarizers and Changing Polarization

- Malus's law can be demonstrated with two polarizing filters. The first is called the *polarizer*, which creates the polarized light, and the second filter is called the *analyzer*.
- The analyzer is rotated by an angle θ relative to the polarizer.



Polarizers and Changing Polarization

- When a polarizer and an analyzer are aligned, ($\theta = 0$), the transmission of the analyzer should be 100%.
- The intensity of the transmission decreases to zero when $\theta = 90°$. Two polarizing filters with perpendicular axes are called *crossed polarizers* and they block all the light.



Polarizers and Changing Polarization

- An object placed between two crossed polarizers can *change* the polarization of light so that light is transmitted from the analyzer.
- Different minerals and different material in teeth change the polarization of light in different ways. This can give an image of the different tissue in teeth.

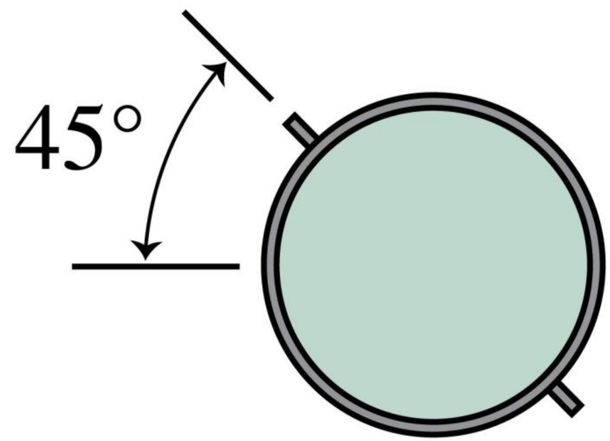
Polarizers and Changing Polarization

- In polarizing sunglasses, the polarization axis is vertical, so the glasses transmit only vertical light.
- *Glare* is the reflection of sunlight from lakes and other horizontal surfaces. It has a strong horizontal polarization, so vertically polarized glasses eliminate that glare.

QuickCheck 25.17

A vertically polarized light wave of intensity 1000 mW/m^2 is coming toward you, out of the screen. After passing through this polarizing filter, the wave's intensity is

A. 707 mW/m^2
B. 500 mW/m^2
C. 333 mW/m^2
D. 250 mW/m^2
E. 0 mW/m^2



Slide 25-161

QuickCheck 25.17

A vertically polarized light wave of intensity 1000 mW/m^2 is coming toward you, out of the screen. After passing through this polarizing filter, the wave's intensity is

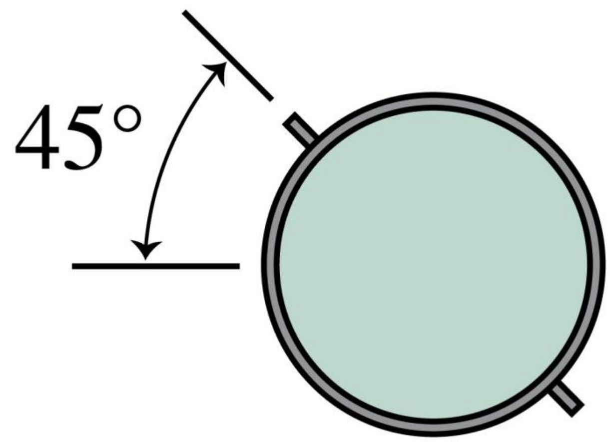
A. 707 mW/m^2

✔ B. 500 mW/m^2 $I = I_0 \cos^2\theta$

C. 333 mW/m^2

D. 250 mW/m^2

E. 0 mW/m^2



Example Problem

Light passed through a polarizing filter has an intensity of 2.0 W/m^2. How should a second polarizing filter be arranged to decrease the intensity to 1.0 W/m^2?

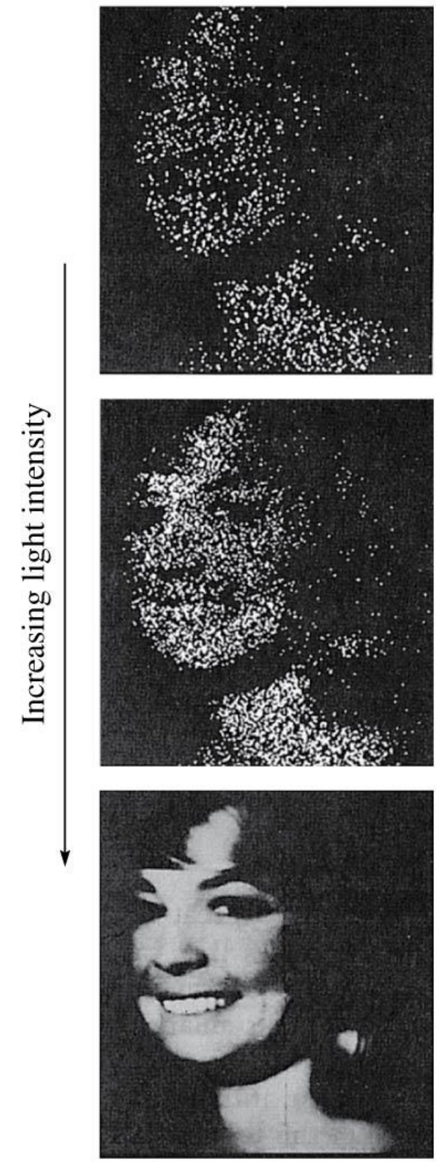
Section 25.6 The Photon Model of Electromagnetic Waves

The Photon Model of Electromagnetic Waves

- We have learned that light is a wave, but many experiments convincingly lead to the surprising result that **electromagnetic waves have a particle-like nature.**
- **Photons** are the particle-like component of the electromagnetic wave.

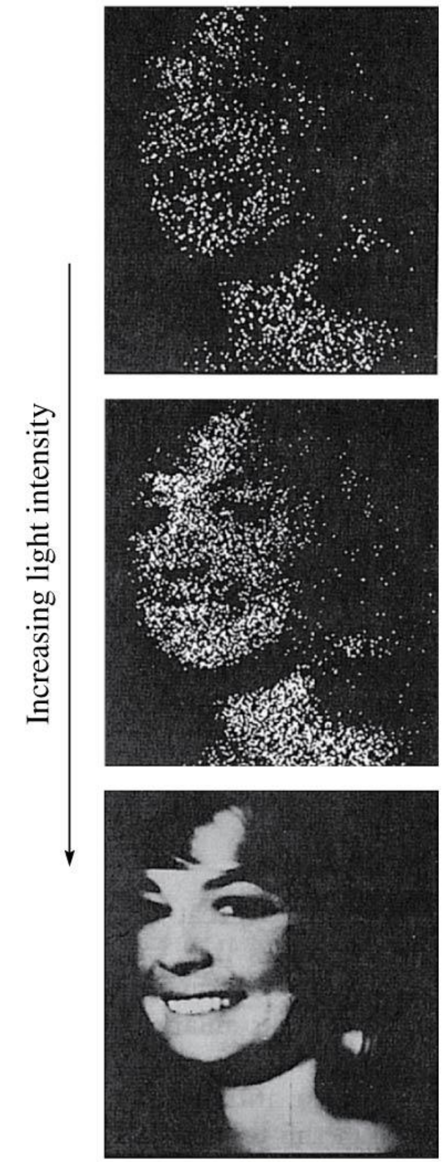
The Photon Model of Electromagnetic Waves

- One experiment that indicates the particle-like behavior of waves is a dim photograph.
- If light acted like a wave, reducing its intensity should cause the image to grow dimmer, but the entire image would remain present.



The Photon Model of Electromagnetic Waves

- In actuality, a dim photo shows that only a few points on the detector registered the presence of light, as if the light came in pieces.
- When the intensity of the light increases, the density of the dots of light is high enough to form a full picture.



The Photon Model of Electromagnetic Waves

- The **photon model** of electromagnetic waves consists of three basic postulates:

1. Electromagnetic waves consist of discrete, massless units called photons. A photon travels in a vacuum at the speed of light.

The Photon Model of Electromagnetic Waves

- The **photon model** of electromagnetic waves consists of three basic postulates:

2. Each photon has energy:

$$E_{\text{photon}} = hf$$

f is the frequency of the wave and *h* is the *universal constant* called **Planck's constant:**

$$h = 6.63 \times 10^{-34}\ \text{J} \cdot \text{s}$$

In other words, the electromagnetic wave comes in discrete "chunks" of energy *hf*.

The Photon Model of Electromagnetic Waves

- The **photon model** of electromagnetic waves consists of three basic postulates:

3. The superposition of a sufficiently large number of photons has the characteristics of a continuous electromagnetic wave.

QuickCheck 25.19

A radio tower emits two 50 W signals, one an AM signal at a frequency of 850 kHz, one an FM signal at a frequency of 85 MHz. Which signal has more photons per second?

A. The AM signal has more photons per second.
B. The FM signal has more photons per second.
C. Both signals have the same photons per second.

Slide 25-171

QuickCheck 25.19

A radio tower emits two 50 W signals, one an AM signal at a frequency of 850 kHz, one an FM signal at a frequency of 85 MHz. Which signal has more photons per second?

✔ A. The AM signal has more photons per second.
B. The FM signal has more photons per second.
C. Both signals have the same photons per second.

Example 25.9 Finding the energy of a photon of visible light

550 nm is the approximate average wavelength of visible light.

a. What is the energy of a photon with a wavelength of 550 nm?

b. A 40 W incandescent lightbulb emits about 1 J of visible light energy every second. Estimate the number of visible light photons emitted per second.

Example 25.9 Finding the energy of a photon of visible light (cont.)

SOLVE a. The frequency of the photon is

$$f = \frac{c}{\lambda} = \frac{3.00 \times 10^{8} \text{ m/s}}{550 \times 10^{-9} \text{ m}} = 5.4 \times 10^{14} \text{ Hz}$$

Equation 25.22 gives us the energy of this photon:

$$E_{\text{photon}} = hf = (6.63 \times 10^{-34} \text{ J} \cdot \text{s})(5.4 \times 10^{14} \text{ Hz}) = 3.6 \times 10^{-19} \text{ J}$$

Example 25.9 Finding the energy of a photon of visible light (cont.)

This is an extremely small energy! In fact, photon energies are so small that they are usually measured in electron volts (eV) rather than joules. Recall that 1 eV = 1.60×10^{-19} J. With this, we find that the photon energy is

$$E_{\text{photon}} = 3.6 \times 10^{-19}\ \text{J} \times \frac{1\ \text{eV}}{1.60 \times 10^{-19}\ \text{J}} = 2.3\ \text{eV}$$

Example 25.9 Finding the energy of a photon of visible light (cont.)

b. The photons emitted by a lightbulb span a range of energies, because the light spans a range of wavelengths, but the average photon energy corresponds to a wavelength near 550 nm. Thus we can estimate the number of photons in 1 J of light as

$$N \approx \frac{1 \text{ J}}{3.6 \times 10^{-19} \text{ J/photon}} \approx 3 \times 10^{18} \text{ photons}$$

A typical lightbulb emits about 3×10^{18} photons every second.

Example 25.9 Finding the energy of a photon of visible light (cont.)

ASSESS The number of photons emitted per second is staggeringly large. It's not surprising that in our everyday life we sense only the river and not the individual particles within the flow.

The Photon Model of Electromagnetic Waves

- Depending on its energy, a single photon can cause a molecular transformation (as it does on the sensory system of an eye), or even break covalent bonds.
- The photon model of light will be essential as we explore the interaction of electromagnetic waves with matter.

The Photon Model of Electromagnetic Waves

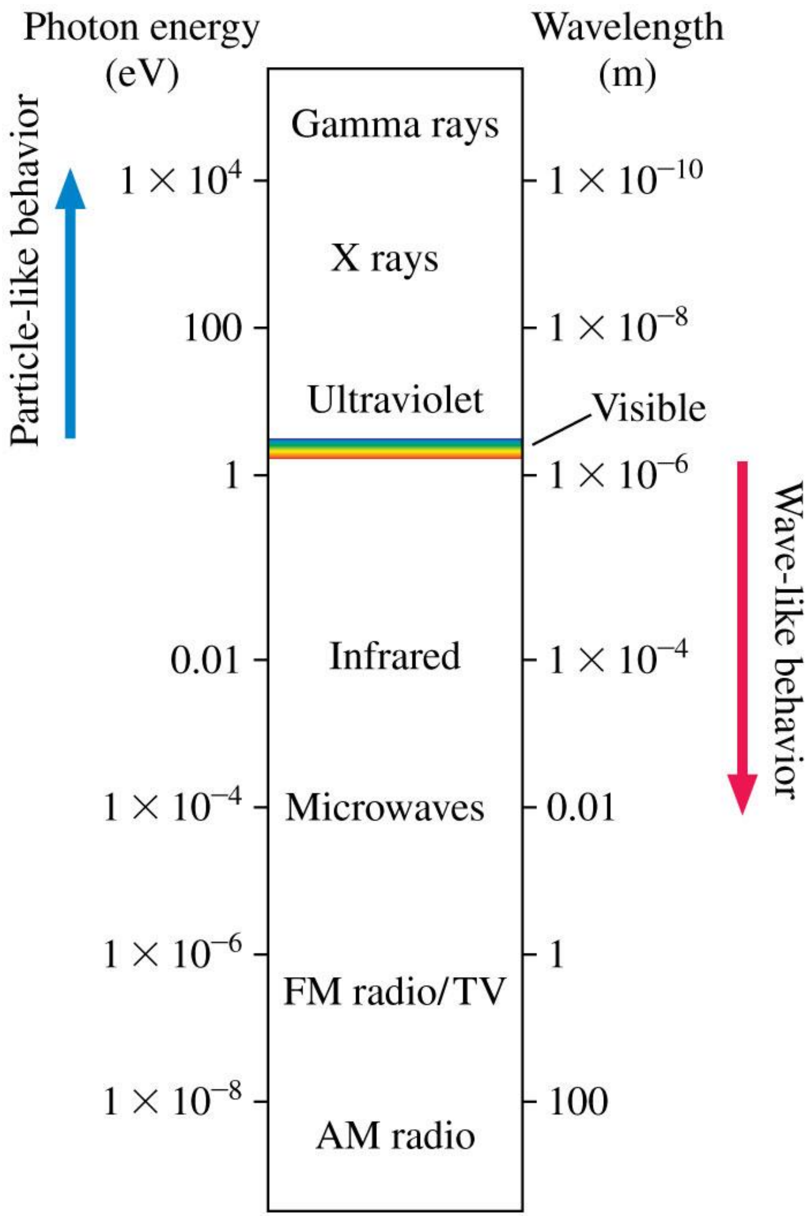
- A single photon of light with a wavelength of 550 nm has the energy of 2.3 eV.

TABLE 25.1 Energies of some atomic and molecular processes

Process	Energy
Breaking a hydrogen bond between two water molecules	0.24 eV
Energy released in metabolizing one molecule of ATP	0.32 eV
Breaking the bond between atoms in a water molecule	4.7 eV
Ionizing a hydrogen atom	13.6 eV

Section 25.7 The Electromagnetic Spectrum

The Electromagnetic Spectrum



The Electromagnetic Spectrum

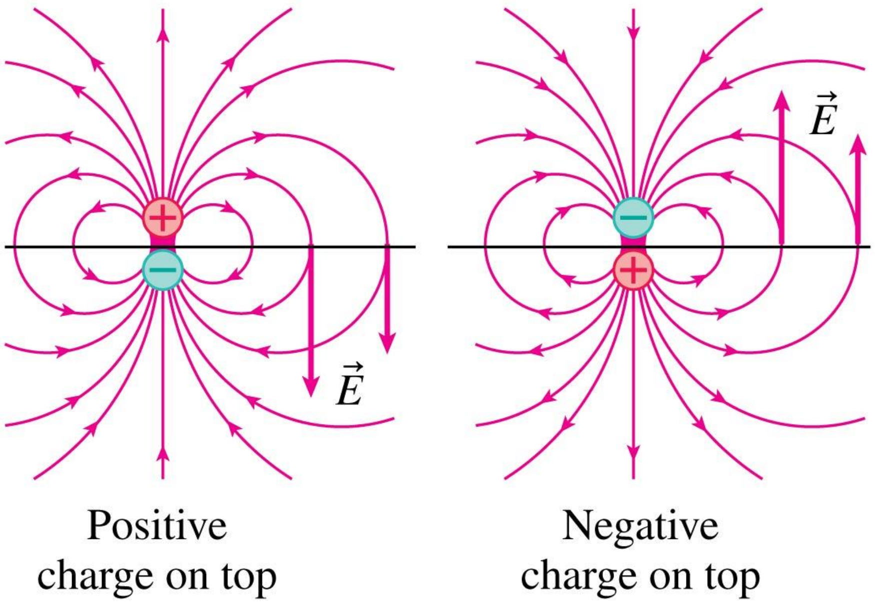
- Electromagnetic waves span a wide range of wavelengths and energies.
- Radio waves have wavelengths of many meters but very low photon energies. Radio waves are therefore best described by Maxwell's theory of electromagnetic waves.
- Gamma rays and x rays have very short wavelengths and high energies, and although they have wave-like characteristics as well, they are best described as photons.
- Visible light, ultraviolet, and infrared can be described as waves or as photons, depending on the situation.

Radio Waves and Microwaves

- An electromagnetic wave is independent of currents or charges, however currents or charges are needed at the *source* of the wave.
- Radio waves and microwaves are generally produced by the motion of charges through an antenna.

Radio Waves and Microwaves

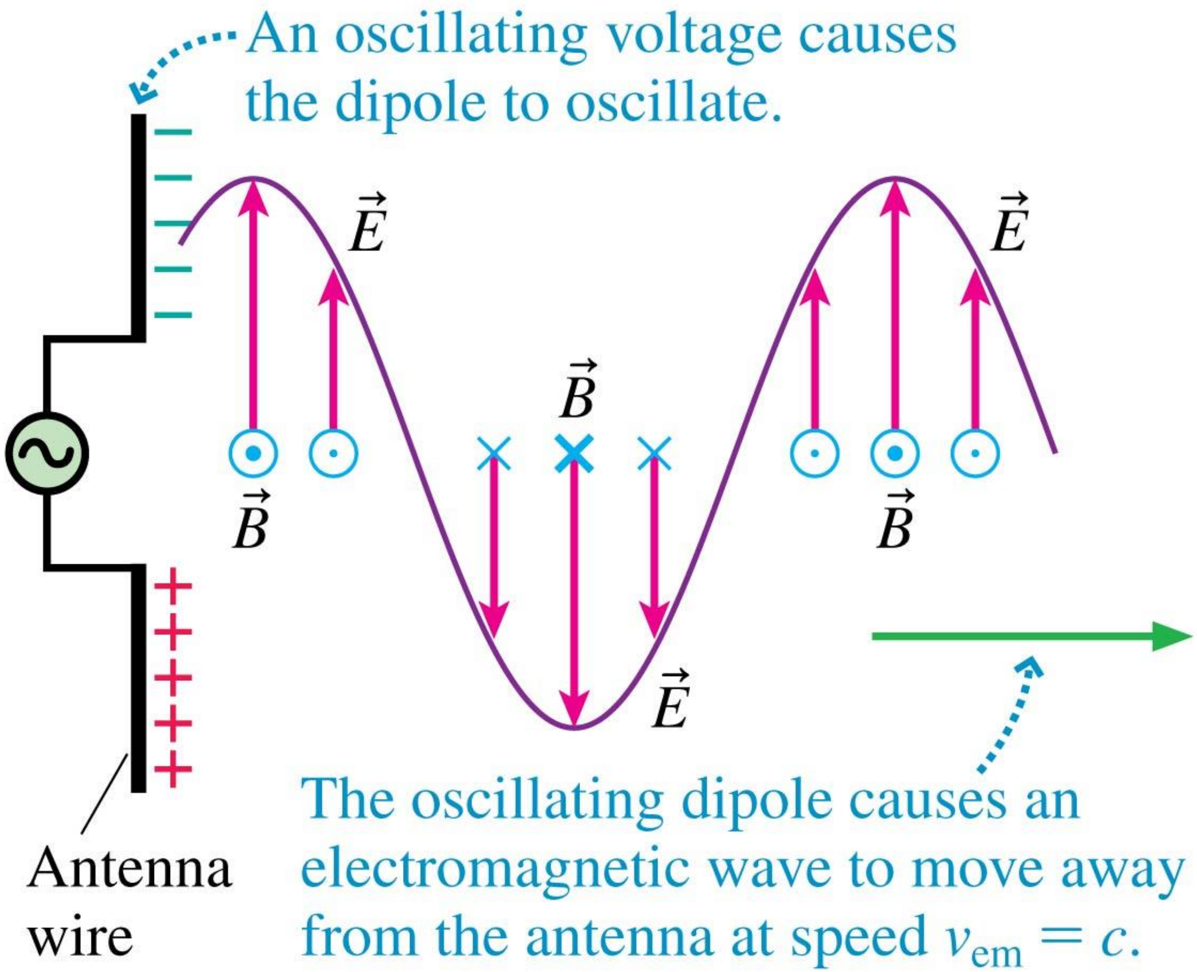
- An **antenna** is a dipole in which the charges are switched at a particular frequency *f*, reversing the electric field at that frequency.



- The oscillation of charges causes the electric field to oscillate, which creates an induced magnetic field. A polarized electromagnetic wave of frequency *f* radiates out into space.

Radio Waves and Microwaves

An antenna generates a self-sustaining electromagnetic wave.



Radio Waves and Microwaves

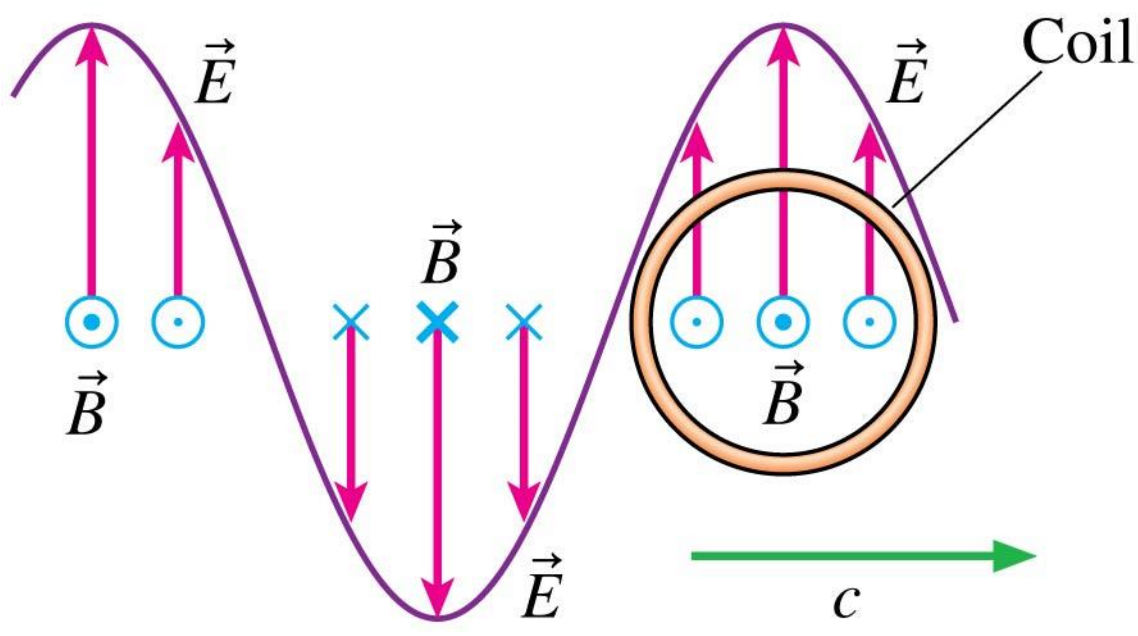
- Radio waves are also *detected* by an antenna.
- The electric field of a vertically polarized radio wave drives a current up and down a vertical conductor, producing a potential difference that can be amplified.
- For the best reception, the antenna should be ¼ of a wavelength.

Radio Waves and Microwaves

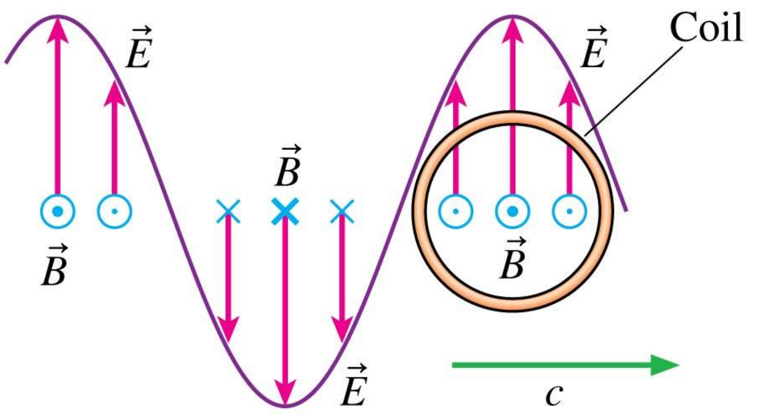
- An AM radio has a lower frequency and thus a longer wavelength. The wavelength is typically 300 m, so the antenna length would need to be 75 meters long.
- Instead, an AM radio detector uses a coil of wire wrapped around a core of magnetic material and detects the *magnetic* field of the radio wave.
- The changing flux of the magnetic field induces an emf on the coil that is detected and amplified by the receiver.

Conceptual Example 25.10 Orienting a coil antenna

A vertically polarized AM radio wave is traveling to the right. How should you orient a coil antenna to detect the oscillating magnetic field component of the wave?



Conceptual Example 25.10 Orienting a coil antenna (cont.)

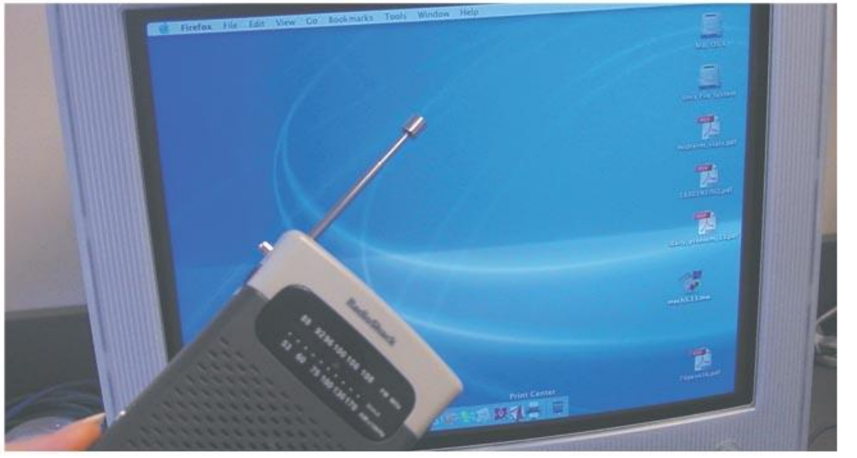


REASON You want the oscillating magnetic field of the wave to produce the maximum possible induced emf in the coil, which requires the maximum changing flux. The flux is maximum when the coil is perpendicular to the magnetic field of the electromagnetic wave, as in **FIGURE 25.36**. Thus the plane of the coil should match the wave's plane of polarization.

Conceptual Example 25.10 Orienting a coil antenna (cont.)

ASSESS Coil antennas are highly directional. If you turn an AM radio—and thus the antenna—in certain directions, you will no longer have the correct orientation of the magnetic field and the coil, and reception will be poor.

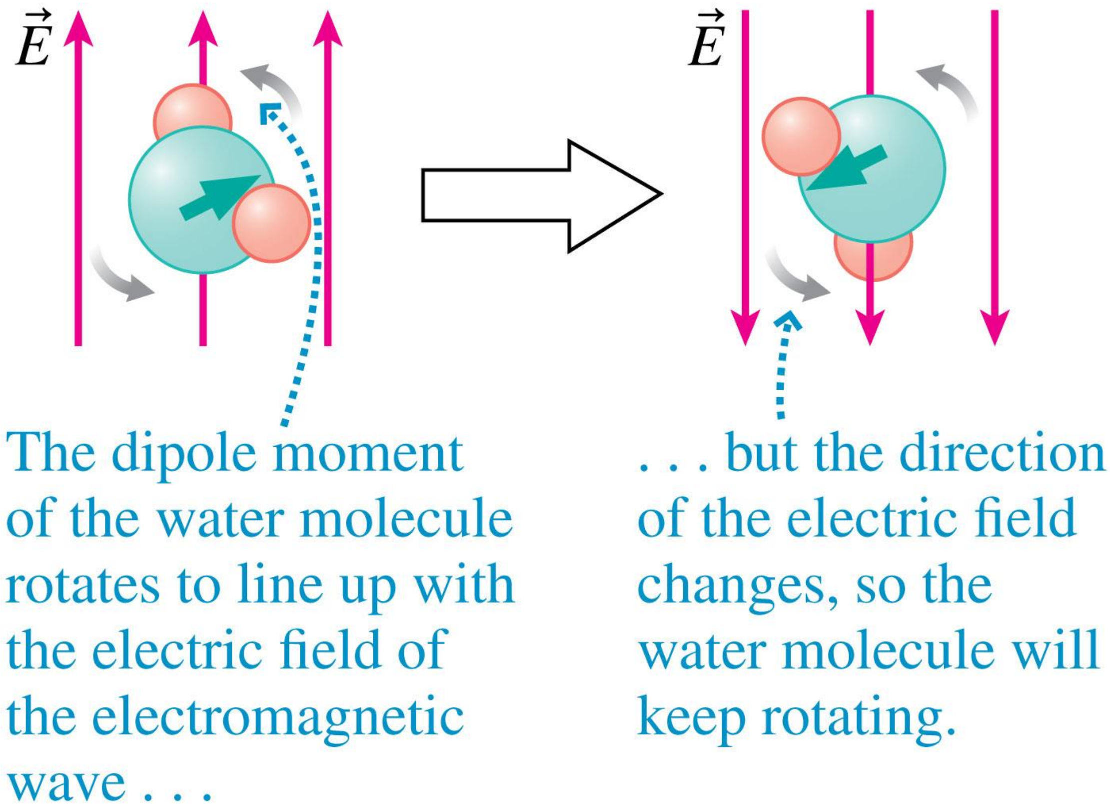
Try It Yourself: Unwanted Transmissions



Airplane passengers are asked to turn off all portable electronic devices during takeoff and landing. To see why, hold an AM radio near your computer and adjust the tuning as the computer performs basic operations, such as opening files. You will pick up intense static because the rapid switching of voltages in circuits causes computers—and other electronic devices—to emit radio waves, whether they're designed for communications or not. These electromagnetic waves could interfere with the airplane's electronics.

Radio Waves and Microwaves

- In materials with no free charges, the electric fields of radio waves and microwaves can still interact with matter by exerting a torque on molecules.



Radio Waves and Microwaves

- Water molecules have a large dipole moment.
- They rotate in response to the electric field of the microwaves in a microwave oven.
- The molecules transfer the rotational energy to the food in the microwave via molecular collisions, warming the food.

Infrared, Visible Light, and Ultraviolet

- The oscillating charges in an antenna that produce radio waves are replaced by individual atoms when producing the higher frequencies of infrared, visible light, and ultraviolet.
- This portion of the electromagnetic spectrum is *atomic radiation*.

Infrared, Visible Light, and Ultraviolet

- Nearly all atomic radiation in our environment is thermal radiation due to the thermal motion of the atoms in an object.
- Thermal radiation is described be Stefan's law: If heat Q is radiated in a time interval Δt by an object with a surface area A and temperature T, the *rate* of heat transfer is

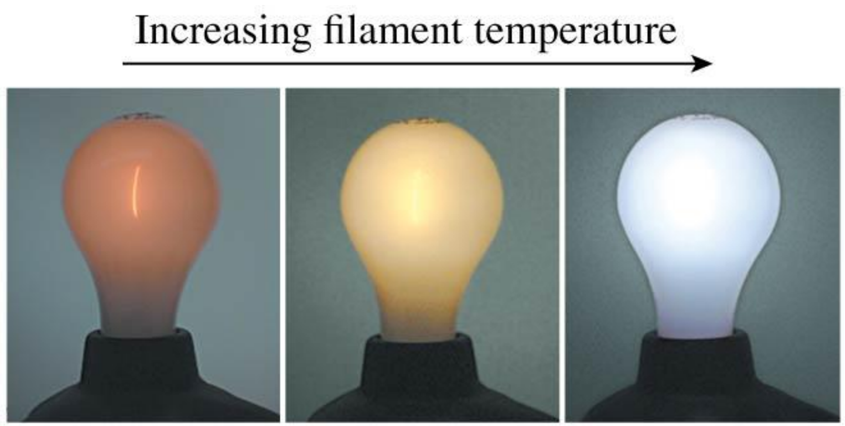
$$\frac{Q}{\Delta t} = e\sigma A T^4$$

- e is the object's emissivity, a measure of its efficiency at emitting electromagnetic waves and σ is the Stefan-Boltzman constant:

$$\sigma = 5.67 \times 10^{-8} \text{ W/(m}^2 \cdot \text{K}^4\text{)}.$$

Infrared, Visible Light, and Ultraviolet

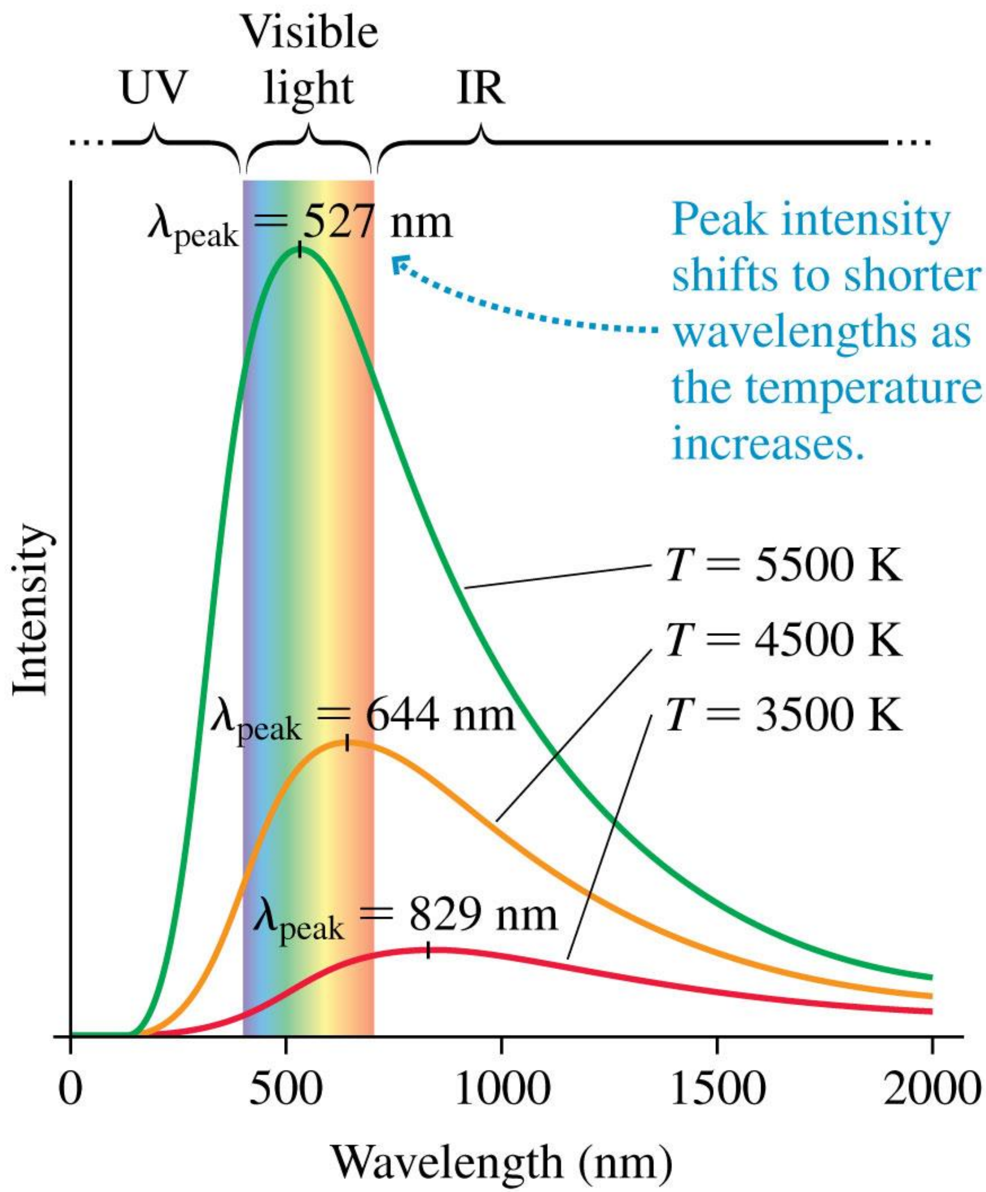
- With increasing temperature (and therefore total energy), the brightness of a bulb increases.
- The *color* of the emitted radiation changes as well.



- **The spectrum of thermal radiation changes with temperature.**

Infrared, Visible Light, and Ultraviolet

- The intensity of thermal radiation as a function of wavelength for an object at three different temperatures is shown below.



Infrared, Visible Light, and Ultraviolet

- Increasing the temperature increases the intensity of the wavelengths. **Making the object hotter causes it to emit more radiation across the entire spectrum.**
- Increasing the temperature causes the peak intensity to shift to a shorter wavelength. **The higher the temperature, the shorter the wavelength of the peak of the spectrum.**
- The temperature dependence of the peak wavelength is known as *Wien's law:*

$$\lambda_{\text{peak}}\,(\text{in nm}) = \frac{2.9 \times 10^6\ \text{nm} \cdot \text{K}}{T\,(\text{in K})}$$

Wien's law for the peak wavelength of a thermal emission spectrum

Example 25.11 Finding peak wavelengths

What are the wavelengths of peak intensity and the corresponding spectral regions for radiating objects at (a) normal human body temperature of 37°C, (b) the temperature of the filament in an incandescent lamp, 1500°C, and (c) the temperature of the surface of the sun, 5800 K?

PREPARE All of the objects emit thermal radiation, so the peak wavelengths are given by Equation 25.24.

Example 25.11 Finding peak wavelengths (cont.)

SOLVE First, we convert temperatures to kelvin. The temperature of the human body is $T = 37 + 273 = 310$ K, and the filament temperature is $T = 1500 + 273 = 1773$ K. Equation 25.24 then gives the wavelengths of peak intensity as

Example 25.11 Finding peak wavelengths (cont.)

$$\text{a. } \lambda_{\text{peak}}(\text{body}) = \frac{2.9 \times 10^6 \text{ nm} \cdot \text{K}}{310 \text{ K}} = 9.4 \times 10^3 \text{ nm} = 9.4\ \mu\text{m}$$

$$\text{b. } \lambda_{\text{peak}}(\text{filament}) = \frac{2.9 \times 10^6 \text{ nm} \cdot \text{K}}{1773 \text{ K}} = 1600 \text{ nm}$$

$$\text{c. } \lambda_{\text{peak}}(\text{sun}) = \frac{2.9 \times 10^6 \text{ nm} \cdot \text{K}}{5800 \text{ K}} = 500 \text{ nm}$$

Example 25.11 Finding peak wavelengths (cont.)

ASSESS The peak of the emission curve at body temperature is far into the infrared region of the spectrum, well below the range of sensitivity of human vision. You don't see someone "glow," although people do indeed emit significant energy in the form of electromagnetic waves, as we saw in Chapter 12.

Example 25.11 Finding peak wavelengths (cont.)

The sun's emission peaks right in the middle of the visible spectrum, which seems reasonable. Interestingly, most of the energy radiated by an incandescent bulb is *not* visible light. The tail of the emission curve extends into the visible region, but the peak of the emission curve—and most of the emitted energy—is in the infrared region of the spectrum. A 100 W bulb emits only a few watts of visible light.

QuickCheck 25.20

A brass plate at room temperature (300 K) radiates 10 W of energy. If its temperature is raised to 600 K, it will radiate

A. 10 W
B. 20 W
C. 40 W
D. 80 W
E. 160 W

Slide 25-204

QuickCheck 25.20

A brass plate at room temperature (300 K) radiates 10 W of energy. If its temperature is raised to 600 K, it will radiate

A. 10 W

B. 20 W

C. 40 W

D. 80 W

✔ E. 160 W   Radiated power $\propto T^4$

Slide 25-205

QuickCheck 25.21

A brass plate at room temperature (300 K) radiates 10 W of energy. If its temperature is raised to 600 K, the wavelength of maximum radiated intensity

A. Increases.
B. Decreases.
C. Remains the same.
D. Not enough information to tell.

Slide 25-206

QuickCheck 25.21

A brass plate at room temperature (300 K) radiates 10 W of energy. If its temperature is raised to 600 K, the wavelength of maximum radiated intensity

A. Increases.

✔ B. Decreases.

$$\lambda_{\text{peak}} \propto \frac{1}{T}$$

C. Remains the same.

D. Not enough information to tell.

Slide 25-207

Example 25.12 Finding the photon energy for ultraviolet light

Ultraviolet radiation with a wavelength of 254 nm is used in germicidal lamps. What is the photon energy in eV for such a lamp?

Example 25.12 Finding the photon energy for ultraviolet light (cont.)

SOLVE The photon energy is $E = hf$:

$$E = hf = \frac{hc}{\lambda} = \frac{(6.63 \times 10^{-34}\ \text{J} \cdot \text{s})(3.00 \times 10^{8}\ \text{m/s})}{254 \times 10^{-9}\ \text{m}}$$
$$= 7.83 \times 10^{-19}\ \text{J}$$

In eV, this is

$$E = 7.83 \times 10^{-19}\ \text{J} \times \frac{1\ \text{eV}}{1.60 \times 10^{-19}\ \text{J}} = 4.89\ \text{eV}$$

Example 25.12 Finding the photon energy for ultraviolet light (cont.)

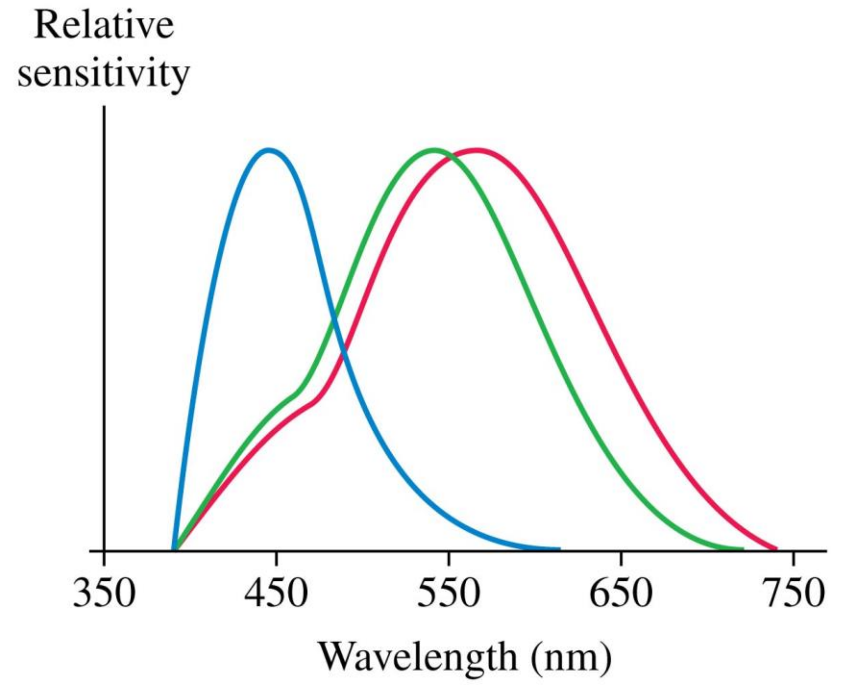
ASSESS Table 25.1 shows that this energy is sufficient to break the bonds in a water molecule. It will be enough energy to break other bonds as well, leading to damage on a cellular level.

Example Problem

A typical digital cell phone emits radio waves with a frequency of 1.9 GHz. What is the wavelength, and what is the energy of individual photons? If the phone emits 0.60 W, how many photons are emitted each second?

Color Vision

- The color-sensitive cells in the retina of the eye, the cones, have one of three slightly different forms of light-sensitive photopigment.
- Our color vision is a result of different responses of three types of cones.

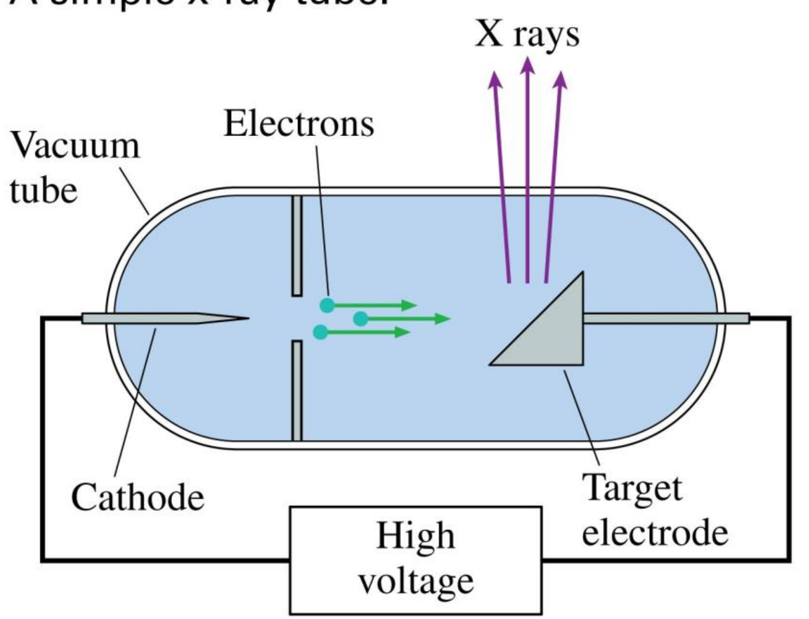


- Some animals, like chickens, have more types of cones and therefore have a keener color vision.

X Rays and Gamma Rays

- High-energy photons emitted by electrons are called x rays.
- If the source is a nuclear process, we call them gamma rays.
- X rays can be produced by emitting electrons and accelerating them in an electric field. The electrons make a sudden stop when they hit a metal target electrode, and the rapid deceleration can emit an x-ray photon.

A simple x-ray tube.



X Rays and Gamma Rays

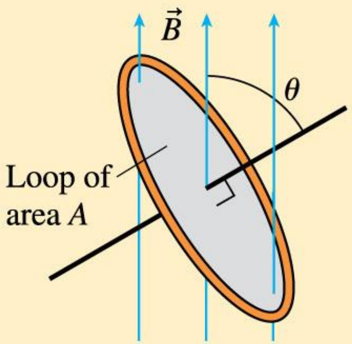
- X rays and gamma rays (and some ultraviolet rays) are **ionizing radiation**; the individual photons have enough energy to ionize atoms.
- When such radiation strikes tissue, the resulting ionization can produce cellular damage.

Summary: General Principles

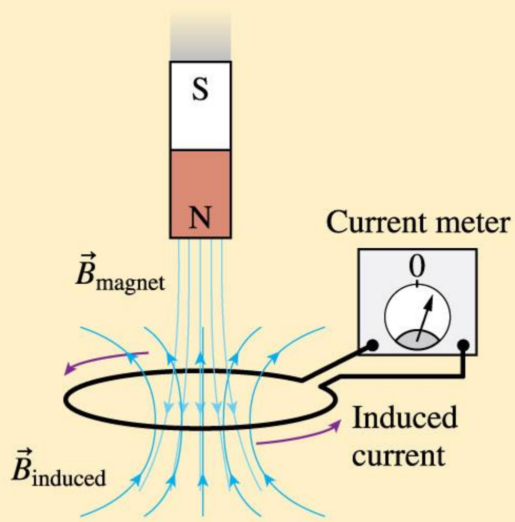
Electromagnetic Induction

The **magnetic flux** measures the amount of magnetic field passing through a surface:

$$\Phi = AB\cos\theta$$



Lenz's law specifies that there is an induced current in a closed conducting loop if the magnetic flux through the loop is changing. The direction of the induced current is such that the induced magnetic field opposes the *change* in flux.



Faraday's law specifies the magnitude of the induced emf in a closed loop:

$$\mathcal{E} = \left|\frac{\Delta\Phi}{\Delta t}\right|$$

Multiply by N for an N-turn coil.

The size of the induced current is

$$I = \frac{\mathcal{E}}{R}$$

Text: p. 831

Summary: General Principles

Electromagnetic Waves

An electromagnetic wave is a self-sustaining oscillation of electric and magnetic fields.

- The wave is a transverse wave with $\vec{E}$, $\vec{B}$, and $\vec{v}$ mutually perpendicular.
- The wave propagates with speed

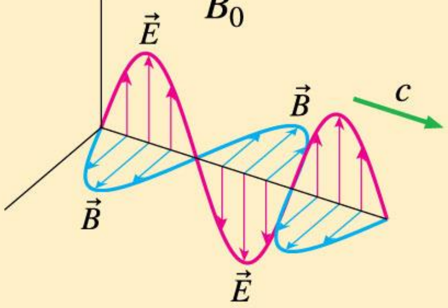
$$v_{em} = c = \frac{1}{\sqrt{\epsilon_0 \mu_0}} = 3.00 \times 10^8 \text{ m/s}$$

- The wavelength, frequency, and speed are related by

$$c = \lambda f$$

- The amplitudes of the fields are related by

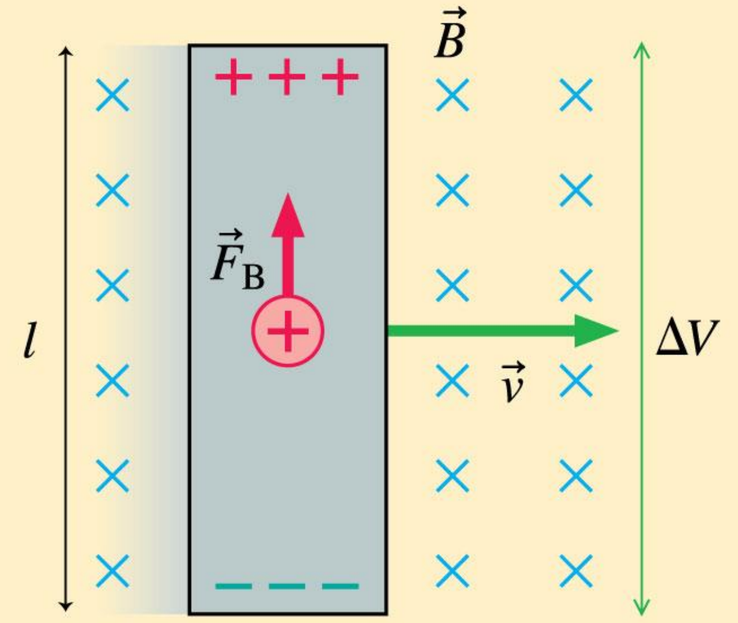
$$\frac{E_0}{B_0} = c$$



Text: p. 831

Summary: Important Concepts

Motional emf



The motion of a conductor through a magnetic field produces a force on the charges. The separation of charges leads to an emf:

$$\mathcal{E} = vlB$$

Text: p. 831

Summary: Important Concepts

The photon model

Electromagnetic waves appear to be made of discrete units called photons. The energy of a photon of frequency f is

$$E = hf$$

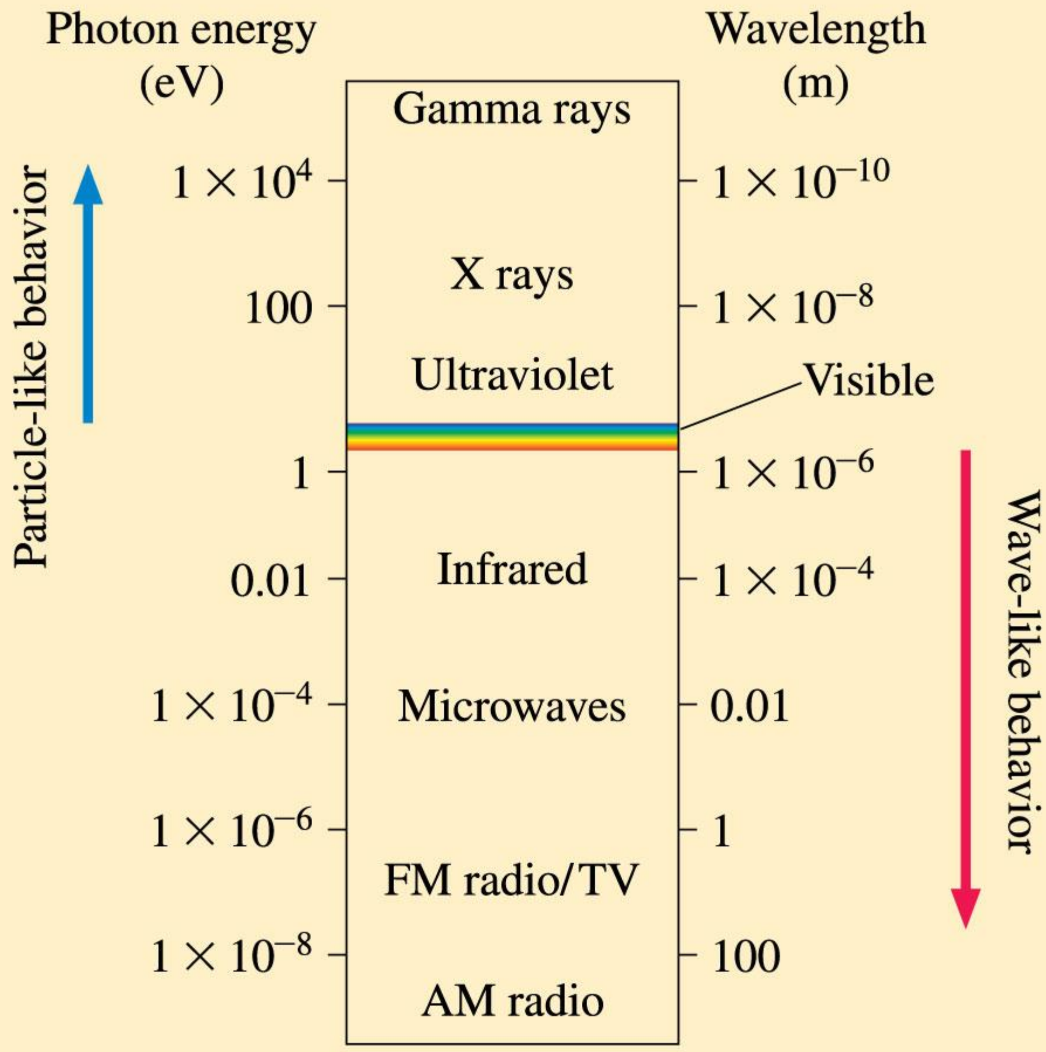
This photon view becomes increasingly important as the photon energy increases.

Text: p. 831

Summary: Important Concepts

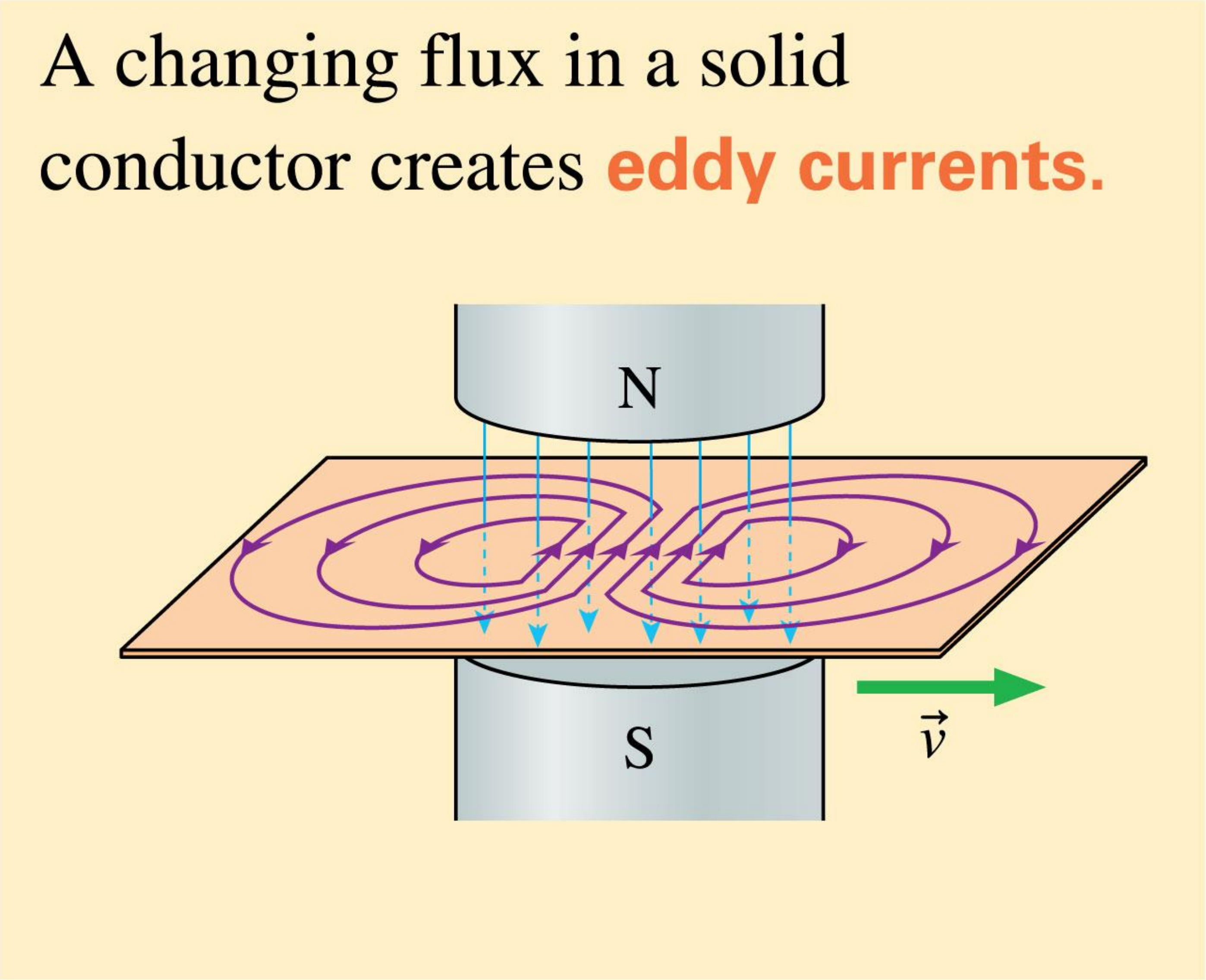
The electromagnetic spectrum

Electromagnetic waves come in a wide range of wavelengths and photon energies.



Text: p. 831

Summary: Applications



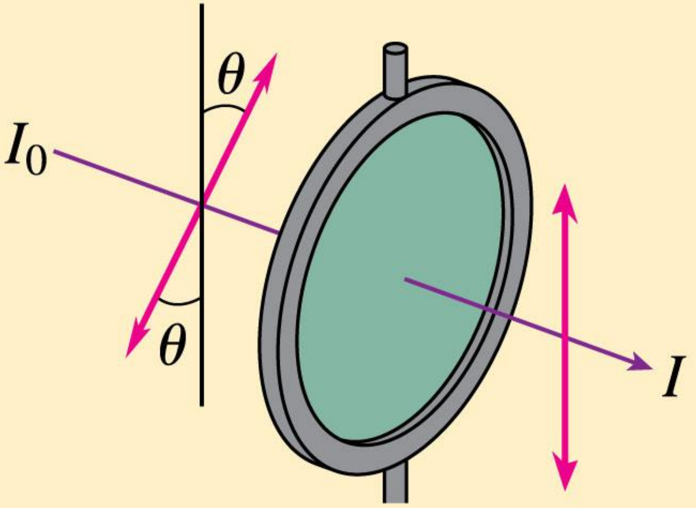
Text: p. 831

Summary: Applications

The plane of the electric field of an electromagnetic wave defines its **polarization.** The intensity of polarized light transmitted through a polarizing filter is given by **Malus's law:**

$$I = I_0 \cos^2 \theta$$

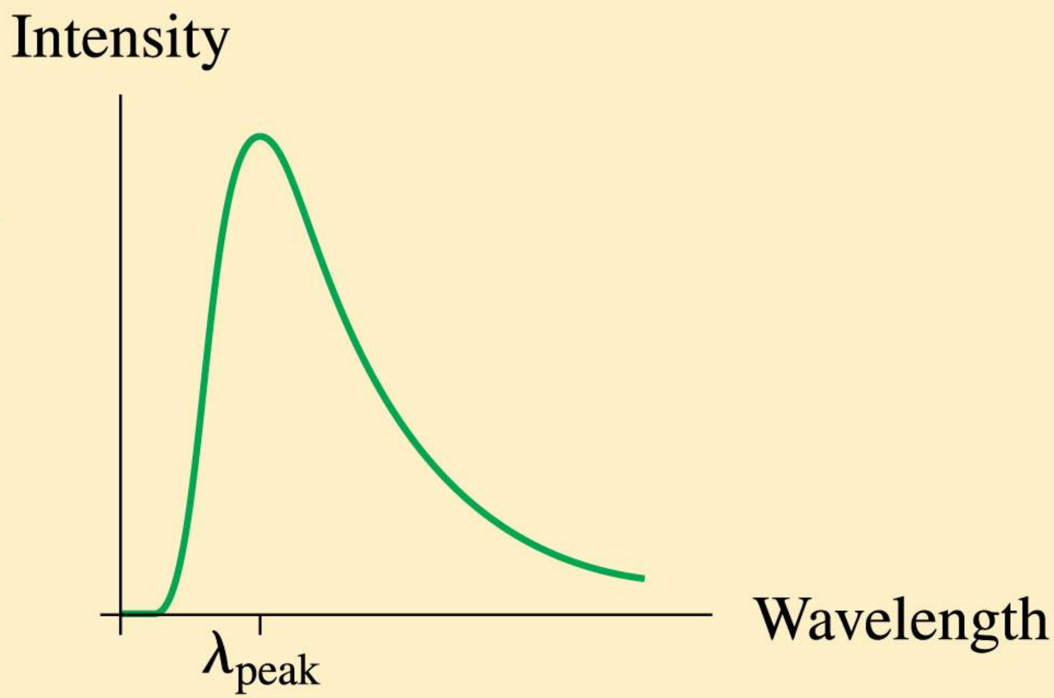
where θ is the angle between the electric field and the polarizer axis.



Text: p. 831

Summary: Applications

Thermal radiation has a peak wavelength that depends on an object's temperature according to **Wien's law:**



$$\lambda_{peak}\,(\text{in nm}) = \frac{2.9 \times 10^6\ \text{nm} \cdot \text{K}}{T}$$

Text: p. 831

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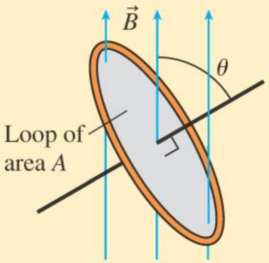

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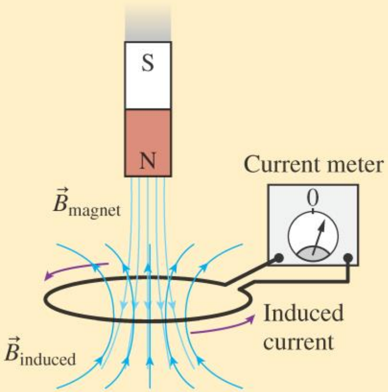

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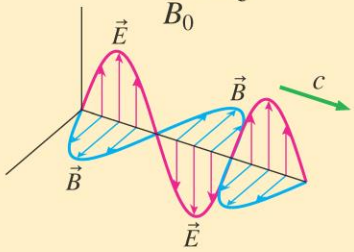
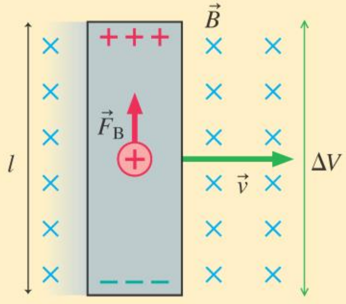


Text: p. 831

Summary

IMPORTANT CONCEPTS

Motional emf



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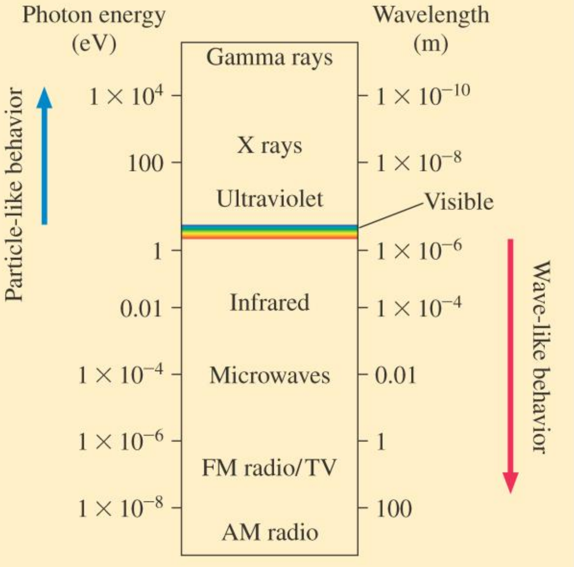

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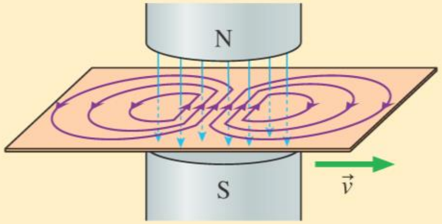
Summary

APPLICATIONS

A changing flux in a solid conductor creates **eddy currents.**



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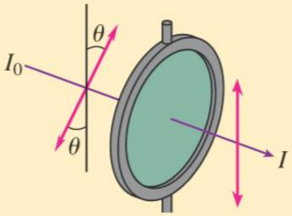

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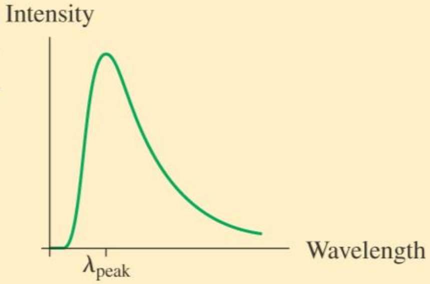

$$\lambda_{peak}\,(\text{in nm}) = \frac{2.9 \times 10^6\ \text{nm} \cdot \text{K}}{T}$$

Text: p. 831