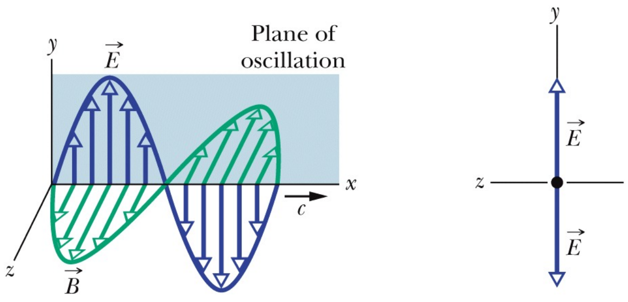
Polarization

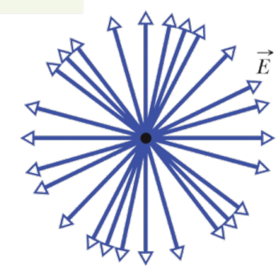
Electromagnetic waves are polarized if their electric field vectors are all in a single plane, called the plane of oscillation. Light waves from common sources are not polarized; that is, they are unpolarized, or polarized randomly.



(a) (b)

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.



(a)

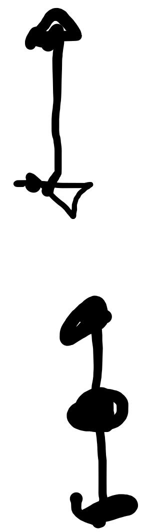
An electric field component parallel to the polarizing direction is passed (*transmitted*) by a polarizing sheet; a component perpendicular to it is absorbed.

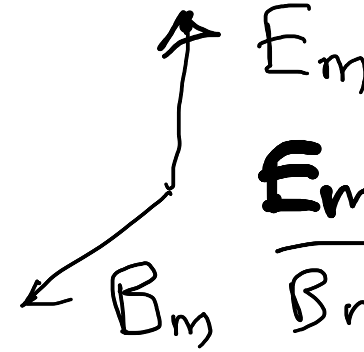
If the original light is initially unpolarized, the transmitted intensity *I* is half the original intensity I_0:

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

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

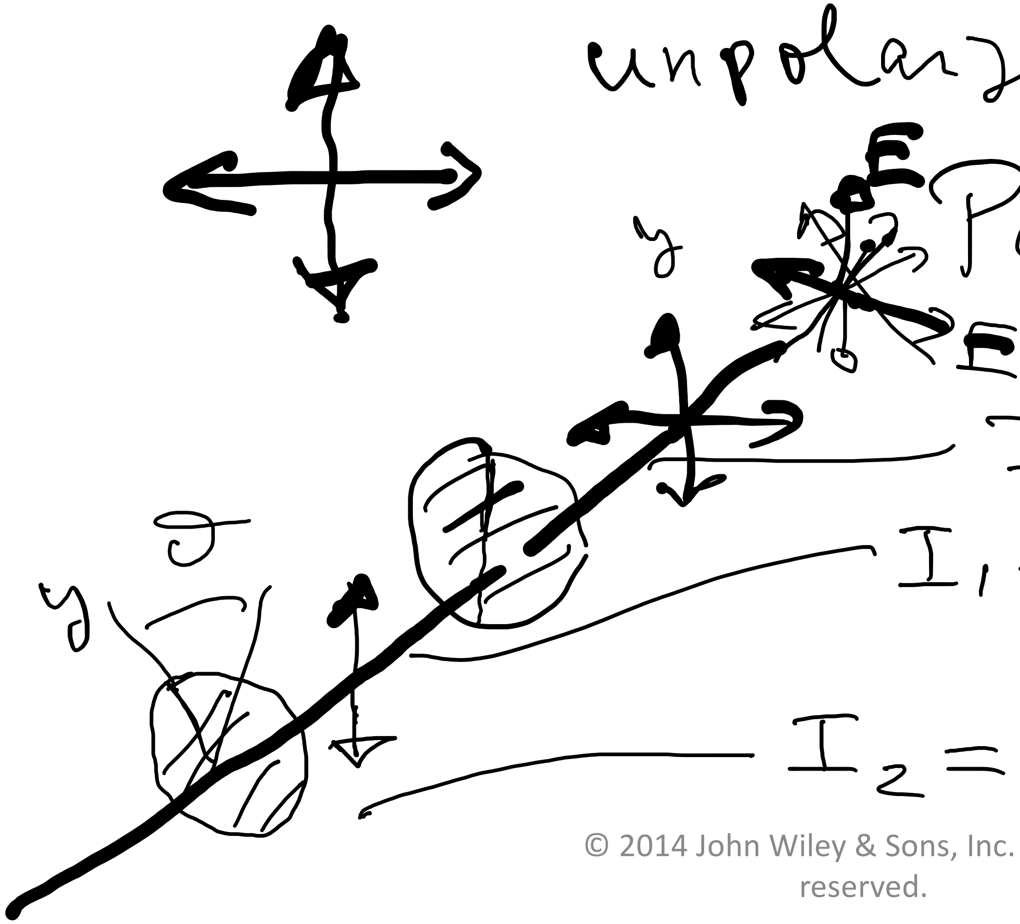
$$I = I_0 \cos^2 \theta \quad \text{(cosine-squared rule).}$$





$$\frac{E_m}{B_m} = C$$

unpolarized light



$E_y = E\cos\theta$

I_0

$I_1 = \frac{1}{2} I_0$

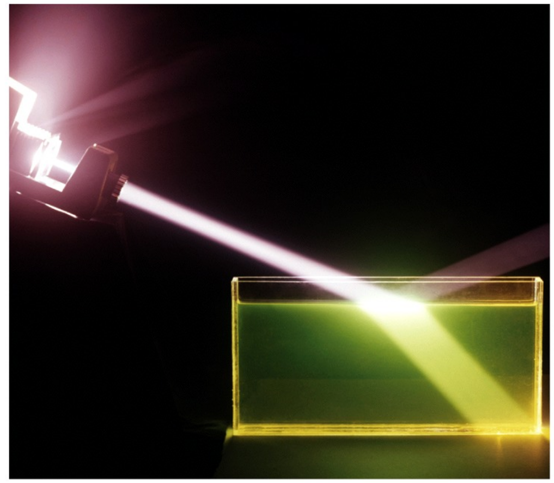
$I_2 = I_1 \cos^2\theta$

Reflection and Refraction

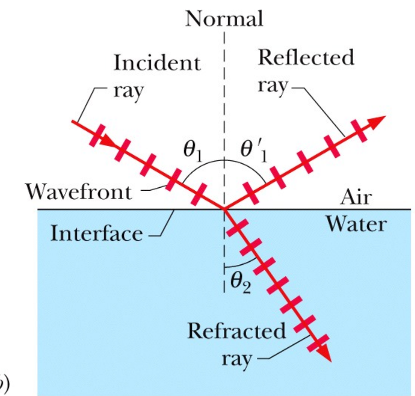
(a) A photograph showing an incident beam of light reflected and refracted by a horizontal water surface.

(b) A ray representation of (a). The angles of incidence (ϑ_1), reflection (ϑ'_1), and refraction (ϑ_2) are marked.

(a)



(b)



©1974 FP/Fundamental Photographs

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

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

Reflection and Refraction

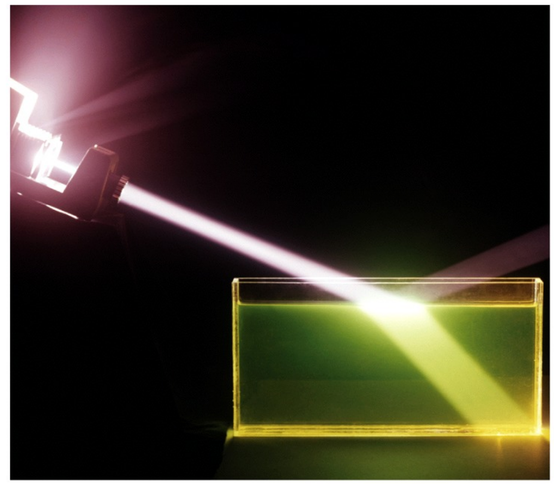
(a) A photograph showing an incident beam of light reflected and refracted by a horizontal water surface.

(b) A ray representation of (a). The angles of incidence (ϑ_1), reflection (ϑ'_1), and refraction (ϑ_2) are marked.

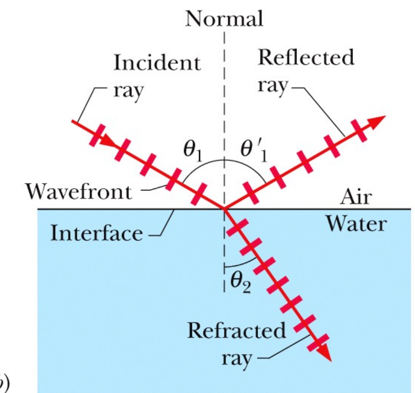
$n_2 > n_1$

$\theta_2 < \theta_1$

(a)



(b)

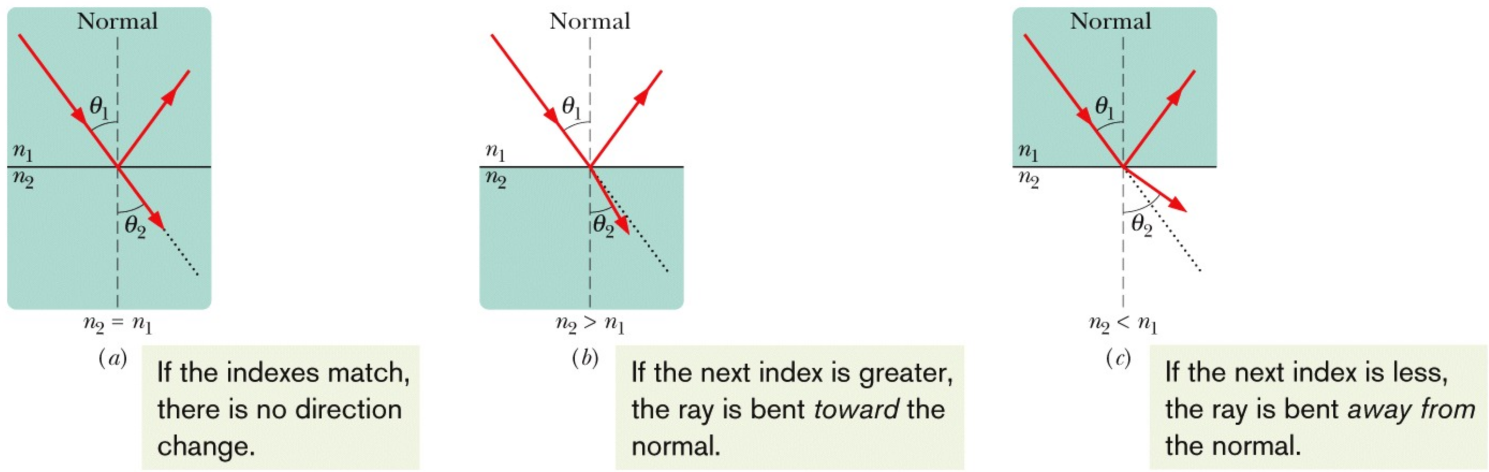


Law of refraction: A refracted ray lies in the plane of incidence and has an angle of refraction ϑ_2 that is related to the angle of incidence ϑ_1 by

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

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.

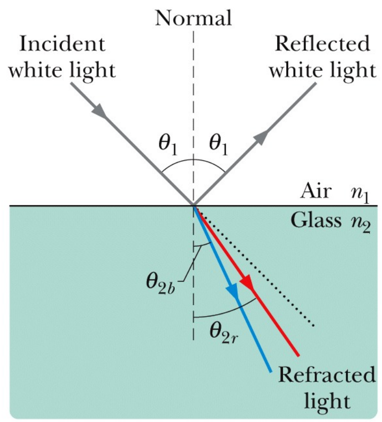
Reflection and Refraction



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

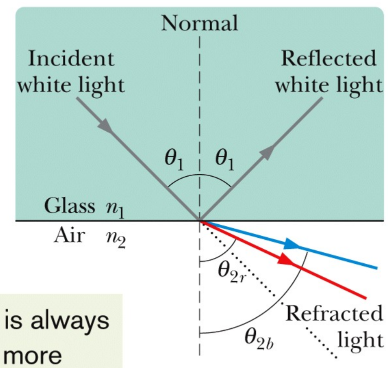
1. If n_2 is equal to n_1, then ϑ_2 is equal to ϑ_1 and refraction does not bend the light beam, which continues in the undeflected direction, as in Fig. (a).
2. If n_2 is greater than n_1, then ϑ_2 is less than ϑ_1. In this case, refraction bends the light beam away from the undeflected direction and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

Reflection and Refraction



(a)

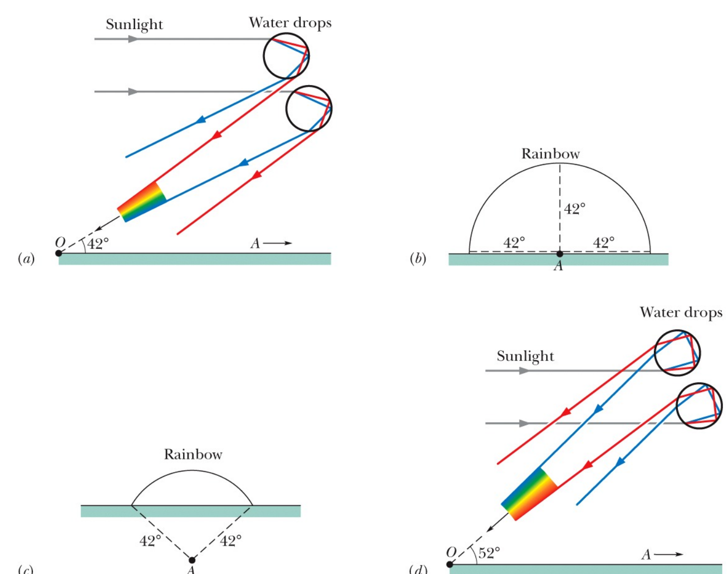
Blue is always bent more than red.

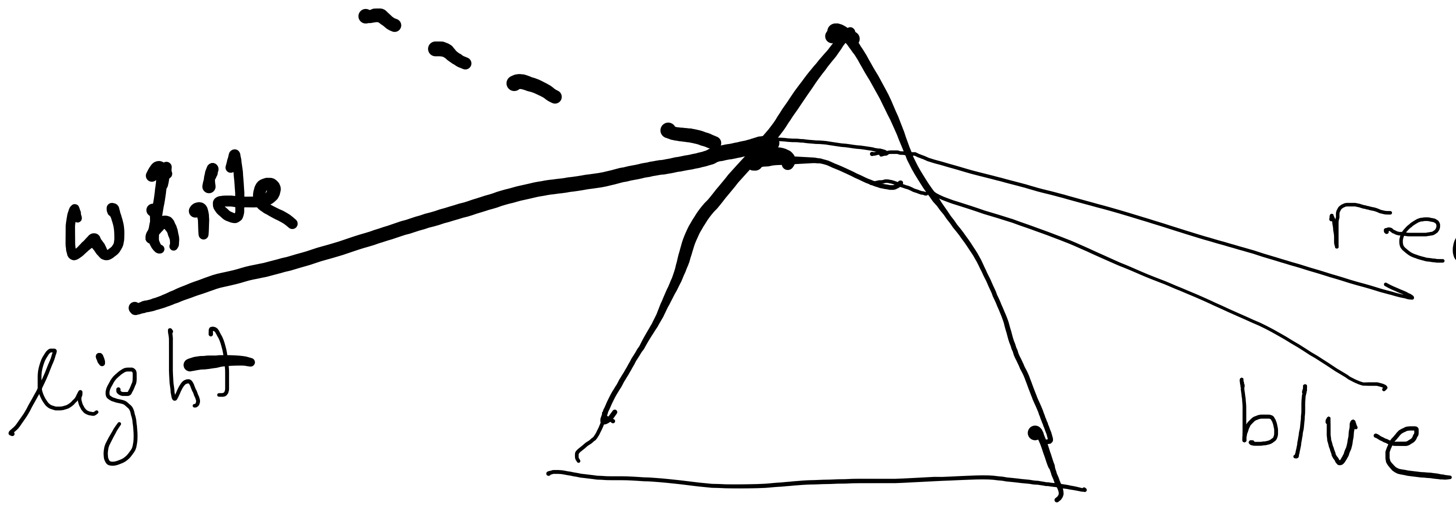


(b)

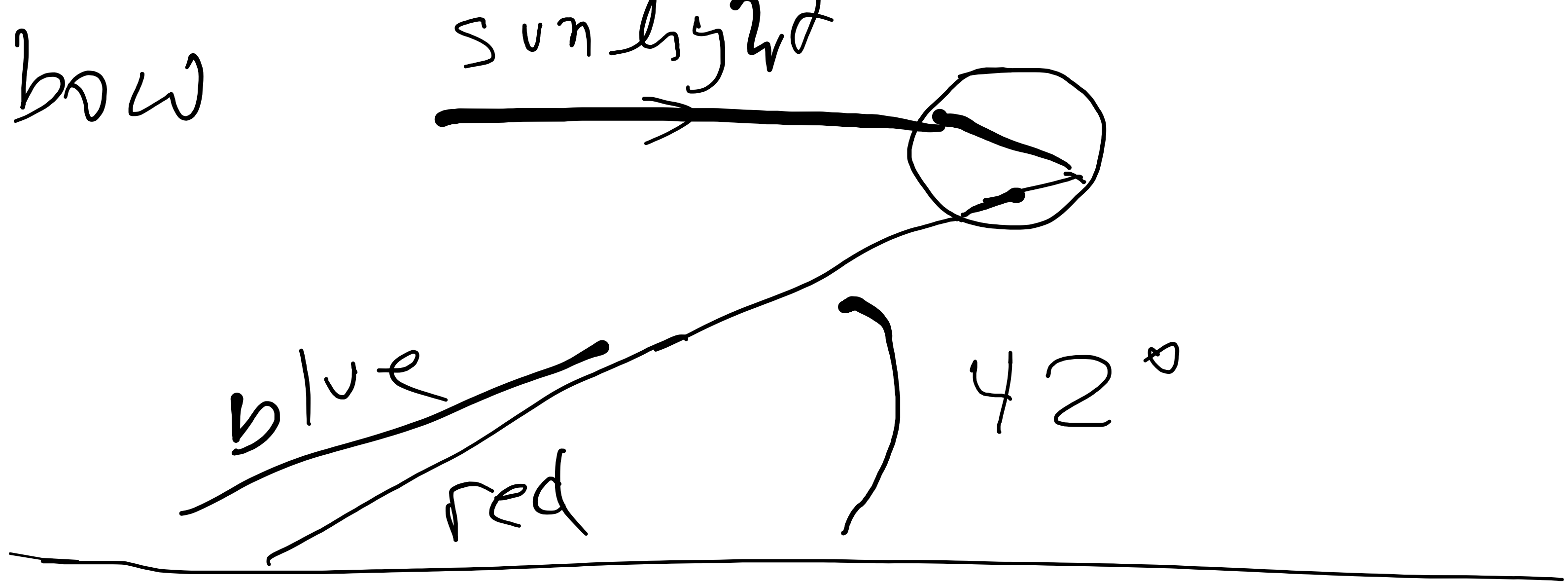
Chromatic dispersion of white light. The blue component is bent more than the red component. (a) Passing from air to glass, the blue component ends up with the smaller angle of refraction. (b) Passing from glass to air, the blue component ends up with the greater angle of refraction. Each dotted line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

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.





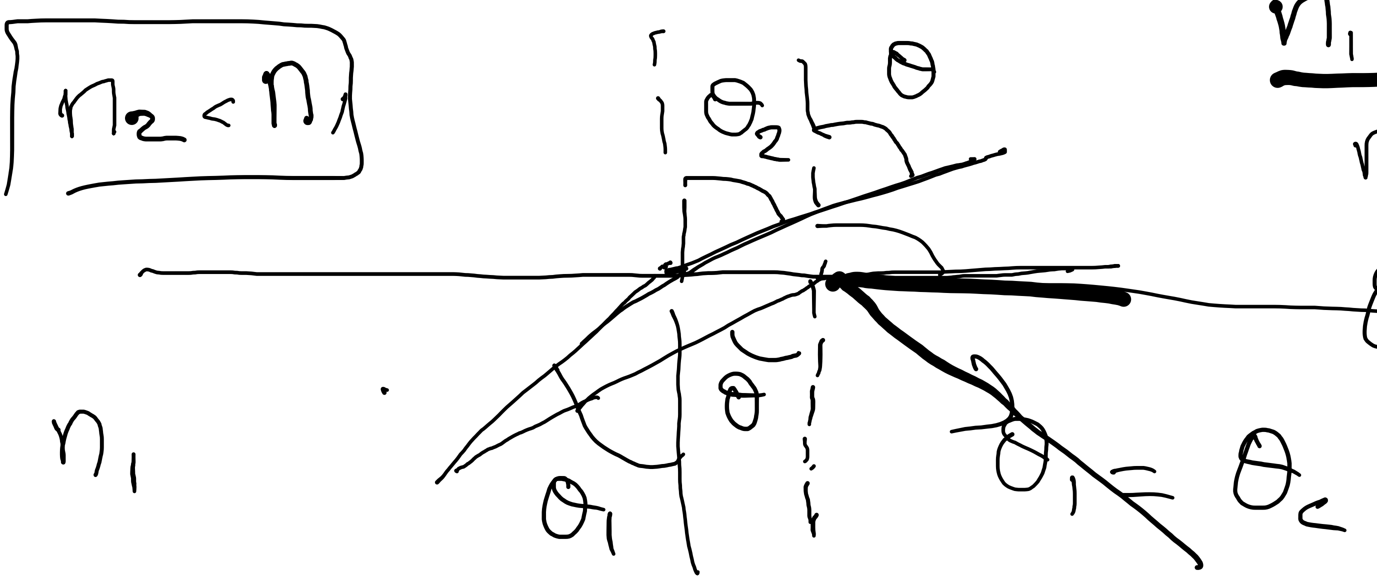
Rainbow



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.



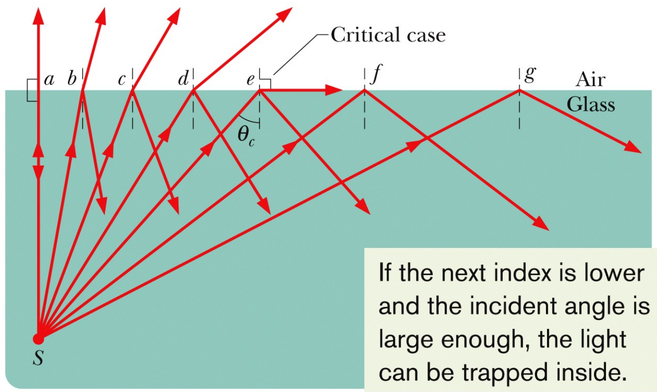
$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

$$n_2 = n_1 \sin\theta_c$$

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

$$\theta_2 = 90^\circ$$

Total Internal Reflection



(a)

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 uc. At the critical angle, the refracted ray points along the air – glass interface. (b) A source in a tank of water.

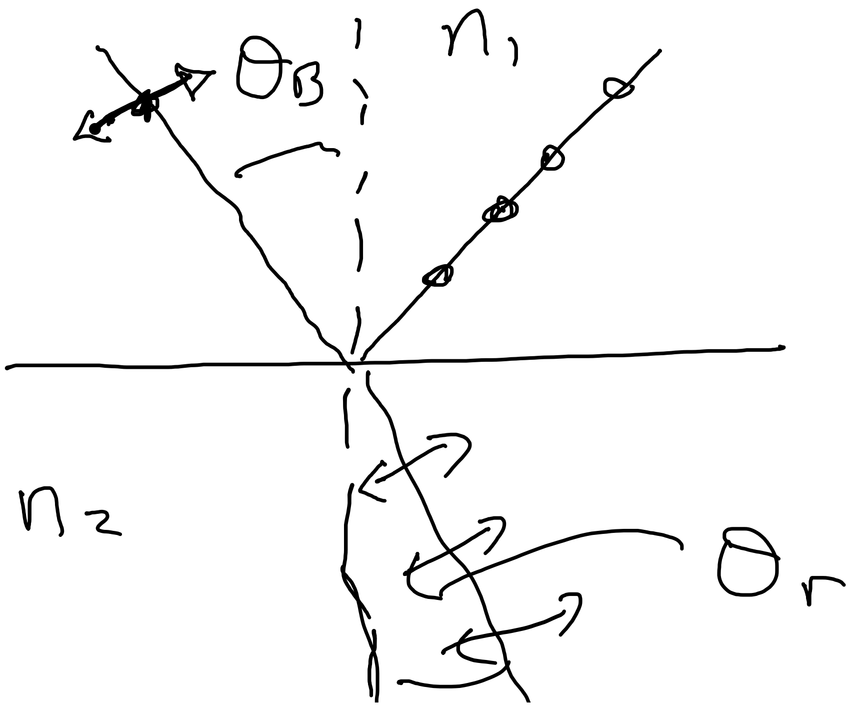
Figure (a) shows rays of monochromatic light from a point source S in glass incident on the interface between the glass and air. For ray a, which is perpendicular to the interface, part of the light reflects at the interface and the rest travels through it with no change in direction. For rays b through 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°, 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.

Polarization by Reflection

$$\tan\theta_B = n_2/n_1$$

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.



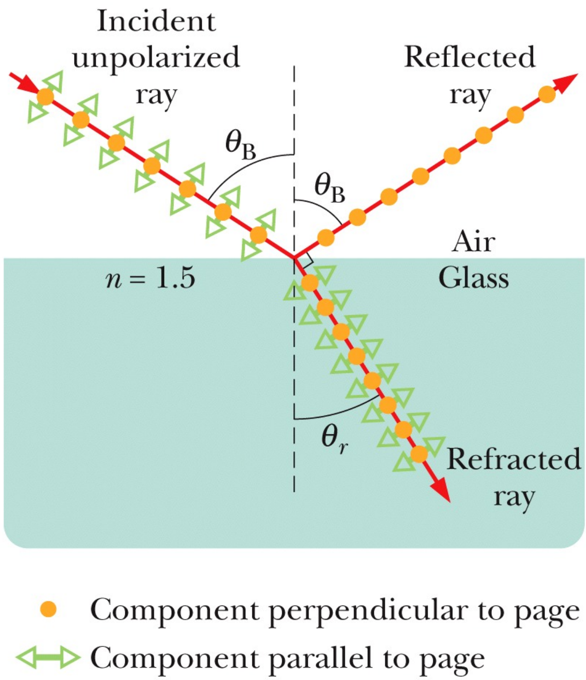
Brewster angle

$$\theta_B + \theta_r = 90^\circ$$

$$n_1 \sin\theta_B = n_2 \sin\theta_r = n_2 \cos\theta_B$$

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

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

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

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:

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

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**

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,

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

17.3.2. In a classroom demonstration, a physics professor breathes in a small amount of helium and begins to talk. The result is that the professor's normally low, baritone voice sounds quite high pitched. Which one of the following statements best describes this phenomena?

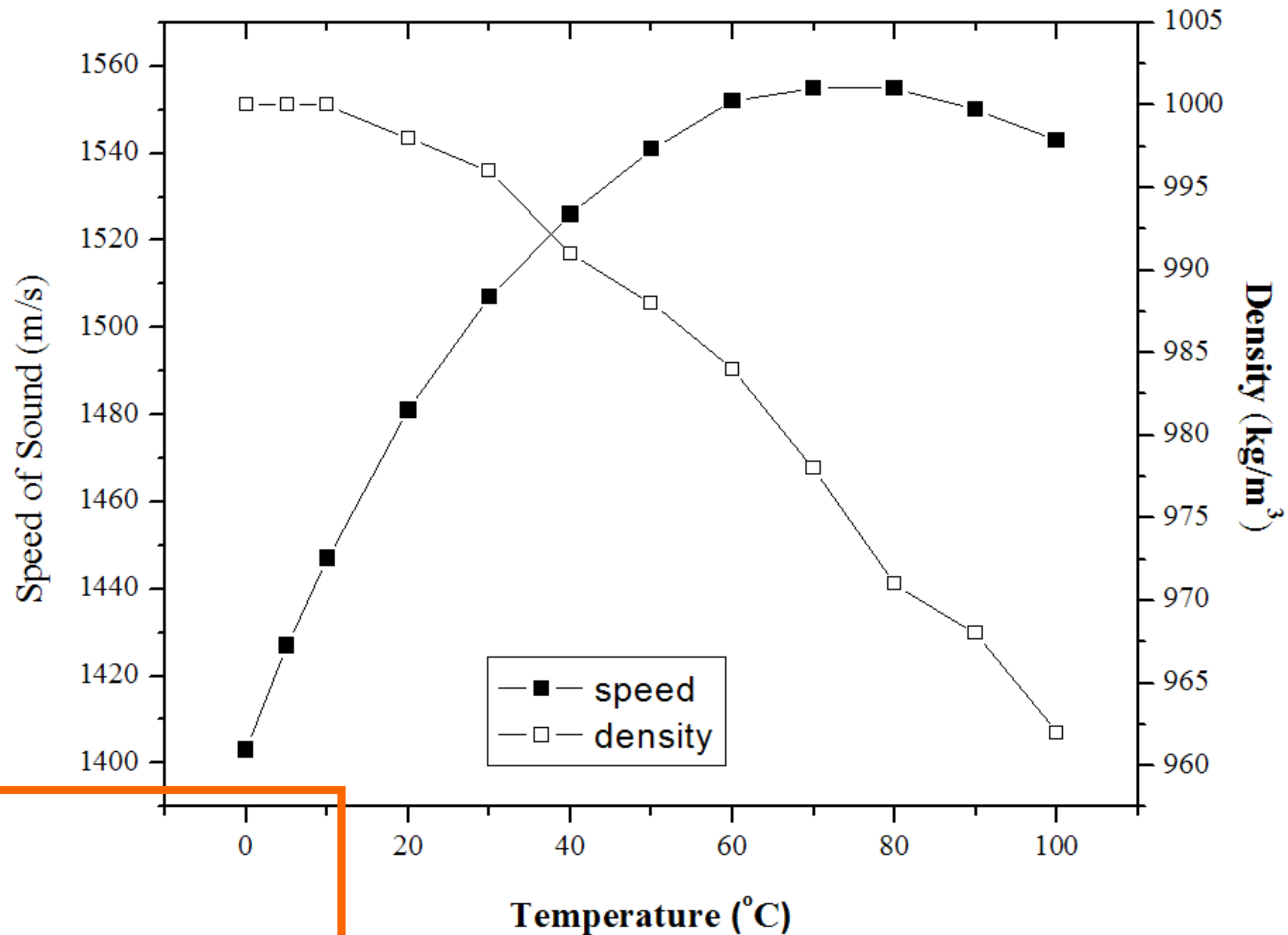
a) The presence of helium changes the speed of sound in the air in the room, causing all sounds to have higher frequencies.

b) The professor played a trick on the class by tightening his vocal cords to produces higher frequencies in his throat and mouth than normal. The helium was only a distraction and had nothing to do with it.

c) The helium significantly alters the vocal chords causing the wavelength of the sounds generated to decrease and thus the frequencies increase.

d) The wavelength of the sound generated in the professor's throat and mouth is only changed slightly, but since the speed of sound in helium is approximately 2.5 times larger than in air, therefore the frequencies generated are about 2.5 times higher.

17.3.3. The graph shows measured data for the speed of sound in water and the density of the water versus temperature. From the graph and your knowledge of the speed of sound in liquids, what can we infer about the bulk modulus of water in the temperature range from 0 to 100 °C?



a) The bulk modulus of water increases linearly with temperature.

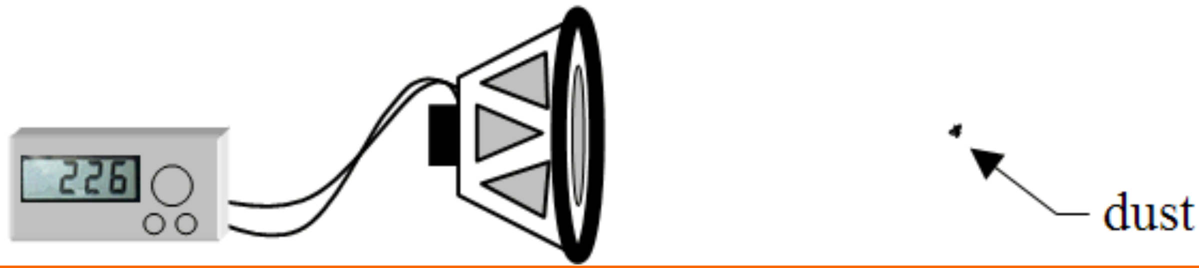
b) The bulk modulus of water decreases non-linearly with temperature.

c) The bulk modulus of water is constant with increasing temperature.

d) The bulk modulus of water increases non-linearly with increasing temperature.

e) The bulk modulus of water increases with increasing temperature until it peaks around 60 °C after which it slowly decreases.

17.4.1. A particle of dust is floating in the air approximately one half meter in front of a speaker. The speaker is then turned on produces a constant pure tone of 226 Hz, as shown. The sound waves produced by the speaker travel horizontally. Which one of the following statements correctly describes the subsequent motion of the dust particle, if any?



a) The particle of dust will oscillate left and right with a frequency of 226 Hz.

b) The particle of dust will oscillate up and down with a frequency of 226 Hz.

c) The particle of dust will be accelerated toward the right and continue moving in that direction.

d) The particle of dust will move toward the right at constant velocity.

e) The dust particle will remain motionless as it cannot be affected by sound waves.

17.5.1. Two identical speakers are emitting a constant tone that has a wavelength of 0.50 m. Speaker A is located to the left of speaker B. At which of the following locations would complete destructive interference occur?

a) 2.15 m from speaker A and 3.00 m from speaker B

b) 3.75 m from speaker A and 2.50 m from speaker B

c) 2.50 m from speaker A and 1.00 m from speaker B

d) 1.35 m from speaker A and 3.75 m from speaker B

e) 2.00 m from speaker A and 3.00 m from speaker B