

## Chapter 33

# Electromagnetic Waves

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## 33-1 Electromagnetic Waves

### Learning Objectives

- 33.01** In the electromagnetic spectrum, identify the relative wavelengths (longer or shorter) of AM radio, FM radio, television, infrared light, visible light, ultraviolet light, x rays, and gamma rays.
- 33.02** Describe the transmission of an electromagnetic wave by an LC oscillator and an antenna.
- 33.03** For a transmitter with an LC oscillator, apply the relationships between the oscillator's inductance  $L$ , capacitance  $C$ , and angular frequency  $\omega$ , and the emitted wave's frequency  $f$  and wavelength  $\lambda$ .
- 33.04** Identify the speed of an electromagnetic wave in vacuum (and approximately in air).
- 33.05** Identify that electromagnetic waves do not require a medium and can travel through vacuum.
- 33.06** Apply the relationship between the speed of an electromagnetic wave, the straight-line distance traveled by the wave, and the time required for the travel.

## 33-1 Electromagnetic Waves

### Learning Objectives (Contd.)

- 33.07** Apply the relationships between an electromagnetic wave's frequency  $f$ , wavelength  $\lambda$ , period  $T$ , angular frequency  $\omega$ , and speed  $c$ .
- 33.08** Identify that an electromagnetic wave consists of an electric component and a magnetic component that are (a) perpendicular to the direction of travel, (b) perpendicular to each other, and (c) sinusoidal waves with the same frequency and phase.
- 33.09** Apply the sinusoidal equations for the electric and magnetic components of an EM wave, written as functions of position and time.
- 33.10** Apply the relationship between the speed of light  $c$ , the permittivity constant  $\epsilon_0$ , and the permeability constant  $\mu_0$ .
- 33.11** For any instant and position, apply the relationship between the electric field magnitude  $E$ , the magnetic field magnitude  $B$ , and the speed of light  $c$ .

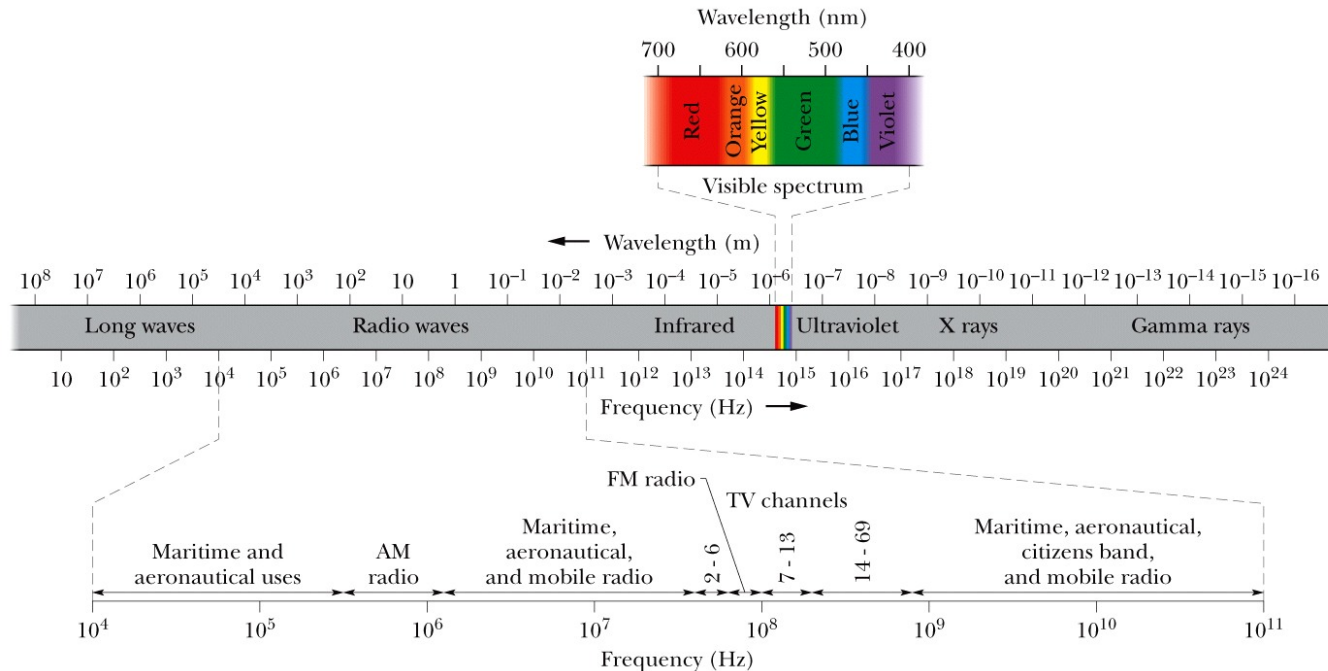
## 33-1 Electromagnetic Waves

### Learning Objectives (Contd.)

**33.12** Describe the derivation of the relationship between the speed of light  $c$  and the ratio of the electric field amplitude  $E$  to the magnetic field amplitude  $B$ .

# 33-1 Electromagnetic Waves

## Maxwell's Rainbow

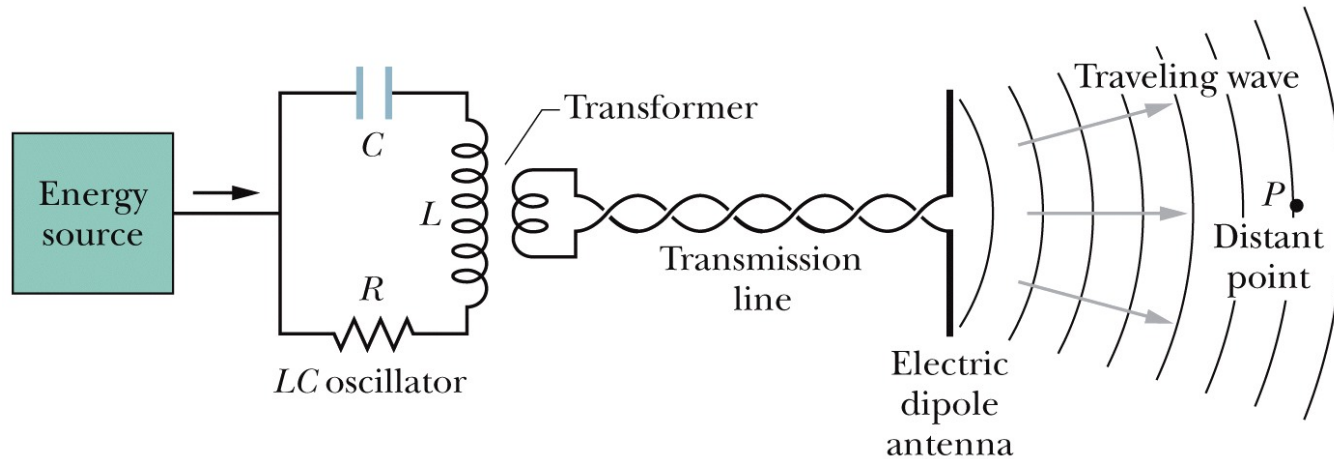


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In Maxwell's time (the mid 1800s), the visible, infrared, and ultraviolet forms of light were the only electromagnetic waves known. Spurred on by Maxwell's work, however, Heinrich Hertz discovered what we now call radio waves and verified that they move through the laboratory at the same speed as visible light, indicating that they have the same basic nature as visible light. As the figure shows, we now know a wide spectrum (or range) of electromagnetic waves: Maxwell's rainbow.

## 33-1 Electromagnetic Waves

### Travelling Electromagnetic Wave



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An arrangement for generating a traveling electromagnetic wave in the shortwave radio region of the spectrum: an LC oscillator produces a sinusoidal current in the antenna, which generates the wave. P is a distant point at which a detector can monitor the wave traveling past it.

# 33-1 Electromagnetic Waves

## Travelling Electromagnetic Wave

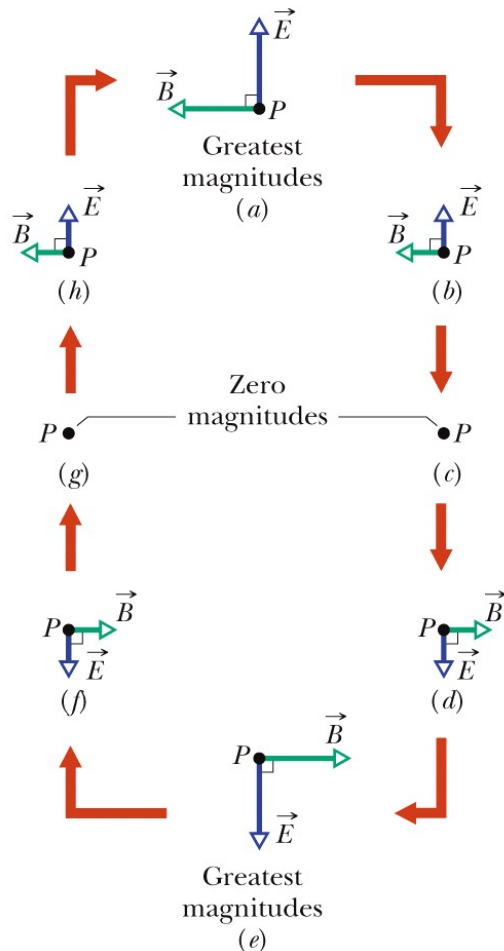
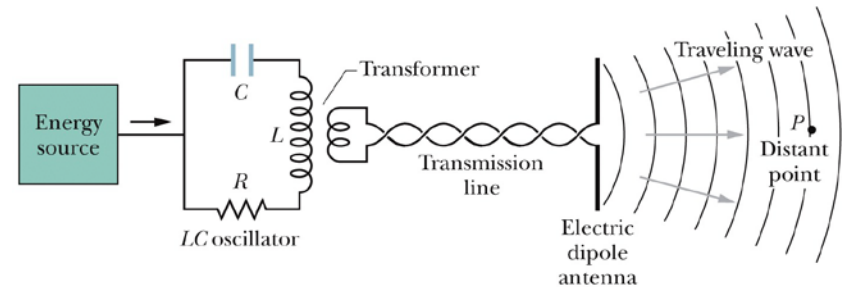


Figure 1

Figure 2



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**Electromagnetic Wave.** Figure 1 shows how the electric field  $\vec{E}$  and the magnetic field  $\vec{B}$  change with time as one wavelength of the wave sweeps past the distant point  $P$  of Fig. 2 ; in each part of Fig. 1, the wave is traveling directly out of the page. (We choose a distant point so that the curvature of the waves suggested in Fig. 2 is small enough to neglect. At such points, the wave is said to be a plane wave, and discussion of the wave is much simplified.) Note several key features in Fig. 2; they are present regardless of how the wave is created:

# 33-1 Electromagnetic Waves

## Travelling Electromagnetic Wave

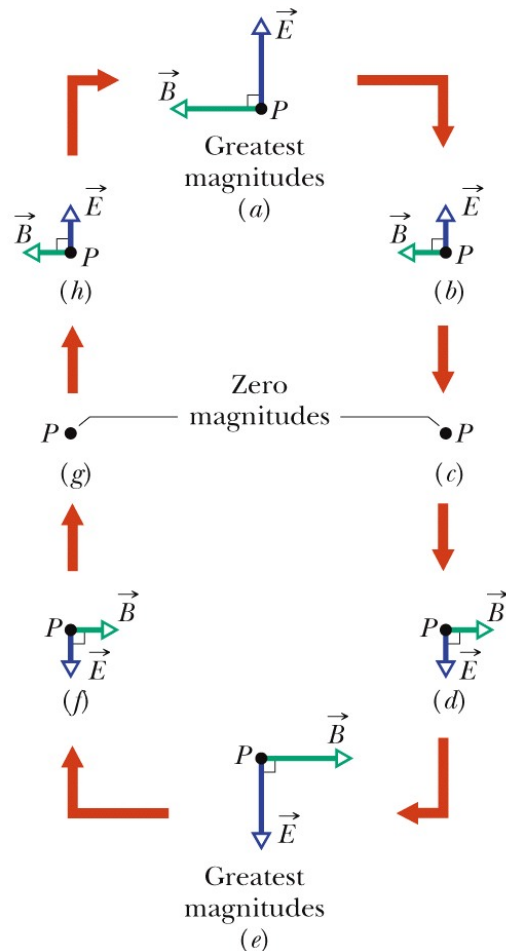
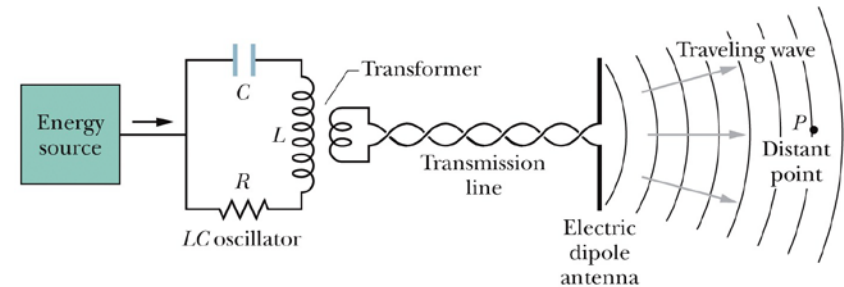


Figure 1

Figure 2



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1. The electric and magnetic fields  $\vec{E}$  and  $\vec{B}$  are always perpendicular to the direction in which the wave is traveling. Thus, the wave is a transverse wave, as discussed in Chapter 16.
2. The electric field is always perpendicular to the magnetic field.
3. The cross product  $\vec{E} \times \vec{B}$  always gives the direction in which the wave travels.
4. The fields always vary sinusoidally, just like the transverse waves discussed in Chapter 16. Moreover, the fields vary with the same frequency and in phase (in step) with each other.



# 33-1 Electromagnetic Waves

## Travelling Electromagnetic Wave

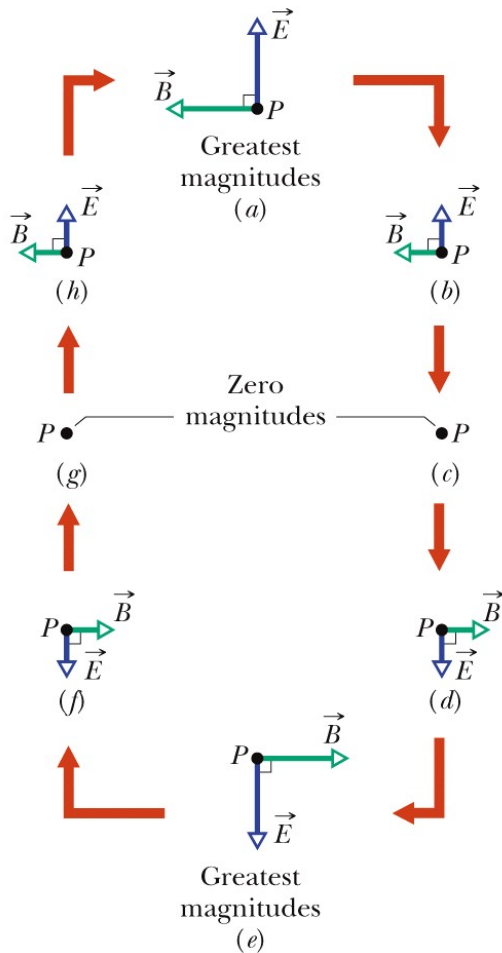
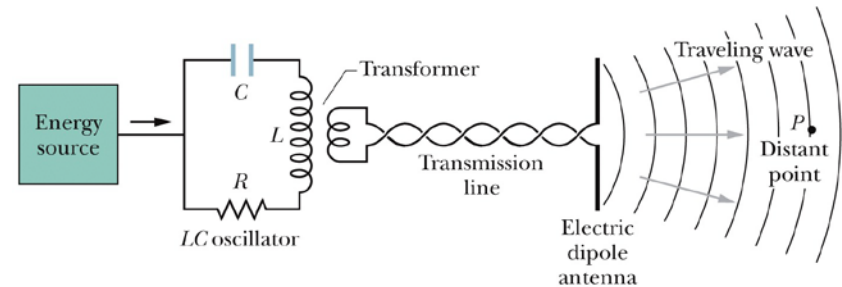


Figure 1

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Figure 2



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In keeping with these features, we can deduce that an electromagnetic wave traveling along an  $x$  axis has an electric field  $\mathbf{E}$  and a magnetic field  $\mathbf{B}$  with magnitudes that depend on  $x$  and  $t$ :

$$E = E_m \sin(kx - \omega t),$$

$$B = B_m \sin(kx - \omega t),$$

where  $E_m$  and  $B_m$  are the amplitudes of  $\mathbf{E}$  and  $\mathbf{B}$ . The electric field induces the magnetic field and vice versa.

# 33-1 Electromagnetic Waves

## Travelling Electromagnetic Wave

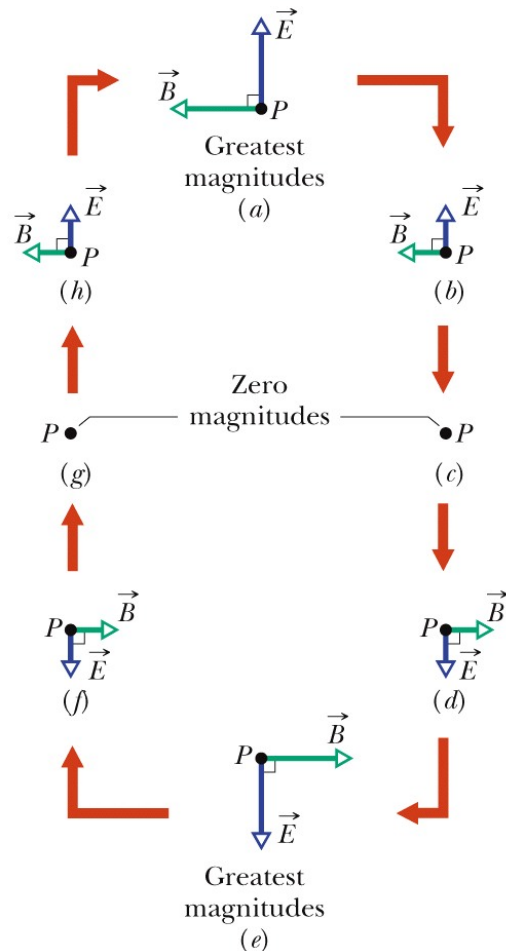
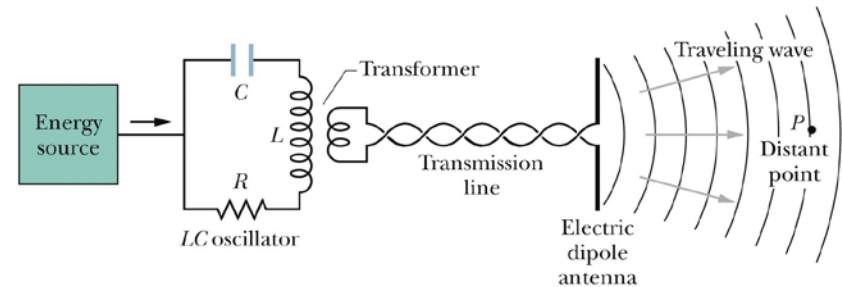


Figure 1

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Figure 2



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**Wave Speed.** From chapter 16 (Eq. 16-13), we know that the speed of the wave is  $\omega/k$ . However, because this is an electromagnetic wave, its speed (in vacuum) is given the symbol  $c$  rather than  $v$  and that  $c$  has the value given by

$$c = \frac{1}{\sqrt{\mu_0 \epsilon_0}} \quad (\text{wave speed}),$$

which is about  $3.0 \times 10^8$  m/s. In other words,



All electromagnetic waves, including visible light, have the same speed  $c$  in vacuum.

## 33-2 Energy Transport and The Poynting Vector

### Learning Objectives

- 33.13** Identify that an electromagnetic wave transports energy.
- 33.14** For a target, identify that an EM wave's rate of energy transport per unit area is given by the Poynting vector  $\mathbf{S}$ , which is related to the cross product of the electric field  $\mathbf{E}$  and magnetic field  $\mathbf{B}$ .
- 33.15** Determine the direction of travel (and thus energy transport) of an electromagnetic wave by applying the cross product for the corresponding Poynting vector.
- 33.16** Calculate the instantaneous rate  $S$  of energy flow of an EM wave in terms of the instantaneous electric field magnitude  $E$ .
- 33.17** For the electric field component of an electromagnetic wave, relate the *rms* value  $E_{rms}$  to the amplitude  $E_m$ .
- 33.18** Identify an EM wave's intensity  $I$  in terms of energy transport.
- 33.19** Apply the relationships between an EM wave's intensity  $I$  and the electric field's *rms* value  $E_{rms}$  and amplitude  $E_m$ .

## 33-2 Energy Transport and The Poynting Vector

### Learning Objectives (Contd.)

- 33.19** Apply the relationships between an EM wave's intensity  $I$  and the electric field's *rms* value  $E_{rms}$  and amplitude  $E_m$ .
- 33.20** Apply the relationship between average power  $P_{avg}$ , energy transfer  $\Delta E$ , and the time  $\Delta t$  taken by that transfer, and apply the relationship between the instantaneous power  $P$  and the rate of energy transfer  $dE/dt$ .
- 33.21** Identify an isotropic point source of light.
- 33.22** For an isotropic point source of light, apply the relationship between the emission power  $P$ , the distance  $r$  to a point of measurement, and the intensity  $I$  at that point.
- 33.23** In terms of energy conservation, explain why the intensity from an isotropic point source of light decreases as  $1/r^2$ .

## 33-2 Energy Transport and The Poynting Vector

**The Poynting Vector:** The rate per unit area at which energy is transported via an electromagnetic wave is given by the Poynting vector

$$\vec{S} = \frac{1}{\mu_0} \vec{E} \times \vec{B}$$



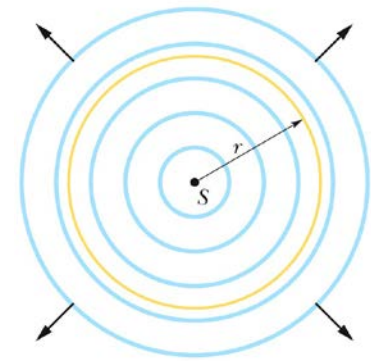
The direction of the Poynting vector  $\vec{S}$  of an electromagnetic wave at any point gives the wave's direction of travel and the direction of energy transport at that point.

The time-averaged rate per unit area at which energy is transported is  $S_{avg}$ , which is called the intensity  $I$  of the wave:

$$I = \frac{1}{c\mu_0} E_{rms}^2$$

in which  $E_{rms} = E_m / \sqrt{2}$ .

The energy emitted by light source  $S$  must pass through the sphere of radius  $r$ .



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A point source of electromagnetic waves emits the waves isotropically—that is, with equal intensity in all directions. The intensity of the waves at distance  $r$  from a point source of power  $P_s$  is

$$I = \frac{\text{power}}{\text{area}} = \frac{P_s}{4\pi r^2},$$

## 33-3 Radiation Pressure

### Learning Objectives

**33.24** Distinguish between force and pressure.

**33.25** Identify that an electromagnetic wave transports momentum and can exert a force and a pressure on a target.

**33.26** For a uniform electromagnetic beam that is perpendicular to a target area, apply the relationships between that area, the wave's intensity, and the force on the target, for both total absorption and total backward reflection.

**33.27** For a uniform electromagnetic beam that is perpendicular to a target area, apply the relationships between the wave's intensity and the pressure on the target, for both total absorption and total backward reflection.

## 33-3 Radiation Pressure

When a surface intercepts electromagnetic radiation, a force and a pressure are exerted on the surface.

If the radiation is totally absorbed by the surface, the force is

$$F = \frac{IA}{c} \quad \textit{Total Absorption}$$

in which  $I$  is the intensity of the radiation and  $A$  is the area of the surface perpendicular to the path of the radiation.

If the radiation is totally reflected back along its original path, the force is

$$F = \frac{2IA}{c} \quad \textit{Total Reflection back along path}$$

The **radiation pressure**  $p_r$  is the force per unit area:

$$p_r = \frac{I}{c} \quad \textit{Total Absorption}$$

and

$$p_r = \frac{2I}{c} \quad \textit{Total Reflection back along path}$$



## 33-4 Polarization

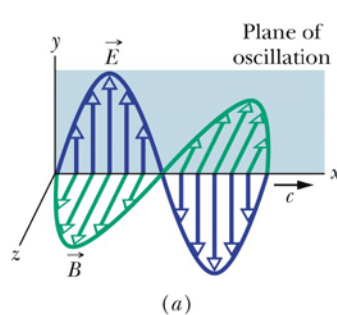
### Learning Objectives

- 33.28** Distinguish between polarized light and unpolarized light.
- 33.29** For a light beam headed toward you, sketch representations of polarized light and unpolarized light.
- 33.30** When a beam is sent into a polarizing sheet, explain the function of the sheet in terms of its polarizing direction (or axis) and the electric field component that is absorbed and the component that is transmitted.
- 33.31** For light that emerges from a polarizing sheet, identify its polarization relative to the sheet's polarizing direction.
- 33.32** For a light beam incident perpendicularly on a polarizing sheet, apply the one-half rule and the cosine-squared rule, distinguishing their uses.
- 33.33** Distinguish between a polarizer and an analyzer.
- 33.34** Explain what is meant if two sheets are crossed.
- 33.35** When a beam is sent into a system of polarizing sheets, work through the sheets one by one, finding the transmitted intensity and polarization.

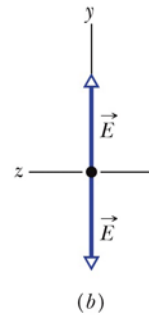


## 33-4 Polarization

Electromagnetic waves are polarized if their electric field vectors are all in a single plane, called the plane of oscillation. Light waves from common sources are not polarized; that is, they are unpolarized, or polarized randomly.

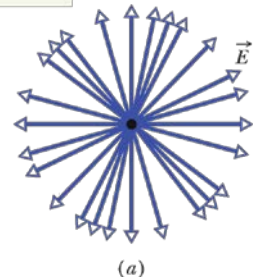


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Vertically polarized light headed toward you—the electric fields are all vertical.

Unpolarized light headed toward you—the electric fields are in all directions in the plane.



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An electric field component parallel to the polarizing direction is passed (*transmitted*) by a polarizing sheet; a component perpendicular to it is absorbed.

If the original light is initially unpolarized, the transmitted intensity  $I$  is half the original intensity  $I_0$ :

$$I = \frac{1}{2}I_0 \quad (\text{one-half rule}).$$

If the original light is initially polarized, the transmitted intensity depends on the angle  $\theta$  between the polarization direction of the original light and the polarizing direction of the sheet:

$$I = I_0 \cos^2 \theta \quad (\text{cosine-squared rule}).$$

## 33-5 Reflection and Refraction

### Learning Objectives

- 33.36** With a sketch, show the reflection of a light ray from an interface and identify the incident ray, the reflected ray, the normal, the angle of incidence, and the angle of reflection.
- 33.37** Relate the angle of incidence and the angle of reflection.
- 33.38** With a sketch, show the refraction of a light ray at an interface and identify the incident ray, the refracted ray, the normal on each side of the interface, the angle of incidence, and the angle of refraction.
- 33.39** For refraction of light, apply Snell's law to relate the index of refraction and the angle of the ray on one side of the interface to those quantities on the other side.
- 33.40** In a sketch and using a line along the undeflected direction, show the refraction of light from one material into a second material that has a greater index, a smaller index, and the same index, and, for each situation, describe the refraction in terms of the ray being bent toward the normal, away from the normal, or not at all.

## 33-5 Reflection and Refraction

### Learning Objectives (Contd.)

**33.41** Identify that refraction occurs only at an interface and not in the interior of a material.

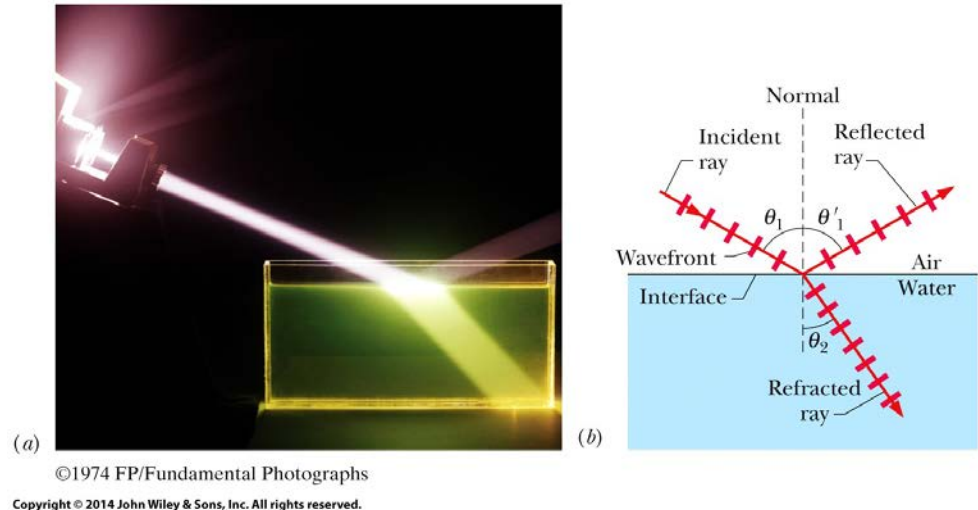
**33.42** Identify chromatic dispersion.

**33.43** For a beam of red and blue light (or other colors) refracting at an interface, identify which color has the greater bending and which has the greater angle of refraction when they enter a material with a lower index than the initial material and a greater index.

**33.44** Describe how the primary and secondary rainbows are formed and explain why they are circular arcs.

## 33-5 Reflection and Refraction

- (a) A photograph showing an incident beam of light reflected and refracted by a horizontal water surface.
- (b) A ray representation of (a). The angles of incidence ( $\theta_1$ ), reflection ( $\theta'_1$ ), and refraction ( $\theta_2$ ) are marked.



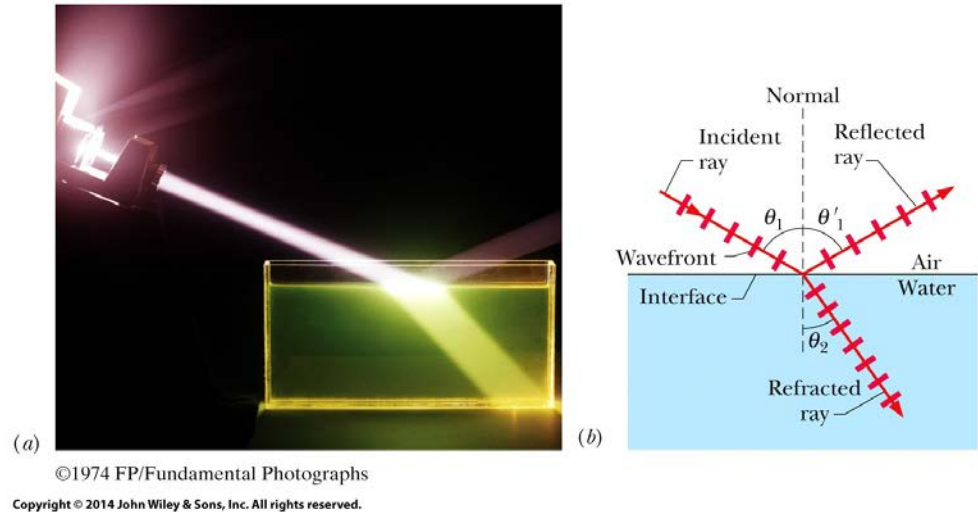
When a light ray encounters a boundary between two transparent media, a reflected ray and a refracted ray generally appear as shown in figure above.

**Law of reflection:** A reflected ray lies in the plane of incidence and has an angle of reflection equal to the angle of incidence (both relative to the normal). In Fig. (b), this means that

$$\theta'_1 = \theta_1 \quad (\text{reflection}).$$

## 33-5 Reflection and Refraction

- (a) A photograph showing an incident beam of light reflected and refracted by a horizontal water surface.
- (b) A ray representation of (a). The angles of incidence ( $\theta_1$ ), reflection ( $\theta'_1$ ), and refraction ( $\theta_2$ ) are marked.

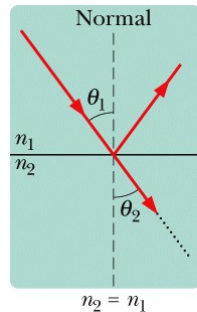


**Law of refraction:** A refracted ray lies in the plane of incidence and has an angle of refraction  $\theta_2$  that is related to the angle of incidence  $\theta_1$  by

$$n_2 \sin \theta_2 = n_1 \sin \theta_1$$

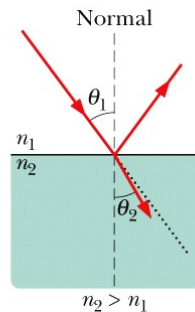
Here each of the symbols  $n_1$  and  $n_2$  is a dimensionless constant, called the **index of refraction**, that is associated with a medium involved in the refraction.

## 33-5 Reflection and Refraction



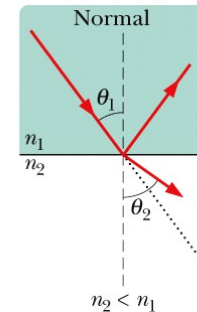
(a)

If the indexes match, there is no direction change.



(b)

If the next index is greater, the ray is bent *toward* the normal.



(c)

If the next index is less, the ray is bent *away from* the normal.

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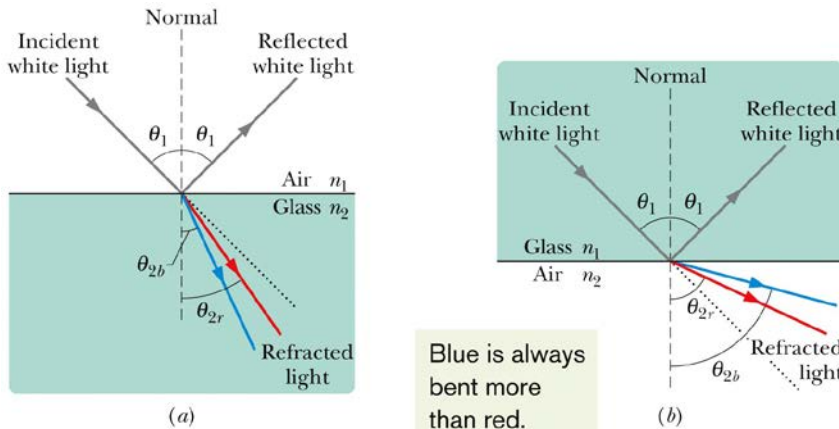
$$n_2 \sin \theta_2 = n_1 \sin \theta_1$$

1. If  $n_2$  is equal to  $n_1$ , then  $\theta_2$  is equal to  $\theta_1$  and refraction does not bend the light beam, which continues in the undeflected direction, as in Fig. (a).
2. If  $n_2$  is greater than  $n_1$ , then  $\theta_2$  is less than  $\theta_1$ . In this case, refraction bends the light beam away from the undeflected direction and toward the normal, as in Fig. (b).
3. If  $n_2$  is less than  $n_1$ , then  $\theta_2$  is greater than  $\theta_1$ . In this case, refraction bends the light beam away from the undeflected direction and away from the normal, as in Fig. (c).



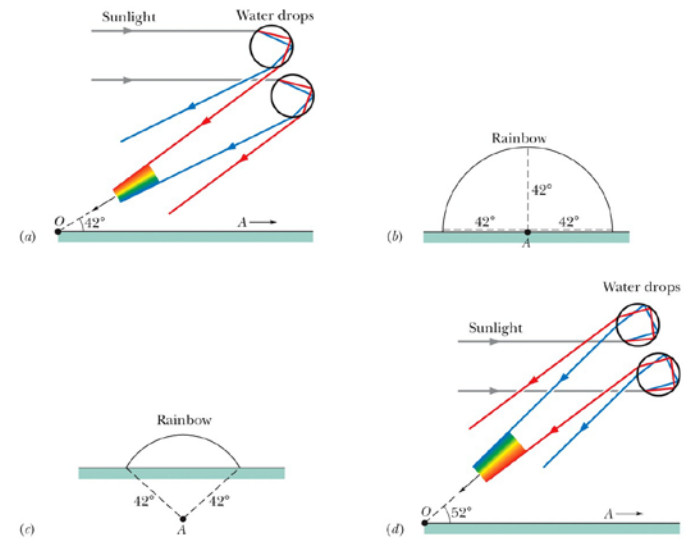
# 33-5 Reflection and Refraction

**Chromatic dispersion** of white light. The blue component is bent more than the red component. (a) Passing from air to glass, the blue component ends up with the smaller angle of refraction. (b) Passing from glass to air, the blue component ends up with the greater angle of refraction. Each dotted line represents the direction in which the light would continue to travel if it were not bent by the refraction.



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**Rainbow:** (a) The separation of colors when sunlight refracts into and out of falling raindrops leads to a primary rainbow. The *antisolar point*  $A$  is on the horizon at the right. The rainbow colors appear at an angle of  $42^\circ$  from the direction of  $A$ . (b) Drops at  $42^\circ$  from  $A$  in any direction can contribute to the rainbow. (c) The rainbow arc when the Sun is higher (and thus  $A$  is lower). (d) The separation of colors leading to a secondary rainbow.



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## 33-6 Total Internal Reflection

### Learning Objectives

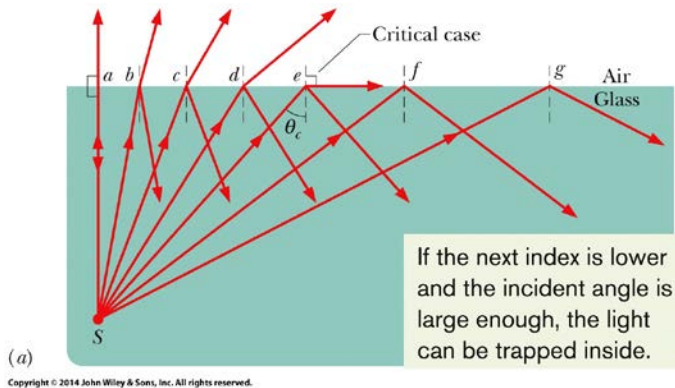
**33.45** With sketches, explain total internal reflection and include the angle of incidence, the critical angle, and the relative values of the indexes of refraction on the two sides of the interface..

**33.46** Identify the angle of refraction for incidence at a critical angle.

**33.47** For a given pair of indexes of refraction, calculate the critical angle.



## 33-6 Total Internal Refraction



Ken Kay/Fundamental Photographs

(a) Total internal reflection of light from a point source  $S$  in glass occurs for all angles of incidence greater than the critical angle  $\theta_c$ . At the critical angle, the refracted ray points along the air – glass interface. (b) A source in a tank of water.

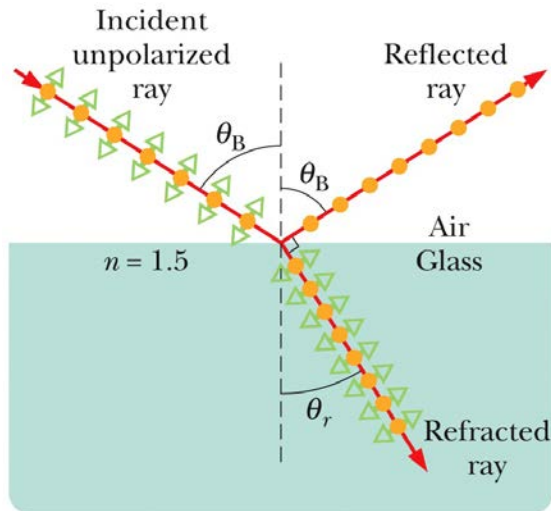
Figure (a) shows rays of monochromatic light from a point source  $S$  in glass incident on the interface between the glass and air. For ray  $a$ , which is perpendicular to the interface, part of the light reflects at the interface and the rest travels through it with no change in direction. For rays  $b$  through  $e$ , which have progressively larger angles of incidence at the interface, there are also both reflection and refraction at the interface. As the angle of incidence increases, the angle of refraction increases; for ray  $e$  it is  $90^\circ$ , which means that the refracted ray points directly along the interface. The angle of incidence giving this situation is called the **critical angle**  $\theta_c$ . For angles of incidence larger than  $\theta_c$ , such as for rays  $f$  and  $g$ , there is no refracted ray and all the light is reflected; this effect is called **total internal reflection** because all the light remains inside the glass.

## 33-7 Polarization by Reflection

### Learning Objectives

- 33.48** With sketches, explain how unpolarized light can be converted to polarized light by reflection from an interface.
- 33.49** Identify Brewster's angle.
- 33.50** Apply the relationship between Brewster's angle and the indexes of refraction on the two sides of an interface.
- 33.51** Explain the function of polarizing sunglasses.

## 33-7 Polarization by Reflection



- Component perpendicular to page
- ↔ Component parallel to page

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A ray of unpolarized light in air is incident on a glass surface at the **Brewster angle**  $\theta_B$ . The electric fields along that ray have been resolved into components perpendicular to the page (the plane of incidence, reflection, and refraction) and components parallel to the page. The reflected light consists only of components perpendicular to the page and is thus polarized in that direction. The refracted light consists of the original components parallel to the page and weaker components perpendicular to the page; this light is partially polarized.

As shown in the figure above a reflected wave will be fully polarized, with its  $\mathbf{E}$  vectors perpendicular to the plane of incidence, if it strikes a boundary at the Brewster angle  $\theta_B$ , where

$$\theta_B = \tan^{-1} \frac{n_2}{n_1} \quad (\text{Brewster angle}).$$

# 33 Summary

## Electromagnetic Waves

- An electromagnetic wave consists of oscillating electric and magnetic fields as given by,

$$E = E_m \sin(kx - \omega t) \quad \text{Eq. 33-1}$$

$$B = B_m \sin(kx - \omega t), \quad \text{Eq. 33-2}$$

- The speed of any electromagnetic wave in vacuum is  $c$ , which can be written as

$$c = \frac{E}{B} = \frac{1}{\sqrt{\mu_0 \epsilon_0}} \quad \text{Eq. 33-5\&3}$$

## Energy Flow

- The rate per unit area at which energy is transported via an electromagnetic wave is given by the Poynting vector  $\vec{S}$ :

$$\vec{S} = \frac{1}{\mu_0} \vec{E} \times \vec{B}. \quad \text{Eq. 33-19}$$

- The intensity  $I$  of the wave is:

$$I = \frac{1}{c\mu_0} E_{\text{rms}}^2 \quad \text{Eq. 33-26}$$

- The intensity of the waves at distance  $r$  from a point source of power  $P_s$  is

$$I = \frac{P_s}{4\pi r^2}. \quad \text{Eq. 33-27}$$

## Radiation Pressure

- If the radiation is totally absorbed by the surface, the force is

$$F = \frac{IA}{c} \quad \text{Eq. 33-32}$$

- If the radiation is totally absorbed by the surface, the force is

$$F = \frac{2IA}{c} \quad \text{Eq. 33-33}$$

## 33 Summary

### Radiation Pressure

- The radiation pressure  $p_r$  is the force per unit area.
- For total absorption

$$p_r = \frac{I}{c} \quad \text{Eq. 33-34}$$

- For total reflection back along path,

$$p_r = \frac{2I}{c} \quad \text{Eq. 33-35}$$

### Polarization

- Electromagnetic waves are polarized if their electric field vectors are all in a single plane, called the plane of oscillation.
- If the original light is initially unpolarized, the transmitted intensity  $I$  is

$$I = \frac{1}{2} I_0. \quad \text{Eq. 33-36}$$

- If the original light is initially polarized, the transmitted intensity depends on the angle  $\theta$  between the polarization direction of the original light (the axis along which the fields oscillate) and the polarizing direction of the sheet:

$$I = I_0 \cos^2 \theta. \quad \text{Eq. 33-26}$$

### Reflection and Refraction

- The angle of reflection is equal to the angle of incidence, and the angle of refraction is related to the angle of incidence by Snell's law,

$$n_2 \sin \theta_2 = n_1 \sin \theta_1 \quad \text{Eq. 33-40}$$

## 33 Summary

### Total Internal Reflection

- A wave encountering a boundary across which the index of refraction decreases will experience total internal reflection if the angle of incidence exceeds a critical angle,

$$\theta_c = \sin^{-1} \frac{n_2}{n_1} \quad \text{Eq. 33-45}$$

### Polarization by Reflection

- A reflected wave will be fully polarized, if the incident, unpolarized wave strikes a boundary at the Brewster angle

$$\theta_B = \tan^{-1} \frac{n_2}{n_1} \quad \text{Eq. 33-49}$$