Chapter 33

Electromagnetic Waves

Lecture 21, 22

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 → Modified by S.H. Seo

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33 Summary

Electromagnetic Waves

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

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

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

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

$$c = \frac{E}{B} = \frac{1}{\sqrt{\mu_0 \varepsilon_0}}$$ Eq. 33-5&3

Energy Flow

- The rate per unit area at which energy is trans- ported via an electromagnetic wave is given by the Poynting vector ***S***:

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

- The intensity *I* of the wave is:

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

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

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

Radiation Pressure

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

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

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

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

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 ω, and the emitted wave's frequency f and wavelength λ.

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 λ, period *T*, angular frequency ω, 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 ε_0, and the permeability constant μ_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*.

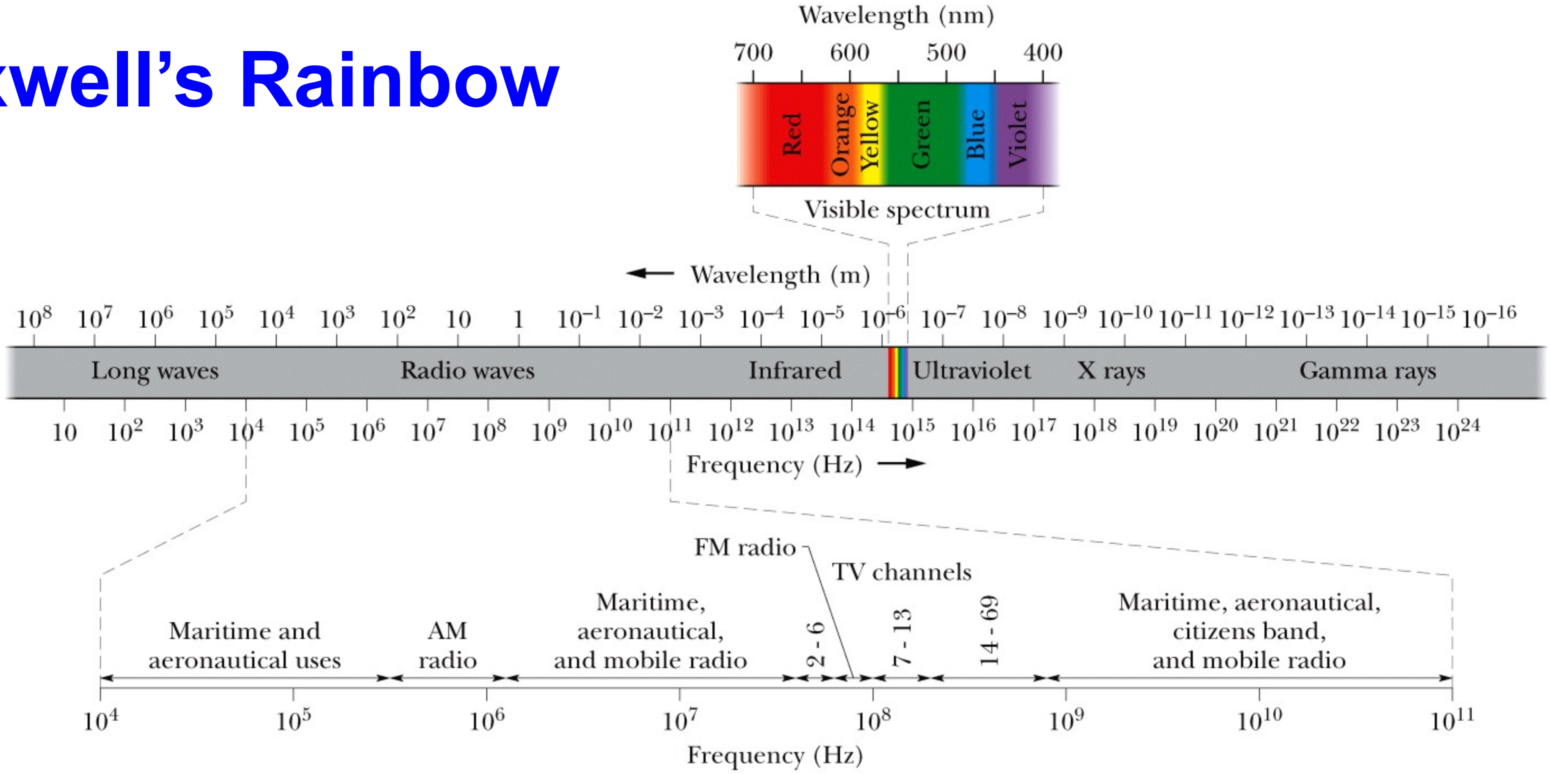
33-1 Electromagnetic Waves

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



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

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Maxwell's Rainbow

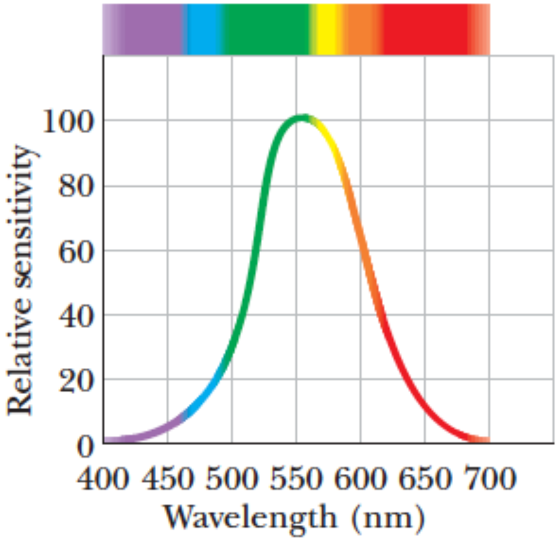

Figure 33-2 The relative sensitivity of the average human eye to electromagnetic waves at different wavelengths. This portion of the electromagnetic spectrum to which the eye is sensitive is called *visible light*.

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33-1 Electromagnetic Waves

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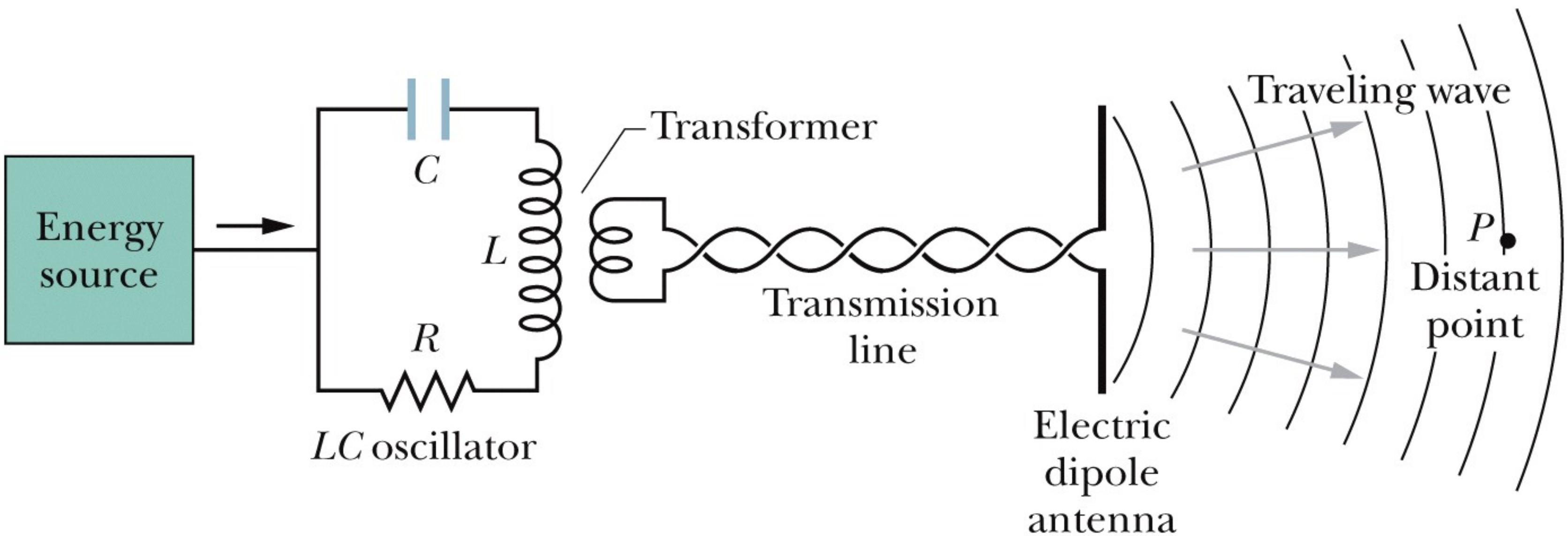
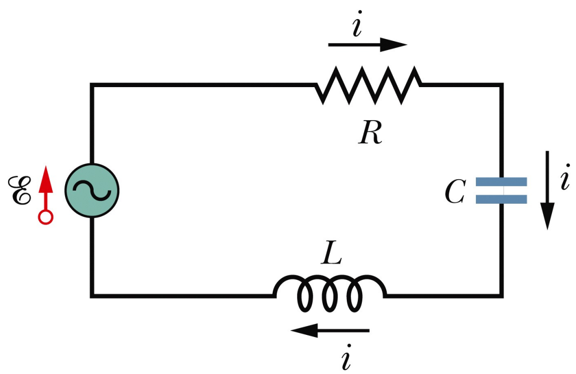
Travelling Electromagnetic Wave



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.

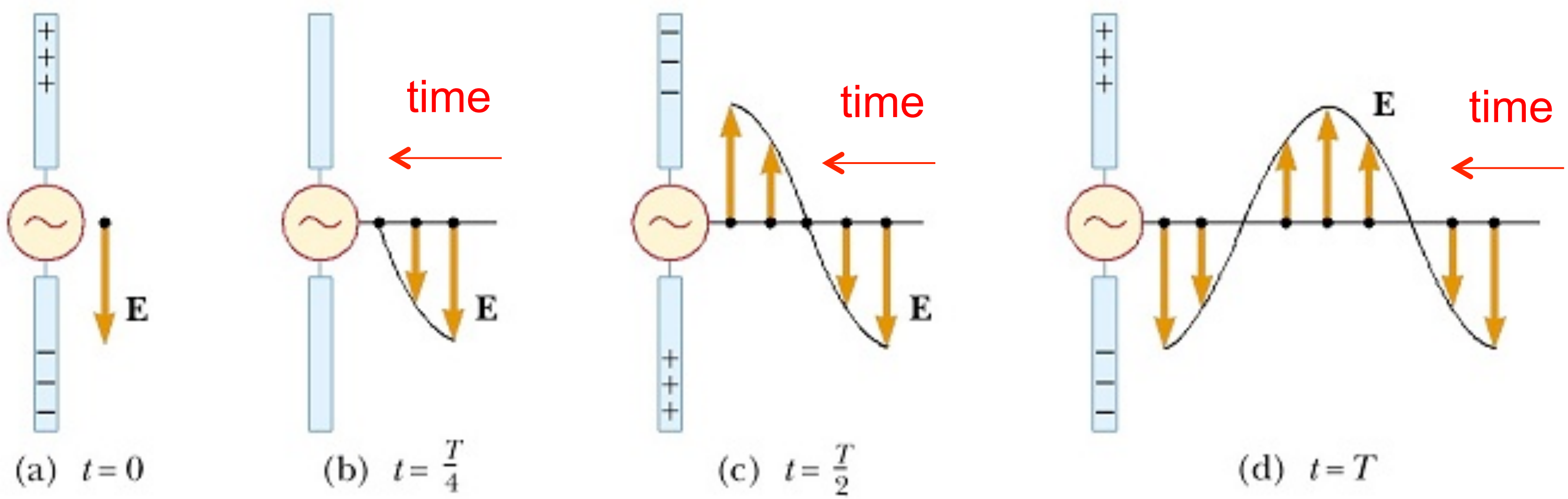
33-1 Electromagnetic Waves

Travelling Electromagnetic Wave



$$\mathscr{E} = \mathscr{E}_m \sin \omega_d t.$$

$$i = I \sin(\omega_d t - \phi)$$



33-1 Electromagnetic Waves

Travelling Electromagnetic Wave

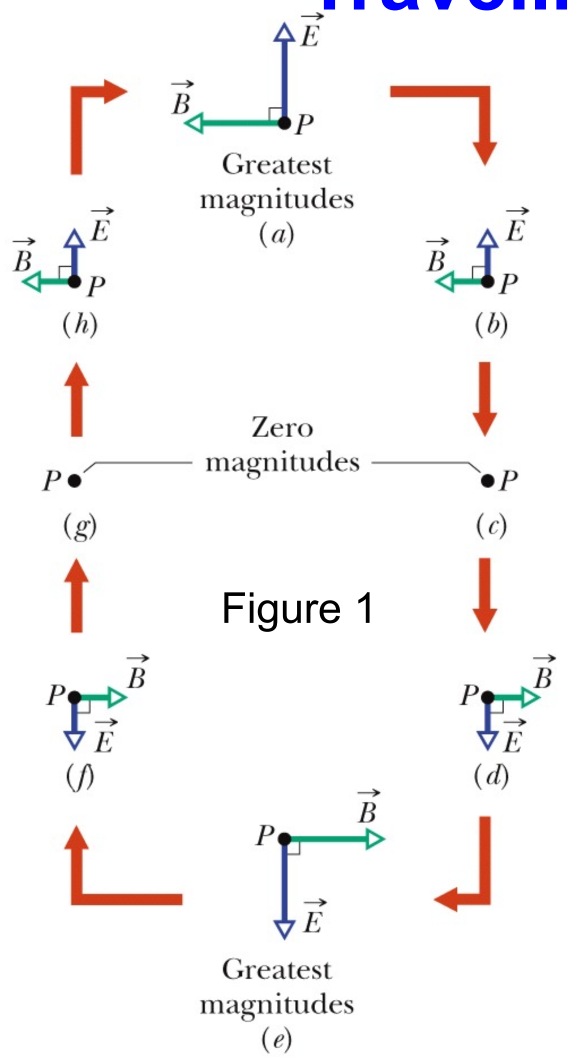


Figure 1

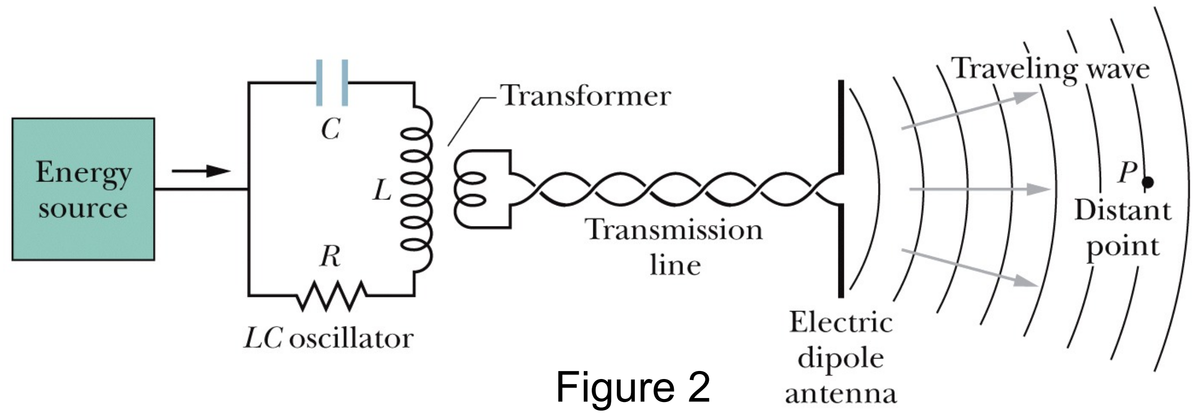


Figure 2

Electromagnetic Wave. Figure 1 shows how the electric field ***E*** and the magnetic field ***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

1. The electric and magnetic fields ***E*** and ***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 ***E*** × ***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

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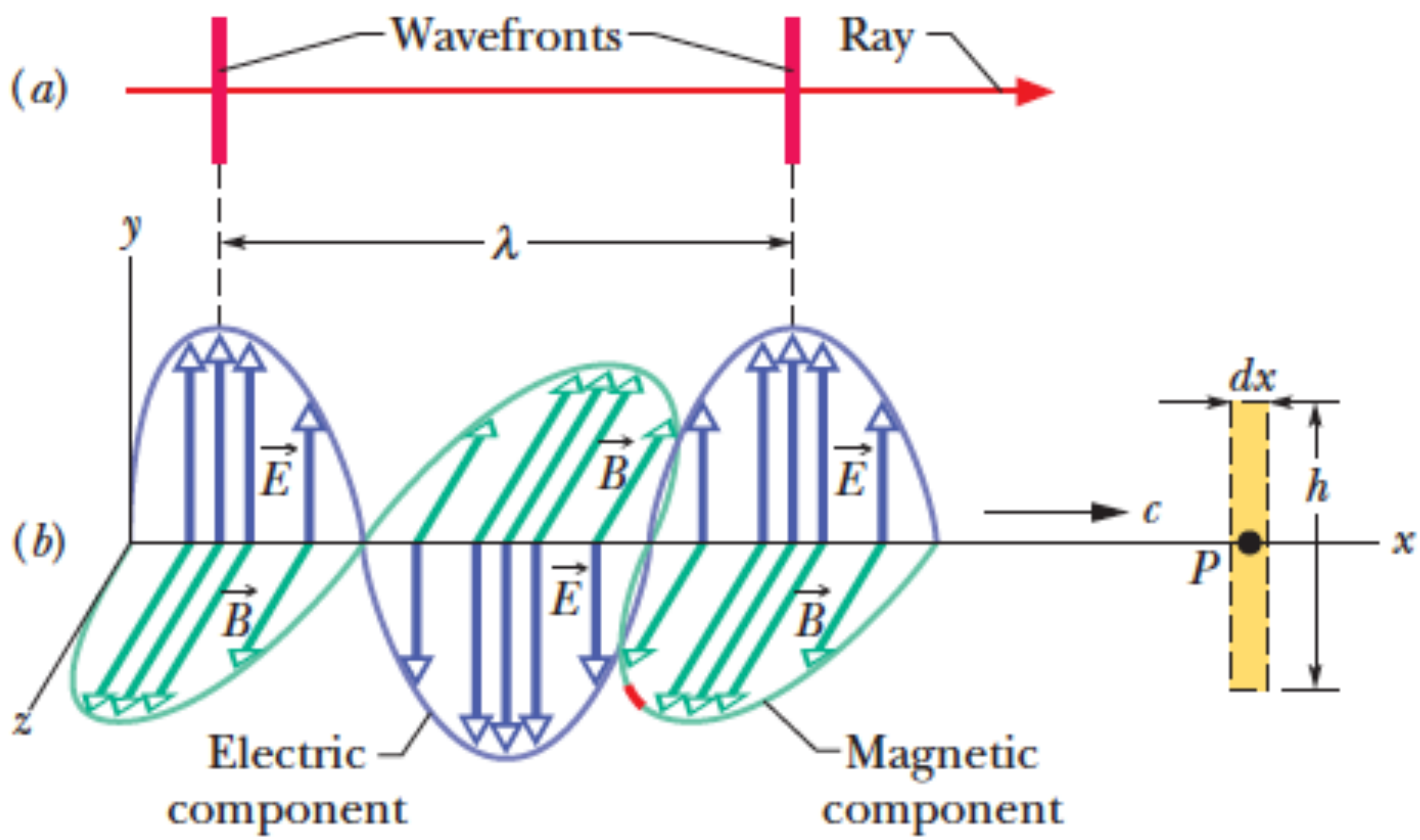
Travelling Electromagnetic Wave



33-1 Electromagnetic Waves

Travelling Electromagnetic Wave

In keeping with these features, we can deduce that an electromagnetic wave traveling along an x axis has an electric field $\boldsymbol{E}$ and a magnetic field $\boldsymbol{B}$ 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 $\boldsymbol{E}$ and $\boldsymbol{B}$. The electric field induces the magnetic field and vice versa.

33-1 Electromagnetic Waves

Travelling Electromagnetic Wave

Wave Speed. From chapter 16 (Eq. 16-13), we know that the speed of the wave is ω/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

$$c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}} \quad \text{(wave speed)},$$

which is about 3.0×10^8 m/s. In other words,

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

33-1 Electromagnetic Waves

Travelling Electromagnetic Wave

The oscillating magnetic field induces an oscillating and perpendicular electric field.

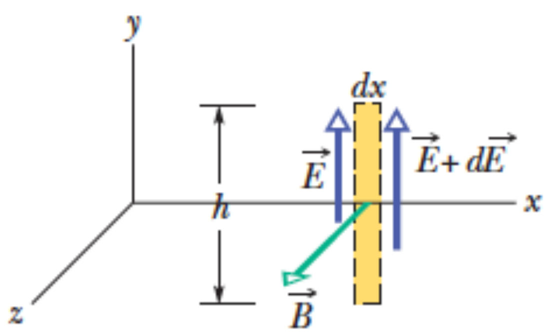


Figure 33-6 As the electromagnetic wave travels rightward past point P in Fig. 33-5b, the sinusoidal variation of the magnetic field $\vec{B}$ through a rectangle centered at P induces electric fields along the rectangle. At the instant shown, $\vec{B}$ is decreasing in magnitude and the induced electric field is therefore greater in magnitude on the right side of the rectangle than on the left.

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

Faraday's law

Fig.33-6

$$\oint \vec{E} \cdot d\vec{s} = (E + dE)h - Eh = h\,dE.$$

$$\Phi_B = (B)(h\,dx),$$

$$\frac{d\Phi_B}{dt} = h\,dx\,\frac{dB}{dt}$$

$$h\,dE = -h\,dx\,\frac{dB}{dt}$$

$$\frac{dE}{dx} = -\frac{dB}{dt}.$$

33-1 Electromagnetic Waves

Travelling Electromagnetic Wave

$$\frac{\partial E}{\partial x} = -\frac{\partial B}{\partial t}$$

$$\left\{\begin{array}{l} \dfrac{\partial E}{\partial x} = kE_m \cos(kx - \omega t) \\[2ex] \dfrac{\partial B}{\partial t} = -\omega B_m \cos(kx - \omega t). \end{array}\right.$$

$$\boxed{\begin{array}{l} E = E_m \sin(kx - \omega t), \\ B = B_m \sin(kx - \omega t), \end{array}}$$

$$kE_m \cos(kx - \omega t) = \omega B_m \cos(kx - \omega t).$$

$$\frac{E_m}{B_m} = c \quad \text{(amplitude ratio)},$$

33-1 Electromagnetic Waves

Travelling Electromagnetic Wave

The oscillating electric field induces an oscillating and perpendicular magnetic field.

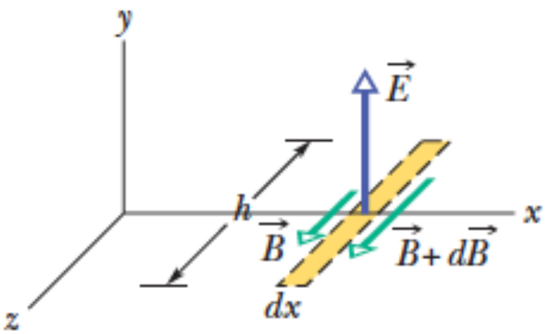


Figure 33-7 The sinusoidal variation of the electric field through this rectangle, located (but not shown) at point P in Fig. 33-5b, induces magnetic fields along the rectangle. The instant shown is that of Fig. 33-6: $\vec{E}$ is decreasing in magnitude, and the magnitude of the induced magnetic field is greater on the right side of the rectangle than on the left.

$$\oint \vec{B}\cdot d\vec{s} = \mu_0\varepsilon_0 \frac{d\Phi_E}{dt}$$ Maxwell' eq.

$$\oint \vec{B}\cdot d\vec{s} = -(B + dB)h + Bh = -h\,dB.$$

$$\Phi_E = (E)(h\,dx), \qquad \frac{d\Phi_E}{dt} = h\,dx\,\frac{dE}{dt}.$$

$$-h\,dB = \mu_0\varepsilon_0\left(h\,dx\,\frac{dE}{dt}\right)$$

$$-\frac{\partial B}{\partial x} = \mu_0\varepsilon_0\frac{\partial E}{\partial t}.$$

$$-kB_m\cos(kx-\omega t) = -\mu_0\varepsilon_0\omega E_m\cos(kx-\omega t),$$

$$\frac{E_m}{B_m} = \frac{1}{\mu_0\varepsilon_0(\omega/k)} = \frac{1}{\mu_0\varepsilon_0 c}.$$

$$\boxed{c = \frac{1}{\sqrt{\mu_0\varepsilon_0}} \quad \text{(wave speed)},}$$

33-2 Energy Transport and The Poynting Vector

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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 ***S***, which is related to the cross product of the electric field ***E*** and magnetic field ***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

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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 Pavg, energy transfer ΔE, and the time Δt 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

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

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

$$S = \left(\frac{\text{energy/time}}{\text{area}}\right)_{\text{inst}} = \left(\frac{\text{power}}{\text{area}}\right)_{\text{inst}}.$$

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.

$$S = \frac{1}{\mu_0}EB,$$

$$S = \frac{1}{c\mu_0}E^2 \quad \text{(instantaneous energy flow rate).}$$

$$I = S_{\text{avg}} = \left(\frac{\text{energy/time}}{\text{area}}\right)_{\text{avg}} = \left(\frac{\text{power}}{\text{area}}\right)_{\text{avg}}.$$

$$I = S_{\text{avg}} = \frac{1}{c\mu_0}[E^2]_{\text{avg}} = \frac{1}{c\mu_0}[E_m^2 \sin^2(kx - \omega t)]_{\text{avg}}.$$

$$E_{\text{rms}} = \frac{E_m}{\sqrt{2}}.$$

33-2 Energy Transport and The Poynting Vector

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

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

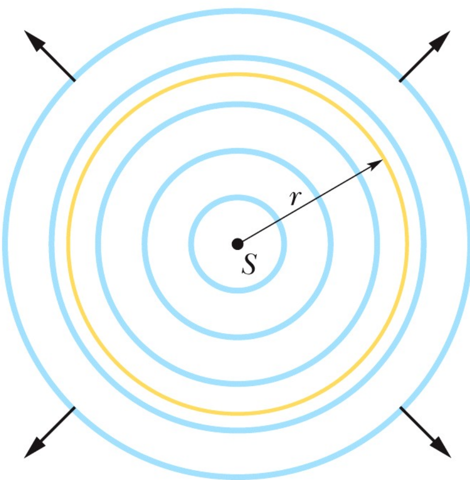
in which $E_{rms} = E_m/\sqrt{2}$.

Eq. 25-25

$$u_E = \tfrac{1}{2}\varepsilon_0 E^2 = \tfrac{1}{2}\varepsilon_0 (cB)^2.$$

$$u_E = \tfrac{1}{2}\varepsilon_0 \frac{1}{\mu_0 \varepsilon_0} B^2 = \frac{B^2}{2\mu_0}.$$

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



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

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

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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.

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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

$$\boxed{F = \frac{IA}{c}}$$ *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

$$\boxed{F = \frac{2IA}{c}}$$ *Total Reflection back along path*

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

$$\boxed{p_r = \frac{I}{c}}$$ *Total Absorption*

and

$$\boxed{p_r = \frac{2I}{c}}$$ *Total Reflection back along path*

33-3 Radiation Pressure

$$\Delta U = F\Delta x = \frac{\Delta P}{\Delta t}\Delta x = \Delta P\frac{\Delta x}{\Delta t} = \Delta P \cdot v = \Delta P \cdot c$$

$$F = \frac{\Delta p}{\Delta t}.$$

$$I = \frac{\text{power}}{\text{area}} = \frac{\text{energy/time}}{\text{area}}. \quad = \frac{\Delta U / \Delta t}{A}$$

$$\Delta U = IA\,\Delta t.$$

$$\Delta p = \frac{\Delta U}{c} \quad \text{(total absorption)},$$

$$\boxed{F = \frac{IA}{c}}$$

Total Absorption

Radiation pressure

$$\boxed{p_r = \frac{I}{c}}$$

Total Absorption

$$\Delta p = \frac{2\,\Delta U}{c} \quad \text{(total reflection back along path)}.$$

$$\boxed{F = \frac{2IA}{c}}$$

Total Reflection back along path

$$\boxed{p_r = \frac{2I}{c}}$$

Total Reflection back along path

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- The intensity *I* of the wave is:

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

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Radiation Pressure

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

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

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

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

33 Summary

Radiation Pressure

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

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

- For total reflection back along path,

$$p_r = \frac{2I}{c}$$ **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

$$I = \tfrac{1}{2}I_0.$$ **Eq. 33-36**

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

$$I = I_0 \cos^2 \theta.$$ **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,

$$n_2 \sin \theta_2 = n_1 \sin \theta_1$$ **Eq. 33-40**

33 Summary

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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,

$$\theta_c = \sin^{-1}\frac{n_2}{n_1}$$

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

$$\theta_B = \tan^{-1}\frac{n_2}{n_1}$$

Eq. 33-49

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 it 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.

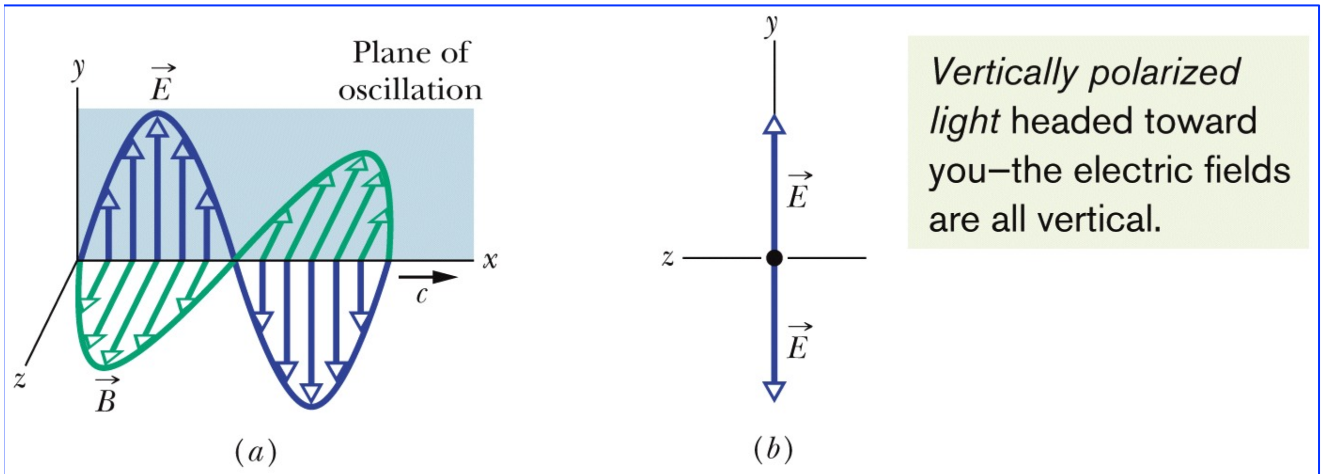
33.33 Distinguish between a polarizer and an analyzer.

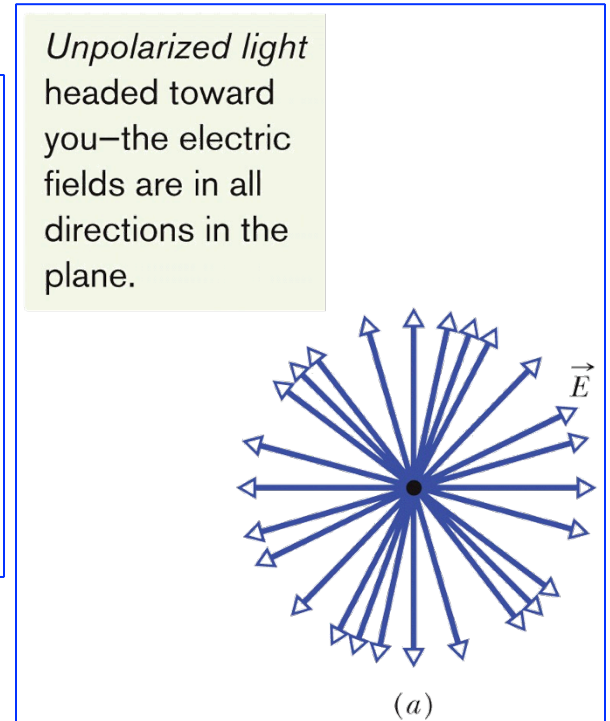
33.34 Explain what is meant if two sheets are crossed.

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.





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

33-4 Polarization

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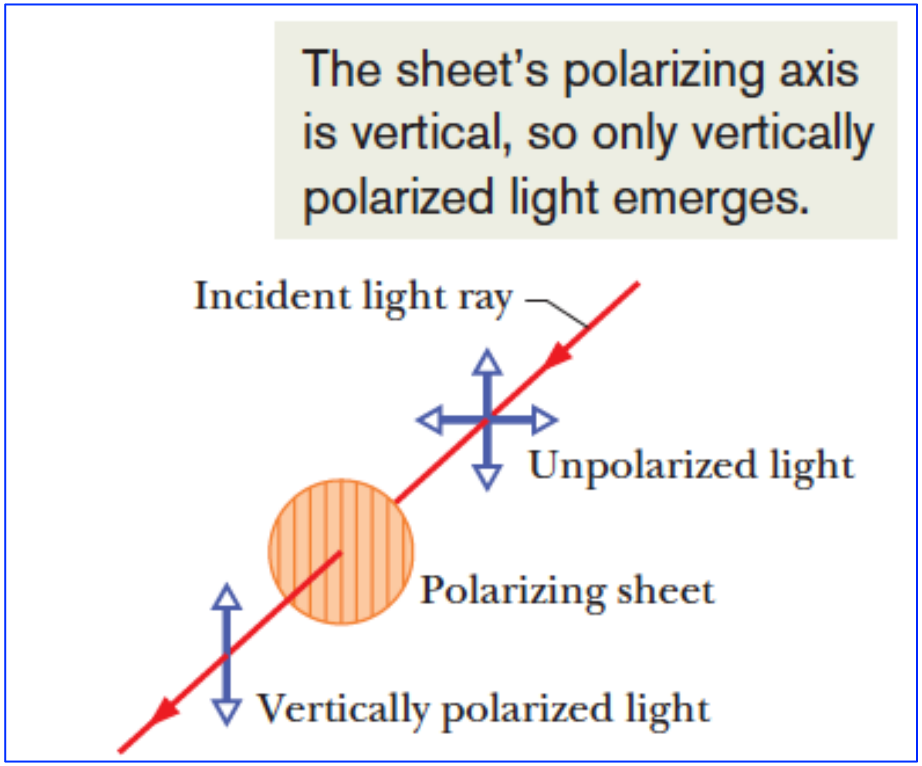
If the original light is initially unpolarized, the transmitted intensity I is half the original intensity I_0:

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



33-4 Polarization

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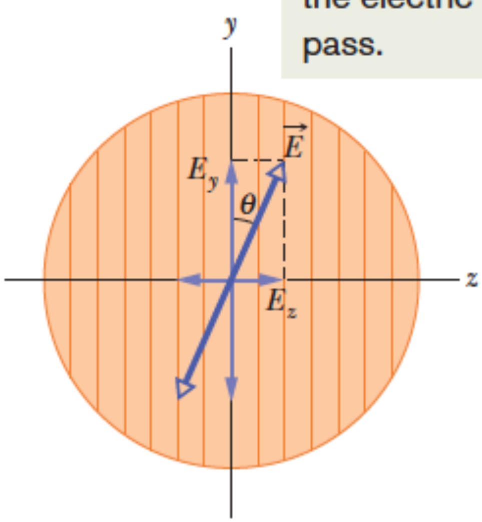
If the original light is initially polarized, the transmitted intensity depends on the angle θ between the polarization direction of the original light and the polarizing direction of the sheet:

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

The sheet's polarizing axis is vertical, so only vertical components of the electric fields pass.



$$E_y = E \cos \theta. \longleftarrow$$ Component passing the polarizer

$$I = \frac{1}{c\mu_0} E_{rms}^2 = \frac{1}{2c\mu_0} E^2 \qquad E_{rms} = E_m/\sqrt{2}$$

$$I_0 = \frac{1}{2c\mu_0} E^2$$

$$I_f = \frac{1}{2c\mu_0} E_y^2 = \frac{1}{2c\mu_0} E^2 \cos^2 \theta = I_0 \cos^2 \theta$$

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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.

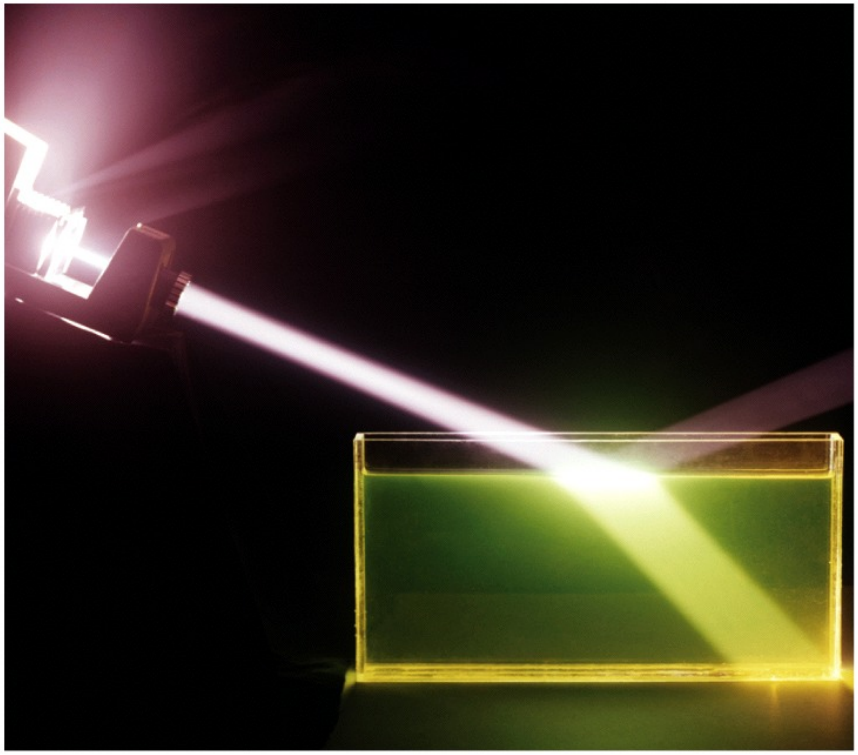
33.42 Identify chromatic dispersion.

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.

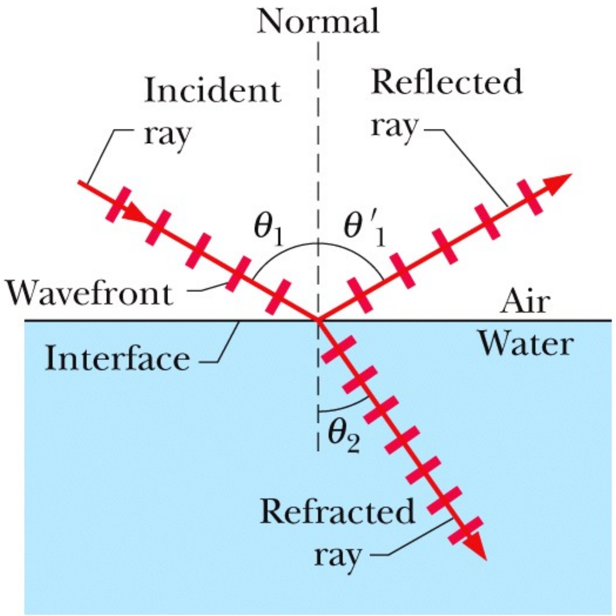
33.44 Describe how the primary and secondary rainbows are formed and explain why they are circular arcs.

33-5 Reflection and Refraction

(a)



(b)



(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 (θ_1), reflection (θ'_1), and refraction (θ_2) are marked.

33-5 Reflection and Refraction

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

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

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

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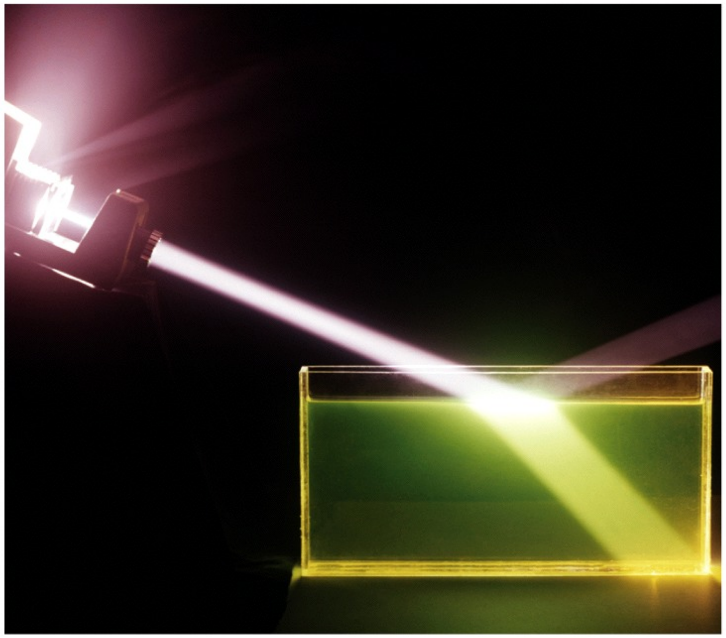
33-5 Reflection and Refraction



(a)

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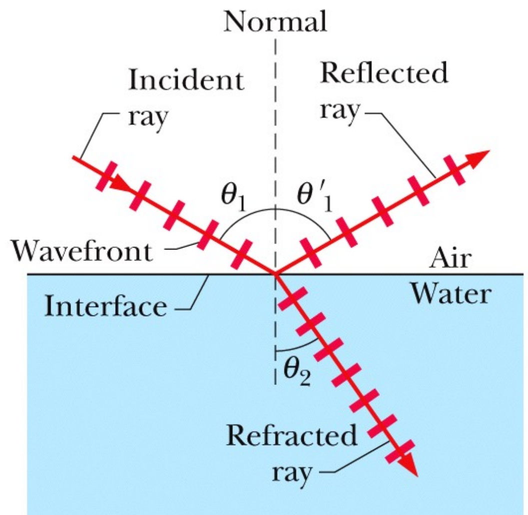

(b)

Law of refraction: A refracted ray lies in the plane of incidence and has an angle of refraction θ_2 that is related to the angle of incidence θ_1 by

$$\boxed{n_2 \sin \theta_2 = n_1 \sin \theta_1}$$ Snell's law

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

Material	Index of Refraction (n)
Vacuum	1.000
Air	1.000277
Water	1.333333
Ice	1.31
Glass	About 1.5
Diamond	2.417

$$\boxed{n_2 \sin \theta_2 = n_1 \sin \theta_1}$$

Snell's law

33-5 Reflection and Refraction

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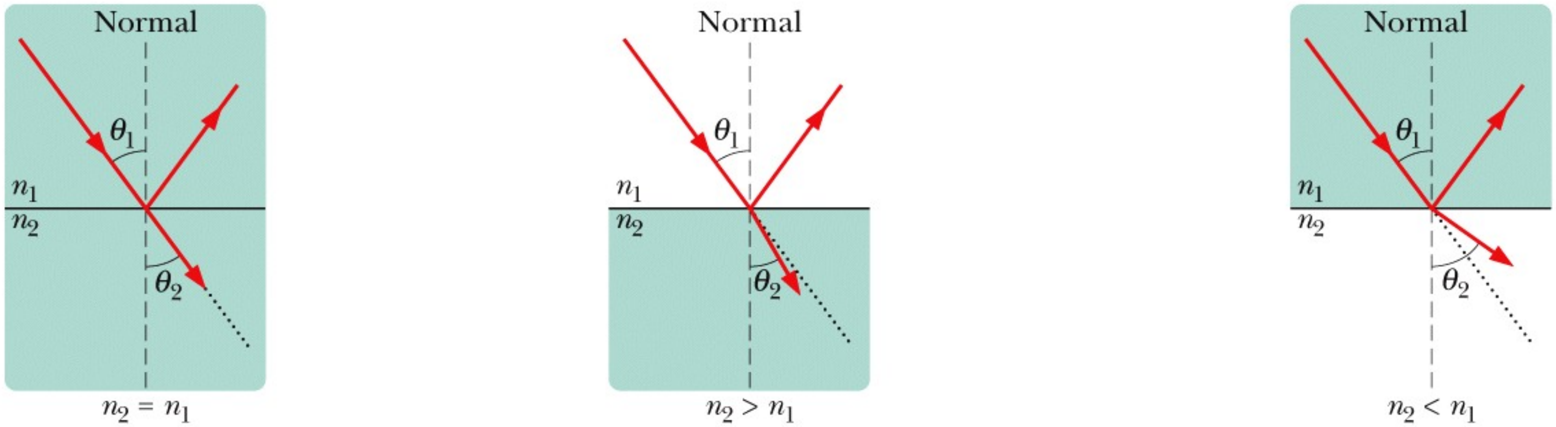


(*a*) If the indexes match, there is no direction change.

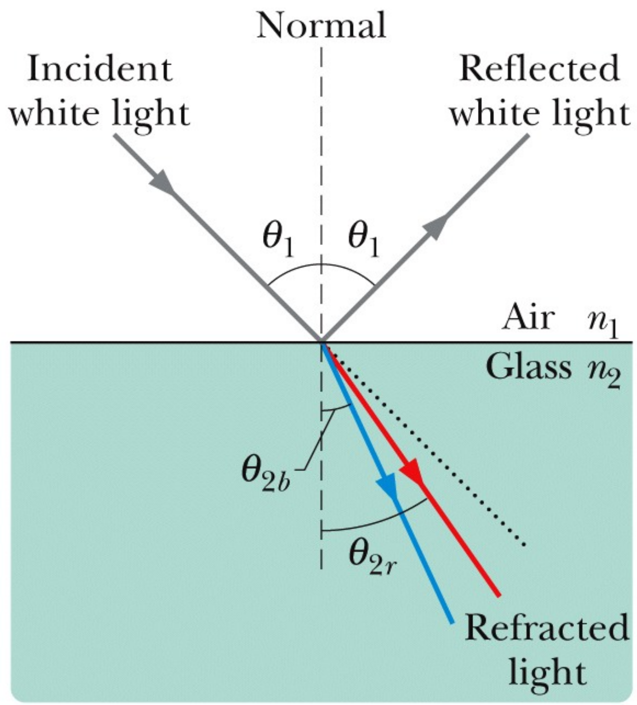
(*b*) If the next index is greater, the ray is bent *toward* the normal.

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

$$\boxed{n_2 \sin\theta_2 = n_1 \sin\theta_1}$$

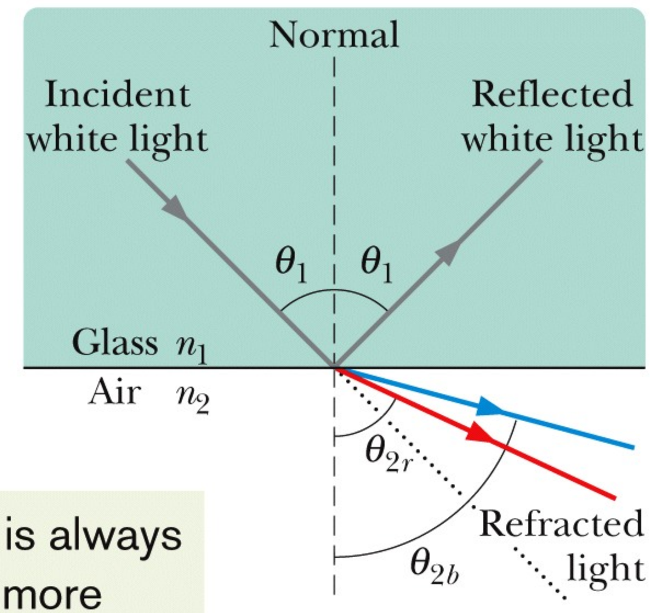
1. If n_2 is equal to n_1, then θ_2 is equal to θ_1 and refraction does not bend the light beam, which continues in the undeflected direction, as in Fig. (a).
2. If n_2 is greater than n_1, then θ_2 is less than θ_1. In this case, refraction bends the light beam away from the undeflected direction and toward the normal, as in Fig. (b).
3. If n_2 is less than n_1, then θ_2 is greater than θ_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



(a)

Blue is always bent more than red.



(b)

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.

33-5 Reflection and Refraction

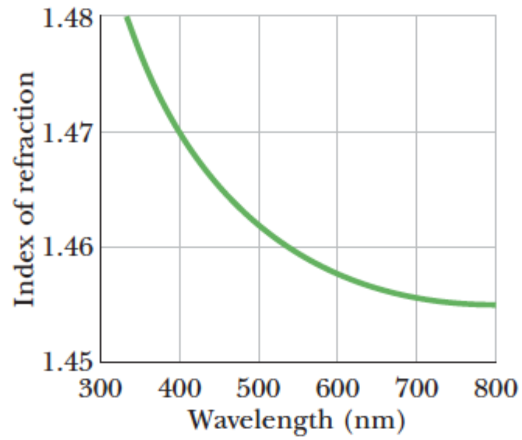
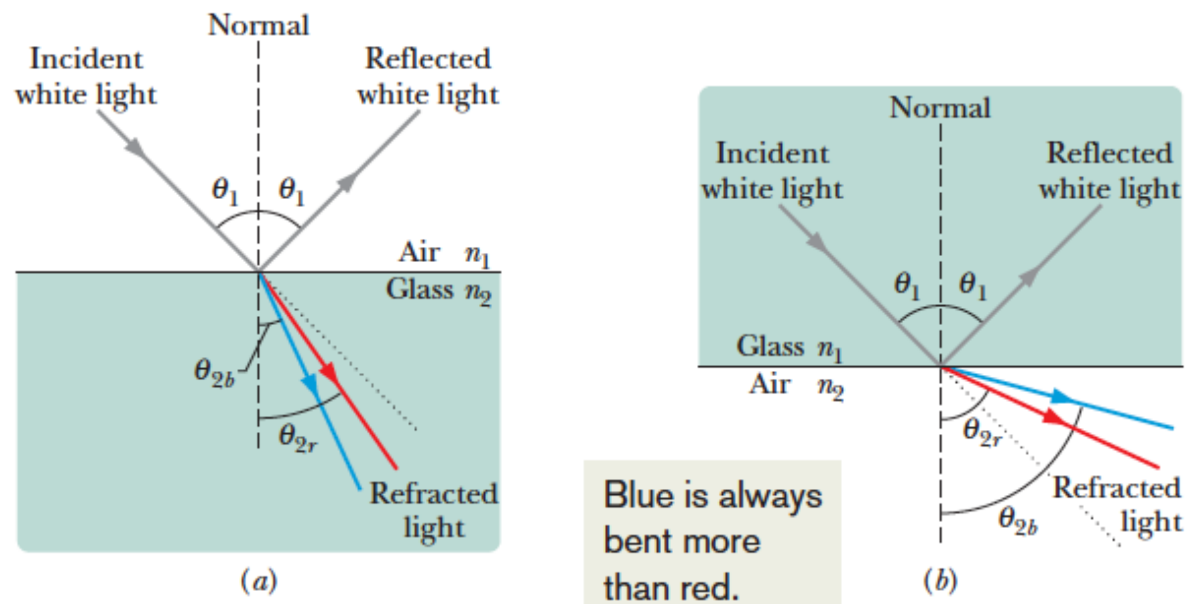


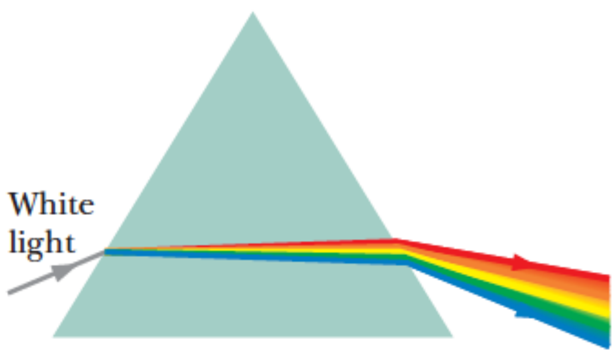
Figure 33-18 The index of refraction as a function of wavelength for fused quartz. The graph indicates that a beam of short-wavelength light, for which the index of refraction is higher, is bent more upon entering or leaving quartz than a beam of long-wavelength light.



Blue is always bent more than red.

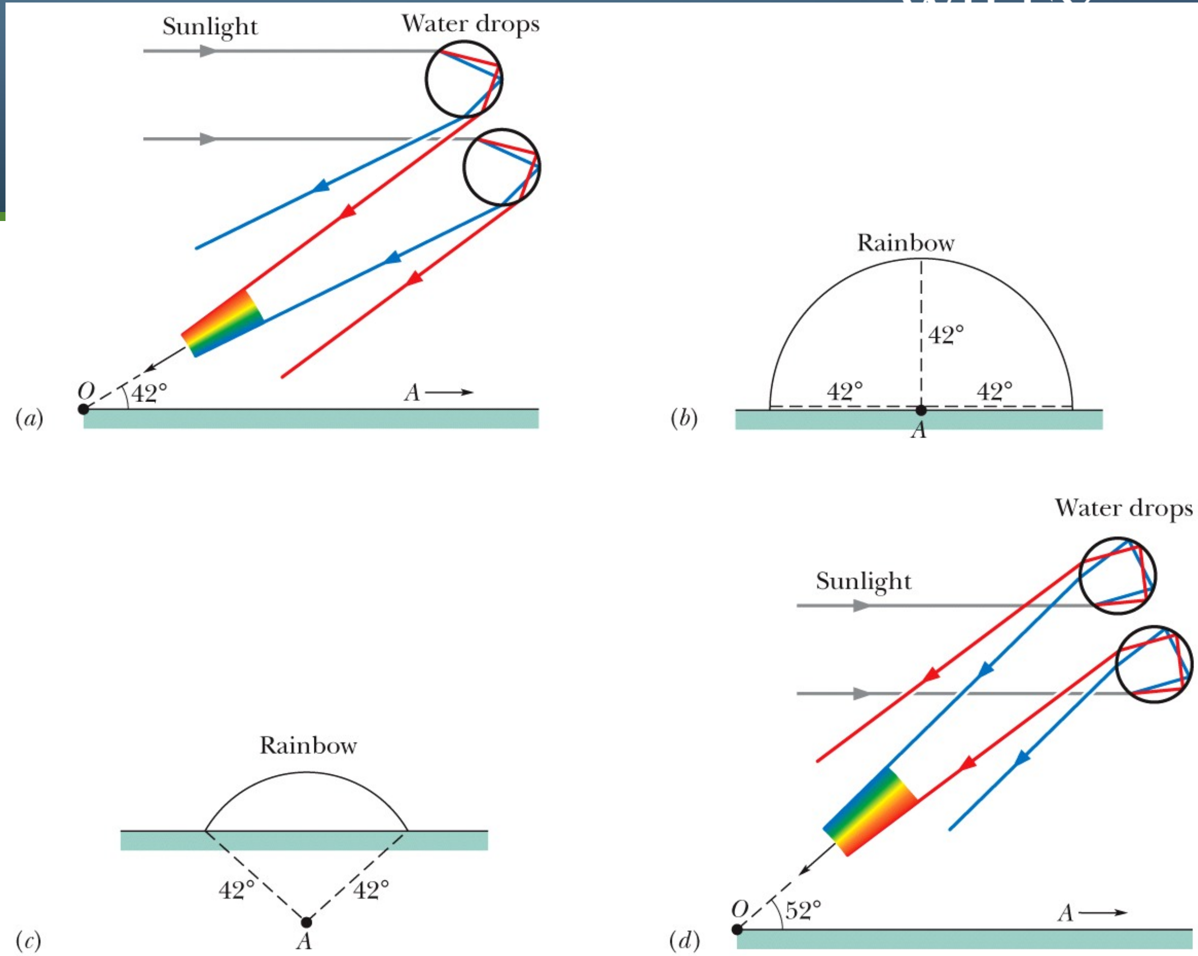
$$\theta_1 > \theta_{2r} > \theta_{2b}$$

$$\theta_1 < \theta_{2r} < \theta_{2b}$$



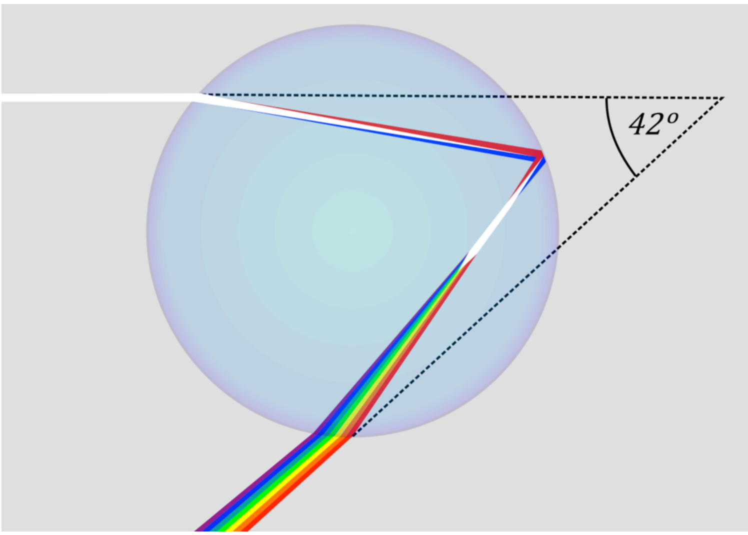
Color with shorter wavelength (blue) is always bent more than color with longer wavelength (red).

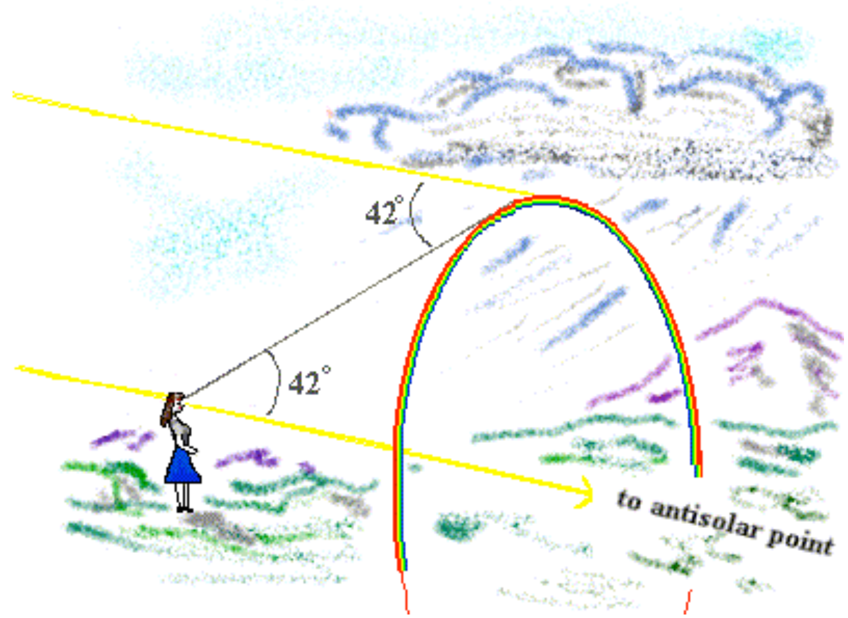
33-5 Reflection and Refraction

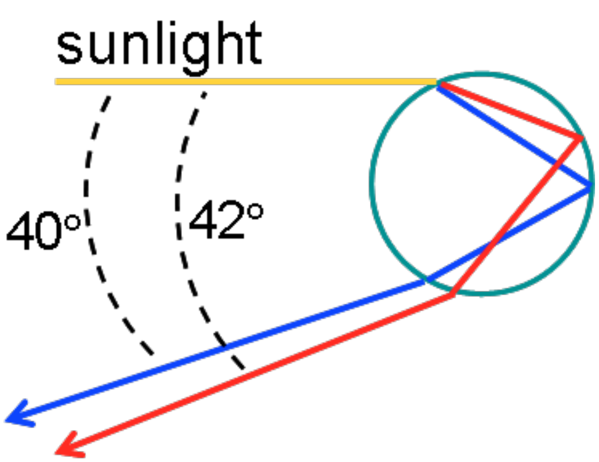


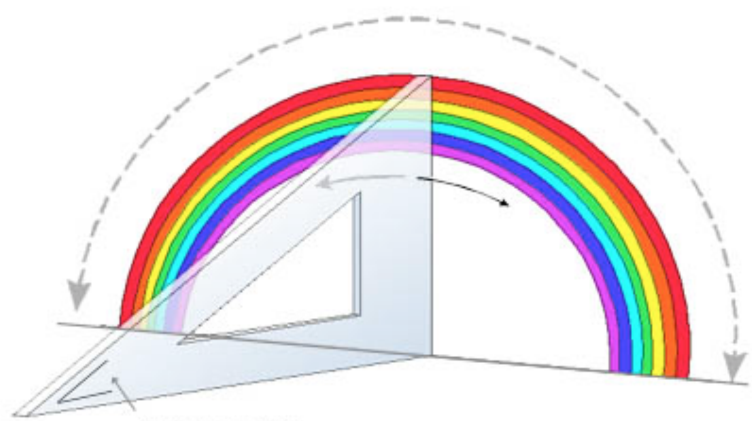
Rainbow: (a) The separation of colors when sunlight refracts into and out of falling raindrops leads to a primary rainbow. The *antisolar point A* is on the horizon at the right. The rainbow colors appear at an angle of 42° from the direction of A. (b) Drops at 42° from A in any direction can contribute 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.

33-5 Reflection and Refraction

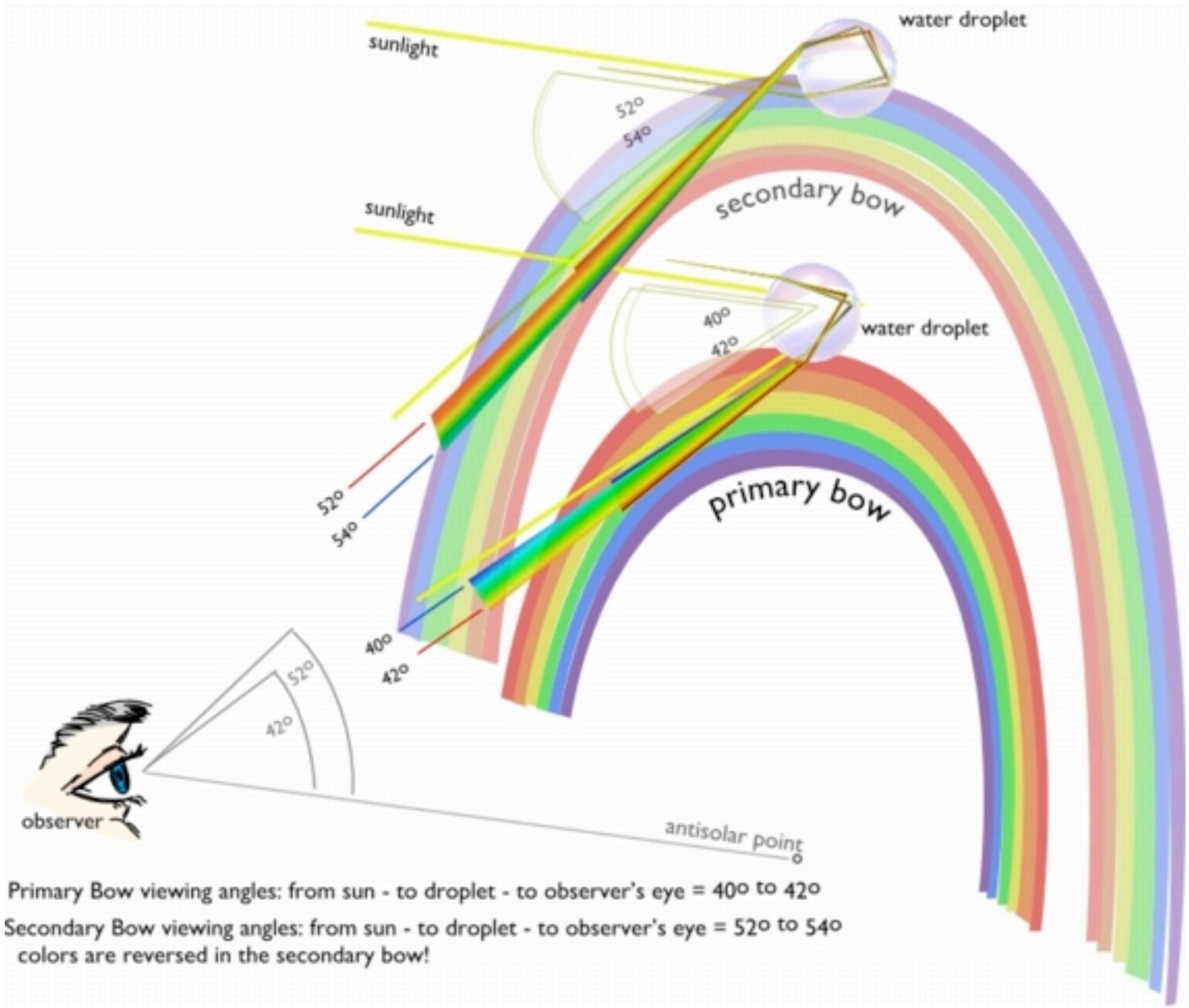








33-5 Reflection and Refraction



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

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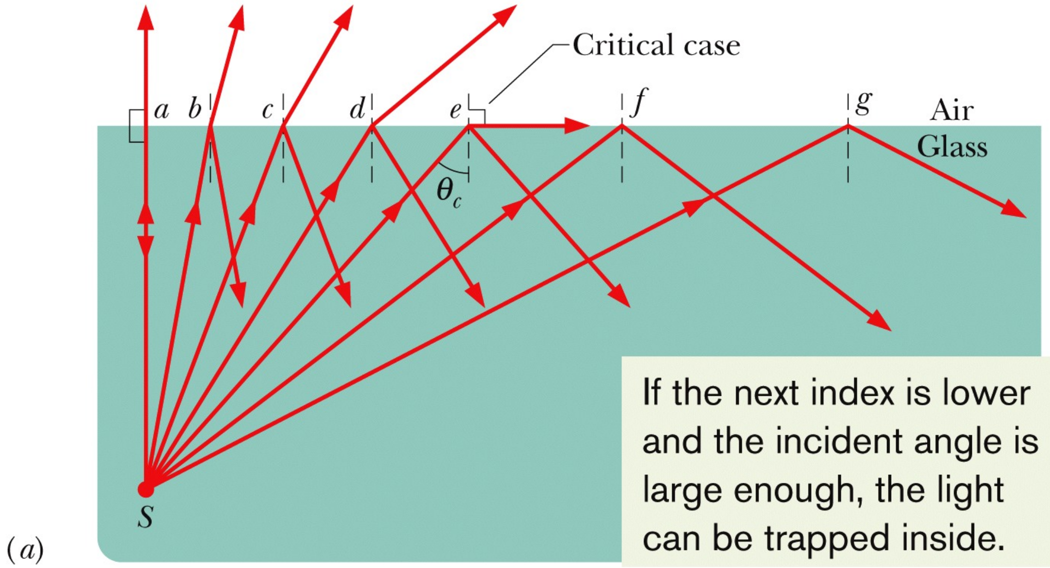

If the next index is lower and the incident angle is large enough, the light can be trapped inside.

Ken Kay/Fundamental Photographs

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°, which means that the refracted ray points directly along the interface. The angle of incidence giving this situation is called the **critical angle θ_c**. For angles of incidence larger than θ_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

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Learning Objectives

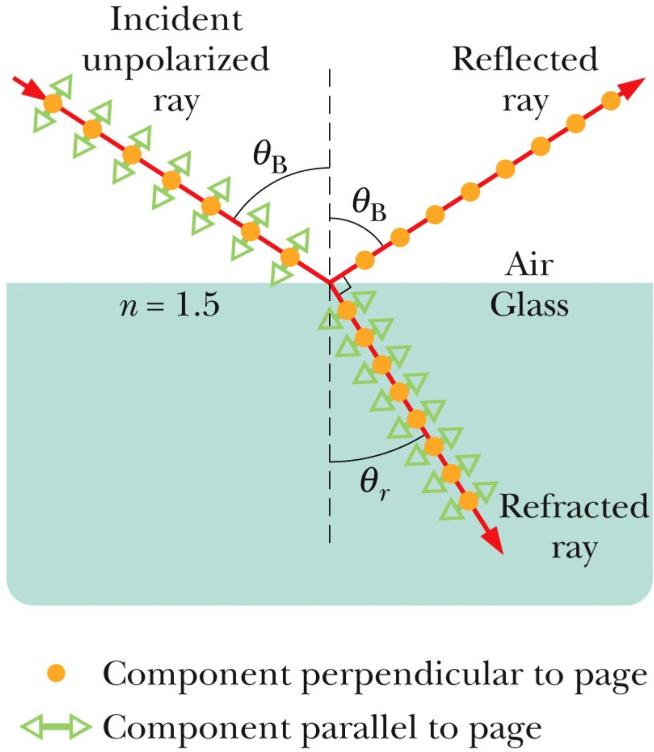
33.48 With sketches, explain how unpolarized light can be converted to polarized light by reflection from an interface.

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



A ray of unpolarized light in air is incident on a glass surface at the **Brewster angle** θ_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 ***E*** vectors perpendicular to the plane of incidence, if it strikes a boundary at the Brewster angle θ_B, where

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

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33 Summary

Electromagnetic Waves

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

$$\boxed{\begin{aligned} E &= E_m \sin(kx - \omega t) \\ B &= B_m \sin(kx - \omega t), \end{aligned}}$$

Eq. 33-1

Eq. 33-2

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

$$\boxed{c = \frac{E}{B} = \frac{1}{\sqrt{\mu_0 \varepsilon_0}}}$$

Eq. 33-5&3

Energy Flow

- The rate per unit area at which energy is trans- ported via an electromagnetic wave is given by the Poynting vector ***S***:

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

Eq. 33-19

- The intensity *I* of the wave is:

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

Eq. 33-26

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

$$\boxed{I = \frac{P_s}{4\pi r^2}.}$$

Eq. 33-27

Radiation Pressure

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

$$\boxed{F = \frac{IA}{c}}$$

Eq. 33-32

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

$$\boxed{F = \frac{2IA}{c}}$$

Eq. 33-33

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33 Summary

Radiation Pressure

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

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

- For total reflection back along path,

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

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

$$\boxed{I = \tfrac{1}{2}I_0.} \quad \textbf{Eq. 33-36}$$

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

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

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,

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

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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,

$$\boxed{\theta_c = \sin^{-1}\frac{n_2}{n_1}}$$

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

$$\boxed{\theta_B = \tan^{-1}\frac{n_2}{n_1}}$$

Eq. 33-49