PHYS1001B College Physics IB

Optics I The Nature and Propagation of Light (Ch. 33)

Introduction

By studying the branch of physics called **optics,** which deals with the behavior of light and other electromagnetic waves, we can reach a deeper appreciation of the visible world.

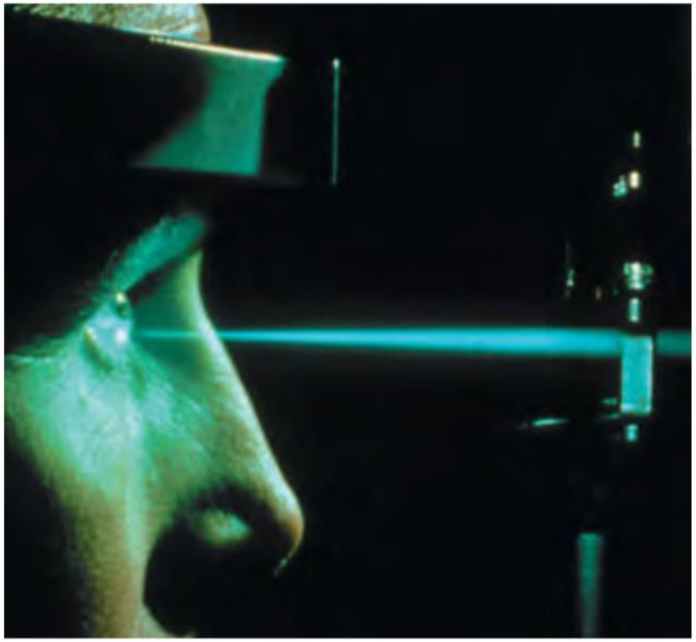
Outline

- 33-1 The Nature of Light
- 33-2 Reflection and Refraction
- 33-3 Total Internal Reflection
- 33-4 Dispersion
- 33-5 Polarization
- 33-6 Scattering of Light
- 33-7 Huygens's Principle

33-1 The Nature of Light

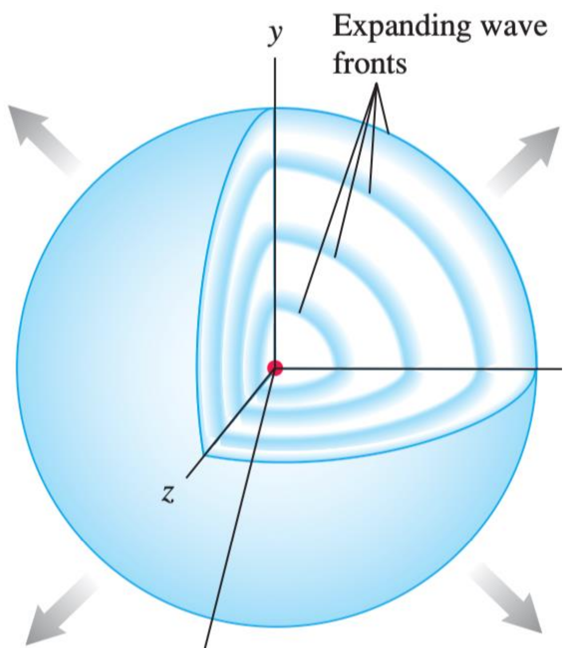
33.1 An electric heating element emits primarily infrared radiation. But if its temperature is high enough, it also emits a discernible amount of visible light.

33.2 Ophthalmic surgeons use lasers for repairing detached retinas and for cauterizing blood vessels in retinopathy. Pulses of blue-green light from an argon laser are ideal for this purpose, since they pass harmlessly through the transparent part of the eye but are absorbed by red pigments in the retina.

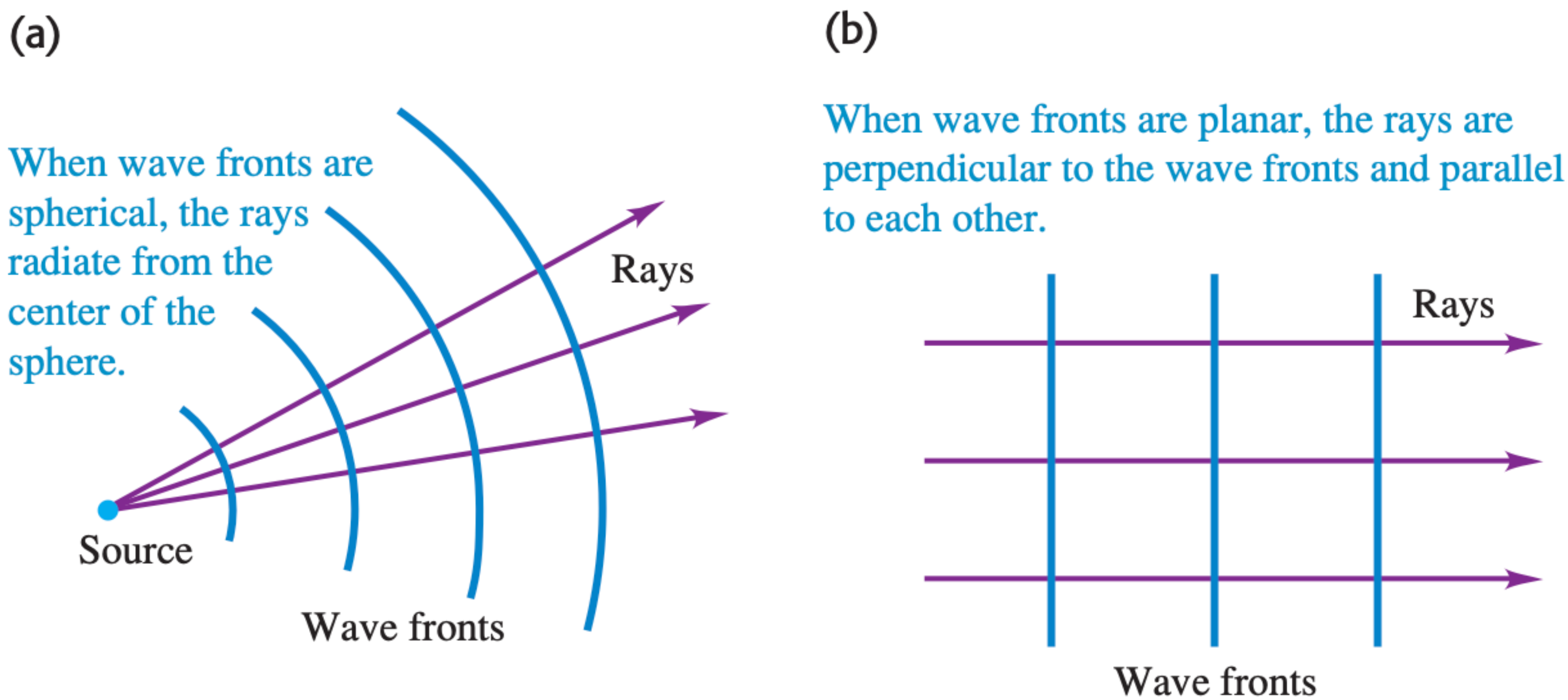


33-1 The Nature of Light

- Source: electric charges in accelerated motion.
- *wave* properties vs *particle* property
- the speed of light in vacuum 3.00 x10^8 m/s



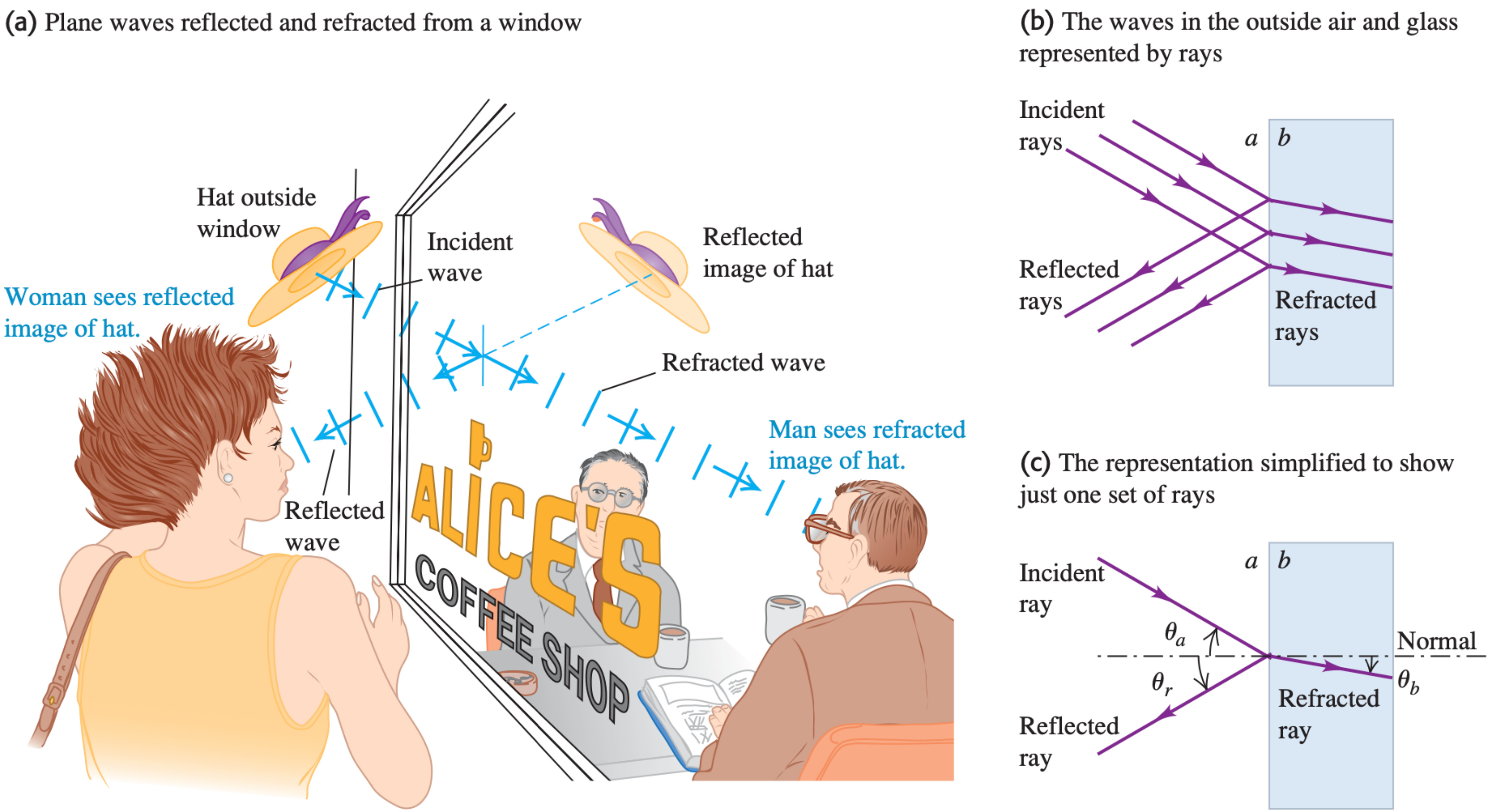
33-1 The Nature of Light



Ray description is adequate: geometric optics Ch 33 Ch 34

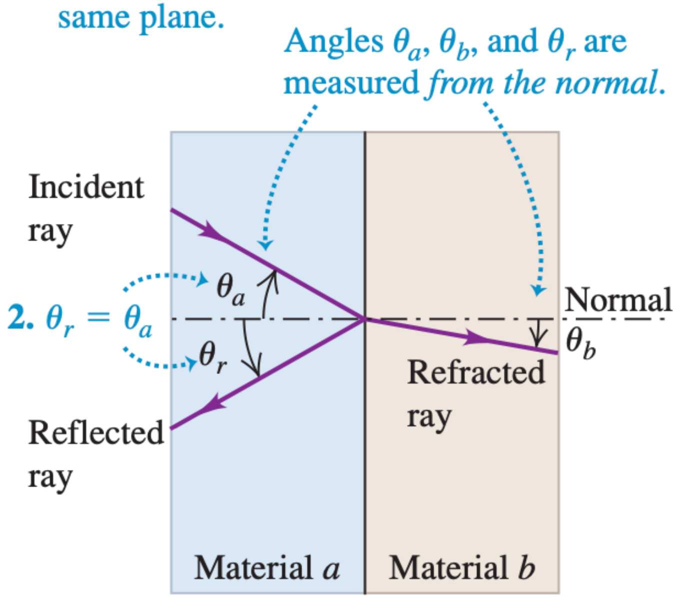
Require consideration of wave behavior: physical optics Ch 35 Ch 36

33-2 Reflection and Refraction



33-2 Reflection and Refraction

1. The incident, reflected, and refracted rays and the normal to the surface all lie in the same plane.



3. When a monochromatic light ray crosses the interface between two given materials a and b, the angles θ_a and θ_b are related to the indexes of refraction of a and b by

$$\frac{\sin\theta_a}{\sin\theta_b} = \frac{n_b}{n_a}$$

$$\theta_r = \theta_a \qquad \text{(law of reflection)}$$

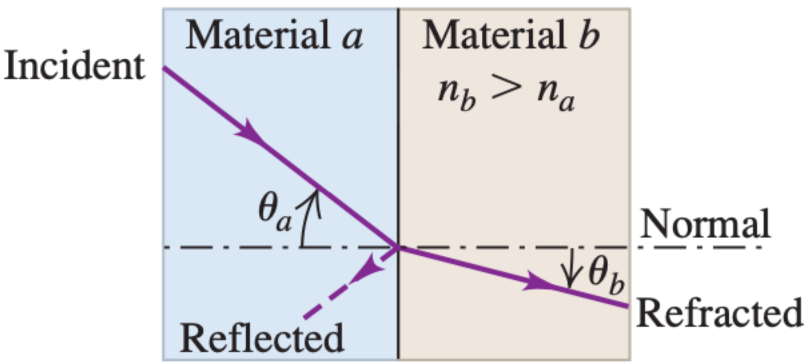
$$n_a \sin\theta_a = n_b \sin\theta_b \qquad \text{(law of refraction)}$$

$$n = \frac{c}{v} \qquad \text{(index of refraction)}$$

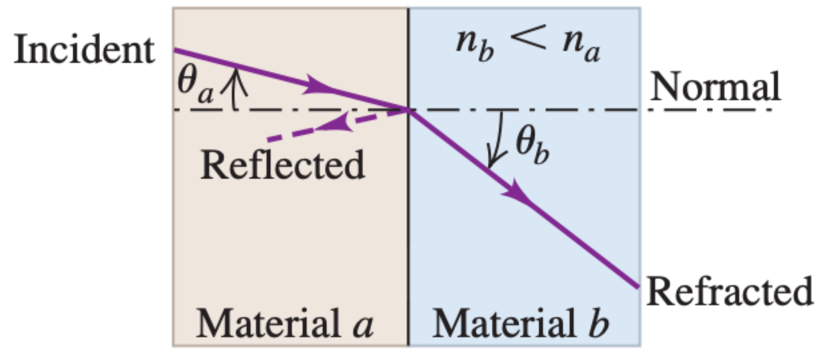
the ratio of the speed of light c in vacuum to the speed v in the material

33-2 Reflection and Refraction

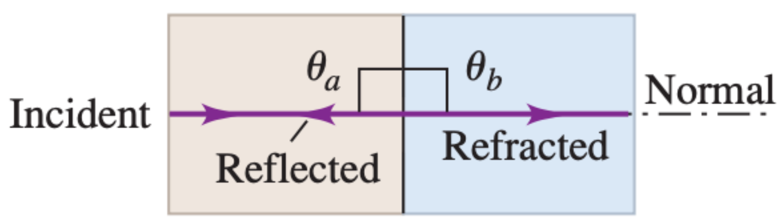
(a) A ray entering a material of *larger* index of refraction bends *toward* the normal.



(b) A ray entering a material of *smaller* index of refraction bends *away from* the normal.



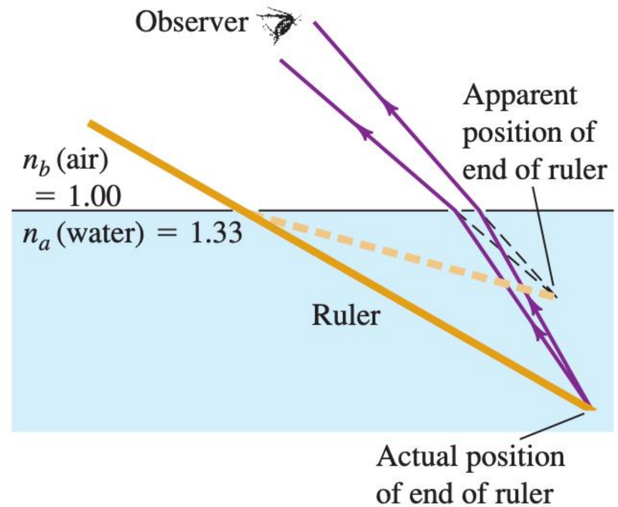
(c) A ray oriented along the normal does not bend, regardless of the materials.

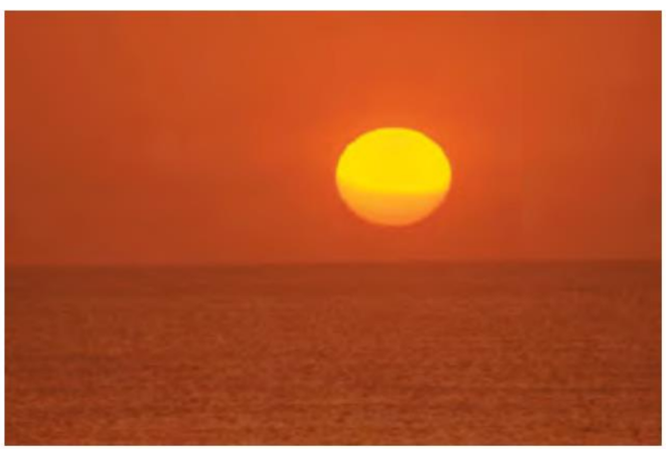


33-2 Reflection and Refraction

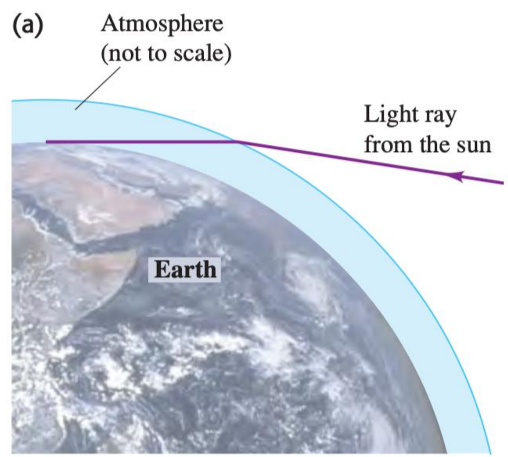
(a) A straight ruler half-immersed in water

(b) Why the ruler appears bent





(a)



Sample Problem

Example 33.1 **Reflection and refraction**

In Fig. 33.11, material a is water and material b is glass with index of refraction 1.52. The incident ray makes an angle of 60.0° with the normal; find the directions of the reflected and refracted rays.

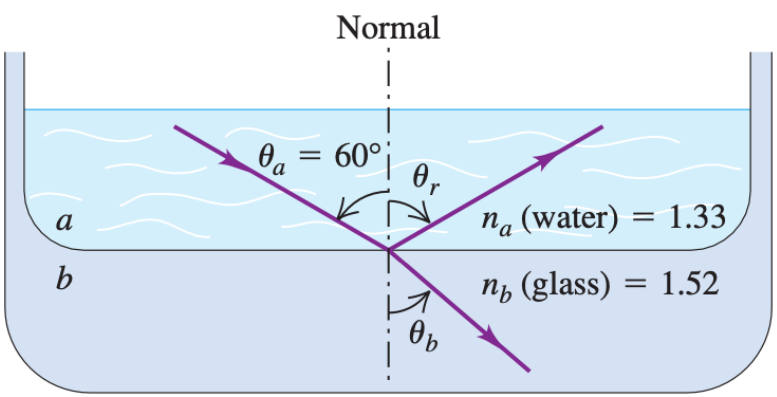
EXECUTE: According to Eq. (33.2), the angle the reflected ray makes with the normal is the same as that of the incident ray, so $\theta_r = \theta_a = 60.0°$.

To find the direction of the refracted ray we use Snell's law, Eq. (33.4):

$$n_a \sin\theta_a = n_b \sin\theta_b$$

$$\sin\theta_b = \frac{n_a}{n_b}\sin\theta_a = \frac{1.33}{1.52}\sin 60.0° = 0.758$$

$$\theta_b = \arcsin(0.758) = 49.3°$$



Sample Problem

Example 33.2 Index of refraction in the eye

The wavelength of the red light from a helium-neon laser is 633 nm in air but 474 nm in the aqueous humor inside your eyeball. Calculate the index of refraction of the aqueous humor and the speed and frequency of the light in it.

EXECUTE: The index of refraction of air is very close to unity, so we assume that the wavelength λ_0 in vacuum is the same as that in air, 633 nm. Then from Eq. (33.5),

$$\lambda = \frac{\lambda_0}{n} \qquad n = \frac{\lambda_0}{\lambda} = \frac{633\text{ nm}}{474\text{ nm}} = 1.34$$

This is about the same index of refraction as for water. Then, using $n = c/v$ and $v = \lambda f$, we find

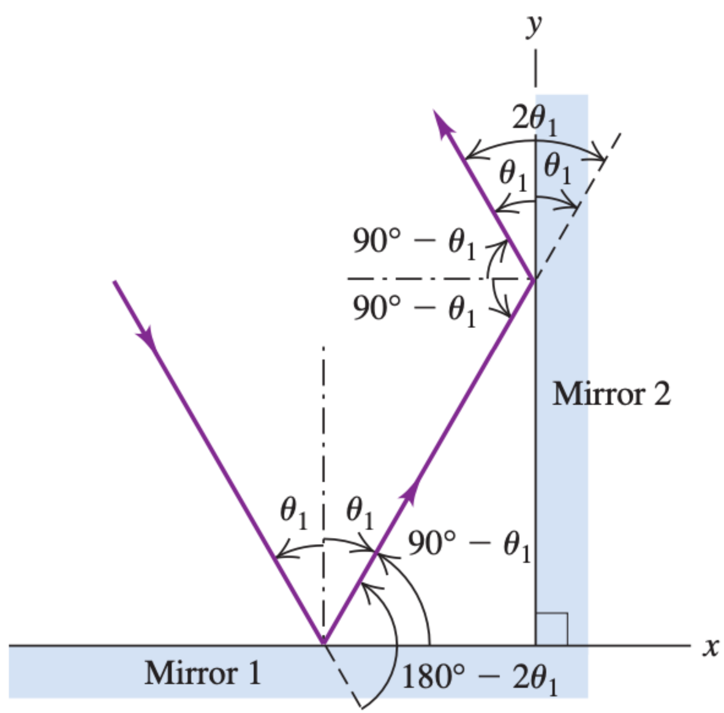
$$v = \frac{c}{n} = \frac{3.00 \times 10^8\,\text{m/s}}{1.34} = 2.25 \times 10^8\,\text{m/s}$$

$$f = \frac{v}{\lambda} = \frac{2.25 \times 10^8\,\text{m/s}}{474 \times 10^{-9}\,\text{m}} = 4.74 \times 10^{14}\text{ Hz}$$

Sample Problem

Example 33.3 A twice-reflected ray

Two mirrors are perpendicular to each other. A ray traveling in a plane perpendicular to both mirrors is reflected from one mirror, then the other, as shown in Fig. 33.12. What is the ray's final direction relative to its original direction?



Sample Problem

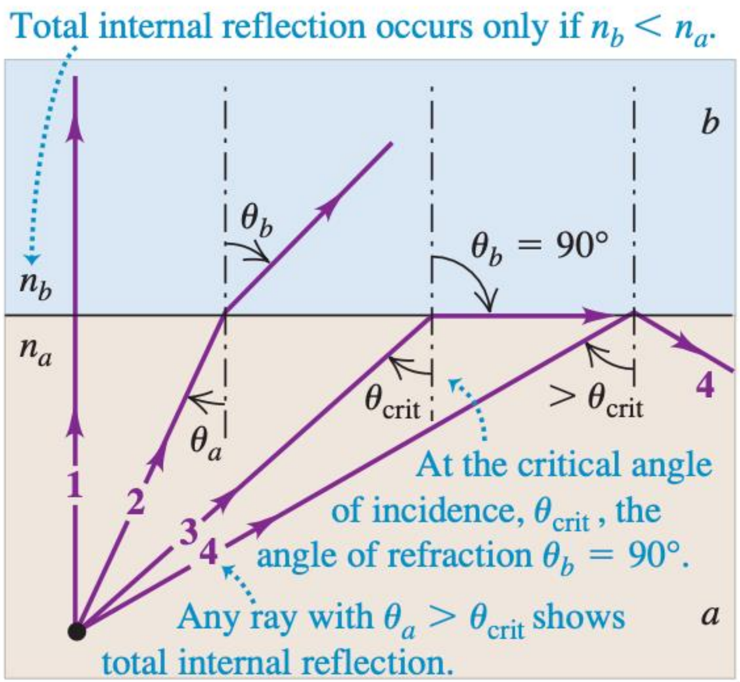
Example 33.3 A twice-reflected ray

Two mirrors are perpendicular to each other. A ray traveling in a plane perpendicular to both mirrors is reflected from one mirror, then the other, as shown in Fig. 33.12. What is the ray's final direction relative to its original direction?

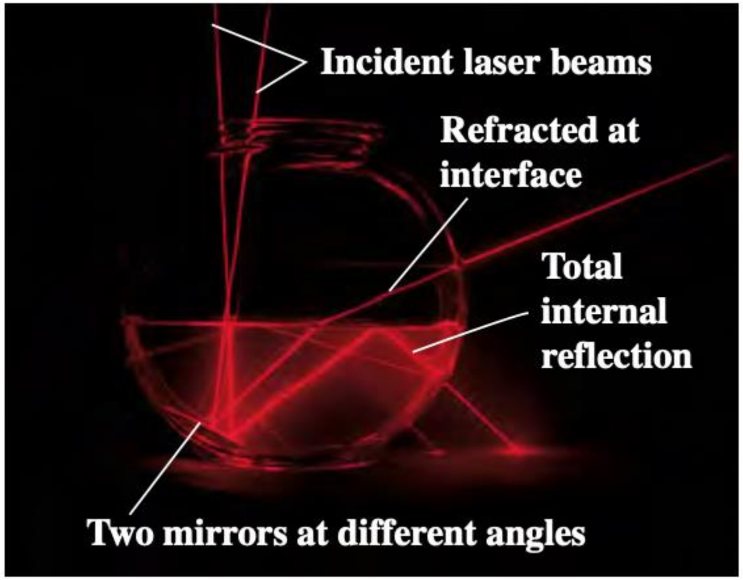
EXECUTE: For mirror 1 the angle of incidence is θ_1, and this equals the angle of reflection. The sum of interior angles in the triangle shown in the figure is 180°, so we see that the angles of incidence and reflection for mirror 2 are both $90° - \theta_1$. The total change in direction of the ray after both reflections is therefore $2(90° - \theta_1) + 2\theta_1 = 180°$. That is, the ray's final direction is opposite to its original direction.

33-3 Total Internal Reflection

(a) Total internal reflection

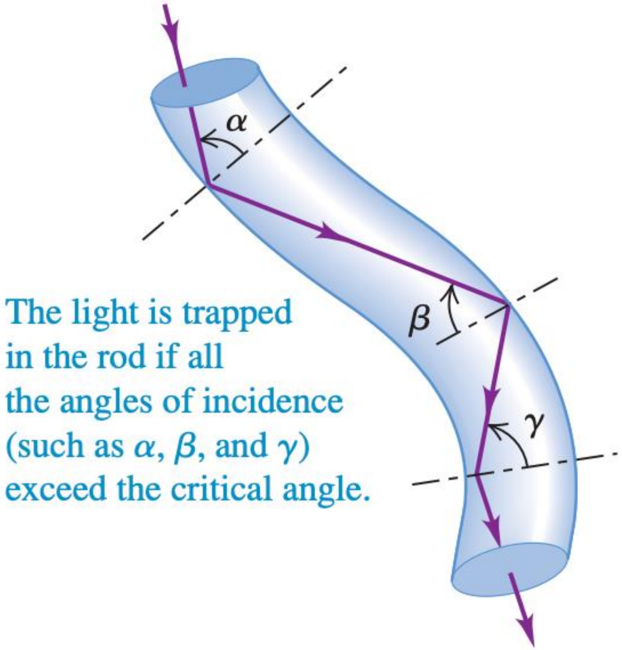


(b) Total internal reflection demonstrated with a laser, mirrors, and water in a fishbowl



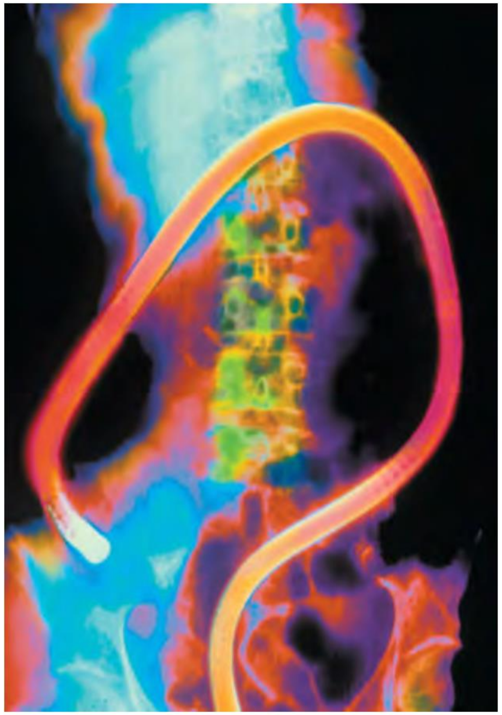
$$\sin\theta_{crit} = \frac{n_b}{n_a} \qquad \text{(critical angle for total internal reflection)}$$

33-3 Total Internal Reflection



light pipe

33.16 This colored x-ray image of a patient's abdomen shows an endoscope winding through the colon.



Cut of diamond

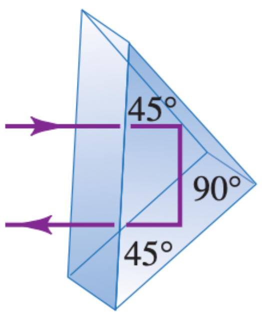
$$\sin \theta_{crit} = \frac{n_b}{n_a} \qquad \text{(critical angle for total internal reflection)}$$

Sample Problem

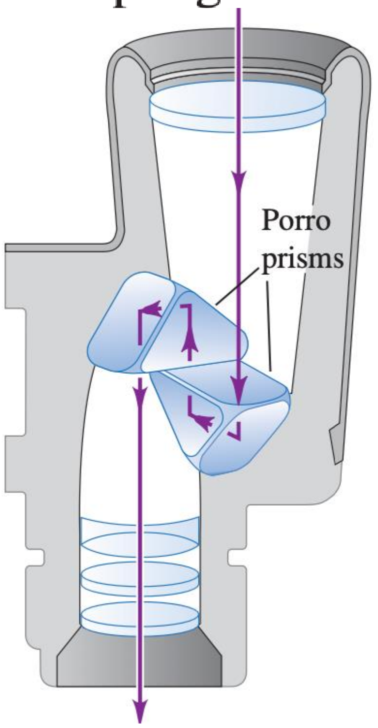
Conceptual Example 33.4 A leaky periscope

A submarine periscope uses two totally reflecting 45°−45°−90° prisms with total internal reflection on the sides adjacent to the 45° angles. Explain why the periscope will no longer work if it springs a leak and the bottom prism is covered with water.

(a) Total internal reflection in a Porro prism



If the incident beam is oriented as shown, total internal reflection occurs on the 45° faces (because, for a glass–air interface, $\theta_{crit} = 41.1$).



Sample Problem

Conceptual Example 33.4 A leaky periscope

A submarine periscope uses two totally reflecting 45°–45°–90° prisms with total internal reflection on the sides adjacent to the 45° angles. Explain why the periscope will no longer work if it springs a leak and the bottom prism is covered with water.

SOLUTION

The critical angle for water ($n_b = 1.33$) on glass ($n_a = 1.52$) is

$$\theta_{\text{crit}} = \arcsin\frac{1.33}{1.52} = 61.0°$$

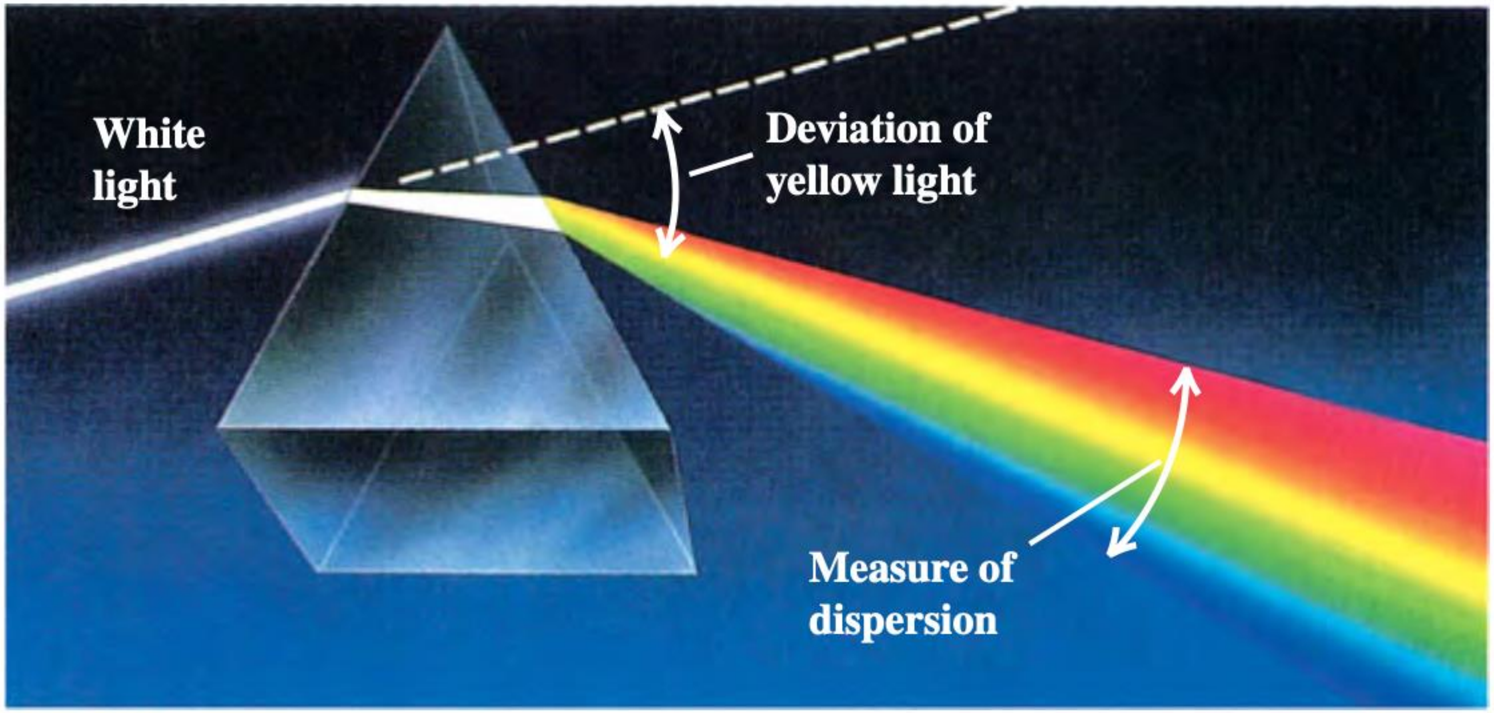
The 45° angle of incidence for a totally reflecting prism is *smaller* than this new 61° critical angle, so total internal reflection does not occur at the glass–water interface. Most of the light is transmitted into the water, and very little is reflected back into the prism.

Sample Problem

Test Your Understanding of Section 33.3 In which of the following situations is there total internal reflection? (i) Light propagating in water ($n = 1.33$) strikes a water–air interface at an incident angle of 70°; (ii) light propagating in glass ($n = 1.52$) strikes a glass–water interface at an incident angle of 70°; (iii) light propagating in water strikes a water–glass interface at an incident angle of 70°.

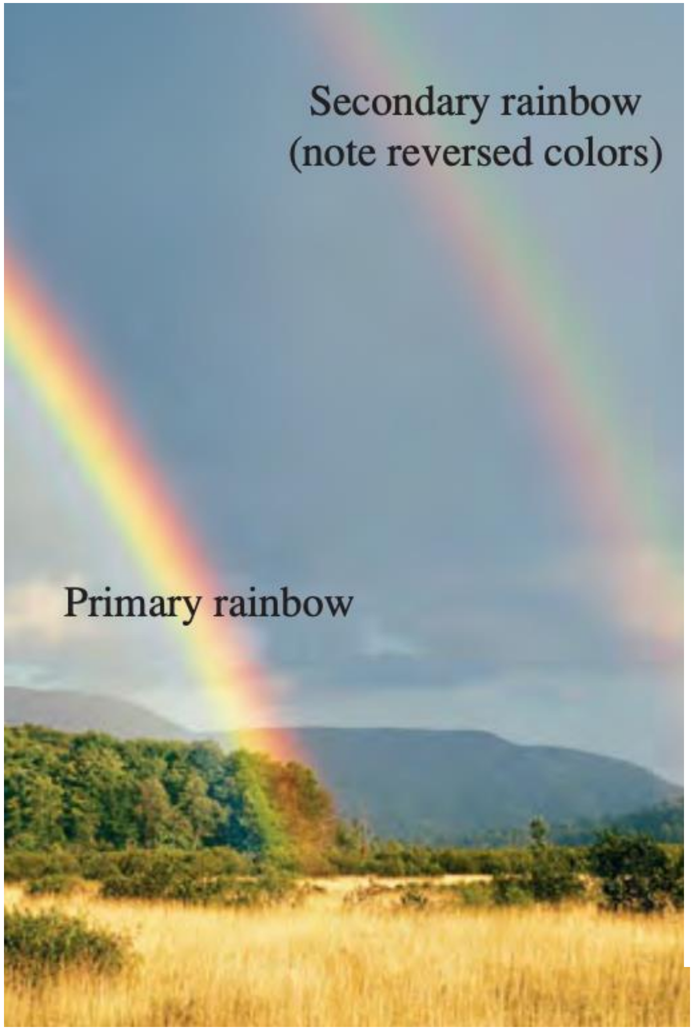
33-4 Dispersion

$$\lambda = \frac{\lambda_0}{n} \qquad \text{(wavelength of light in a material)}$$

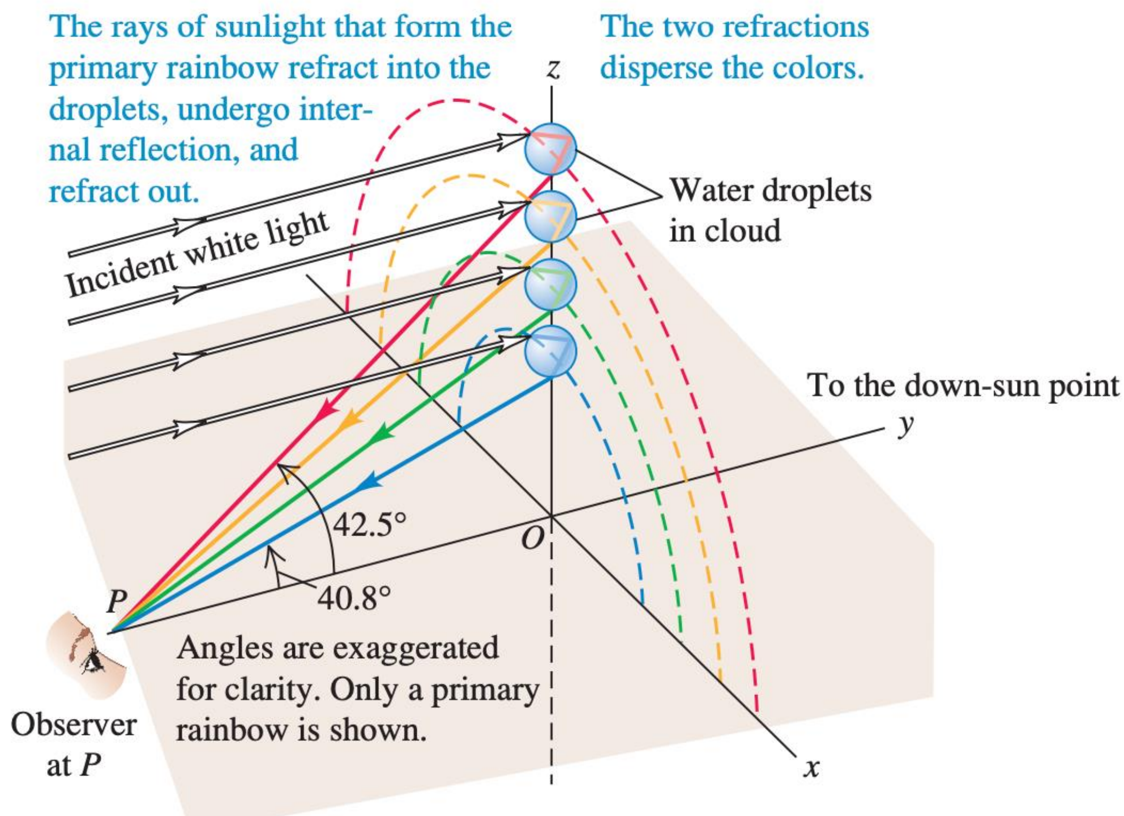


The dependence of wave speed and index of refraction on wavelength is called **dispersion.**

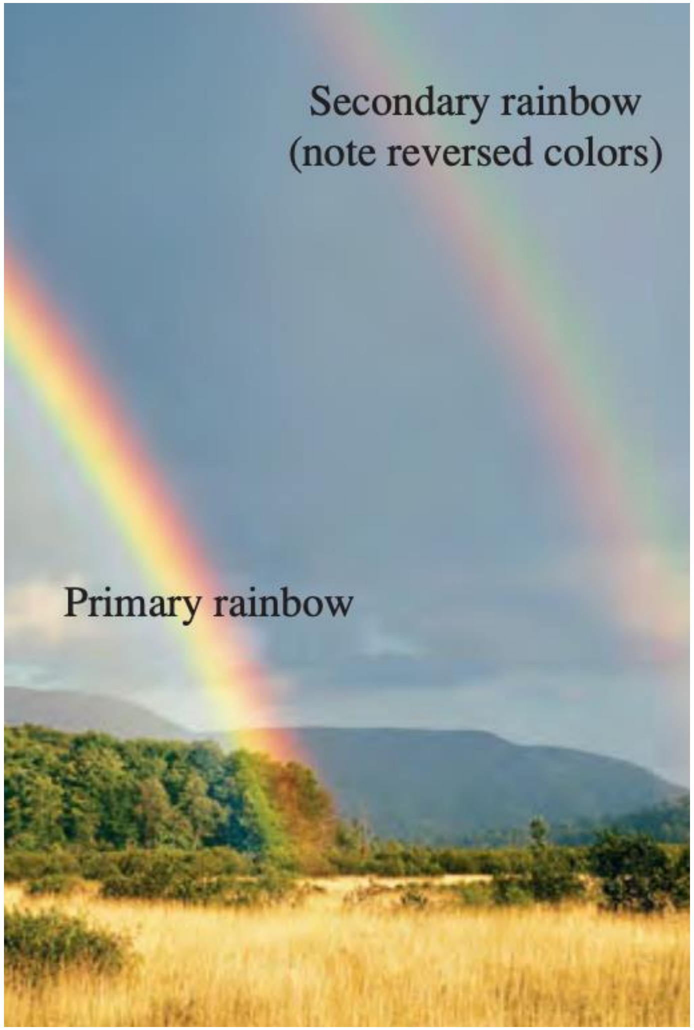
33-4 Dispersion



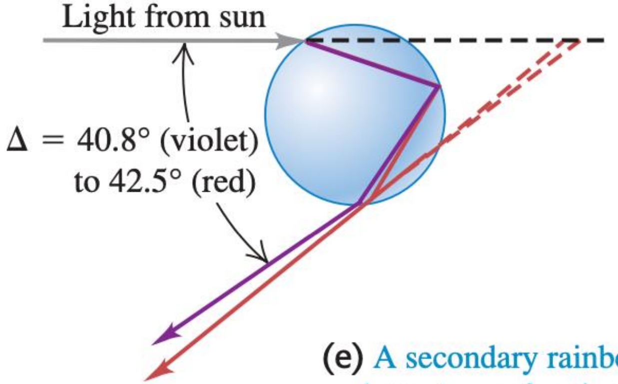
(c) Forming a rainbow. The sun in this illustration is directly behind the observer at *P*.



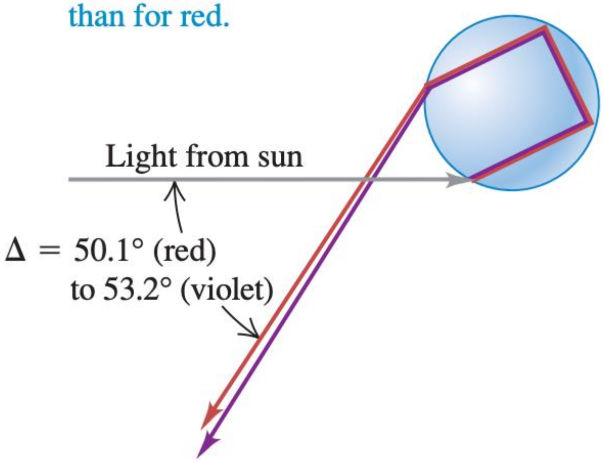
33-4 Dispersion



(d) A primary rainbow is formed by rays that undergo two refractions and one internal reflection. The angle Δ is larger for red light than for violet.

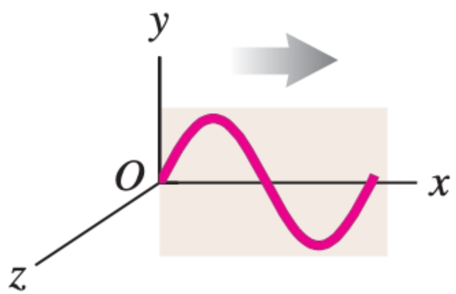


(e) A secondary rainbow is formed by rays that undergo two refractions and *two* internal reflections. The angle Δ is larger for violet light than for red.

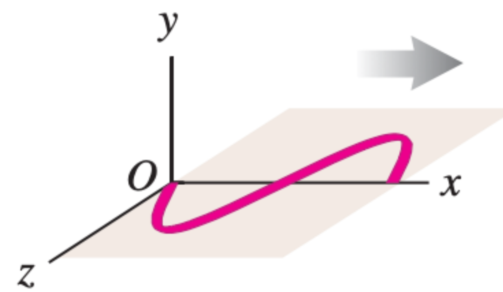


33-5 Polarization

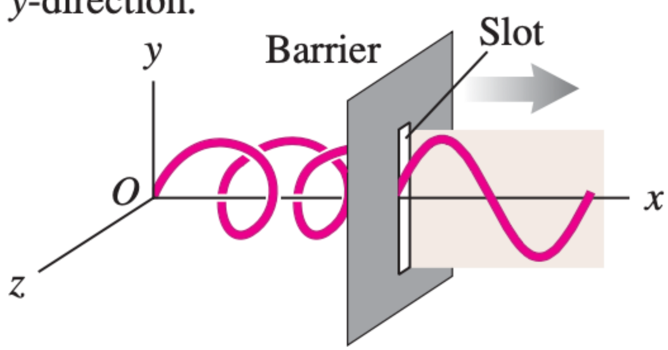
(a) Transverse wave linearly polarized in the *y*-direction



(b) Transverse wave linearly polarized in the *z*-direction



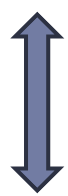
(c) The slot functions as a polarizing filter, passing only components polarized in the *y*-direction.

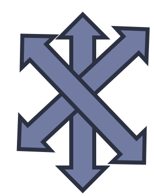


33-5 Polarization

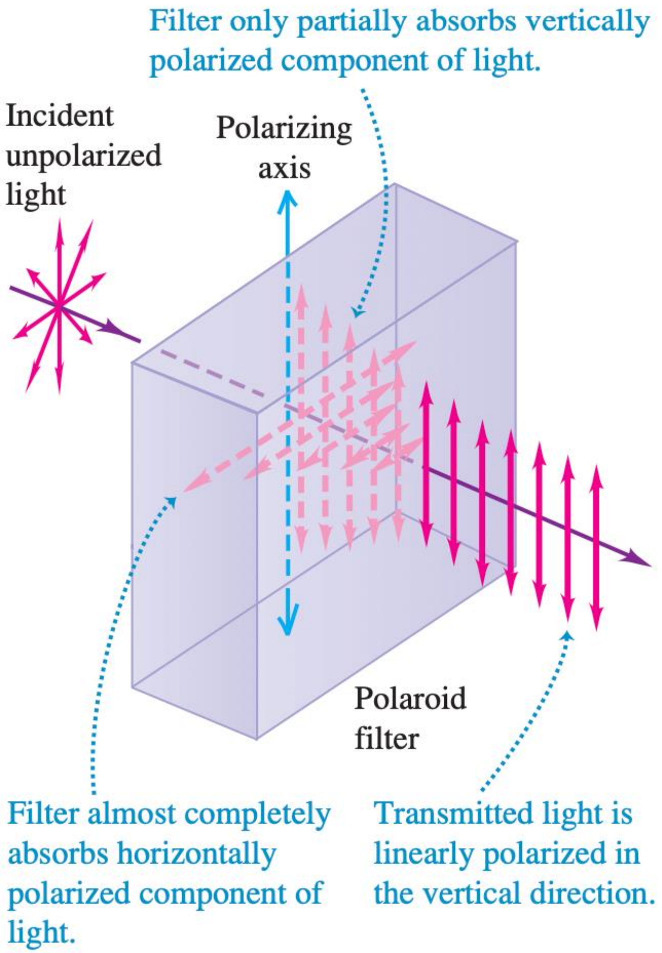
33.22 **(a)** Electrons in the red and white broadcast antenna oscillate vertically, producing vertically polarized electromagnetic waves that propagate away from the antenna in the horizontal direction. (The small gray antennas are for relaying cellular phone signals.) **(b)** No matter how this light bulb is oriented, the random motion of electrons in the filament produces unpolarized light waves.

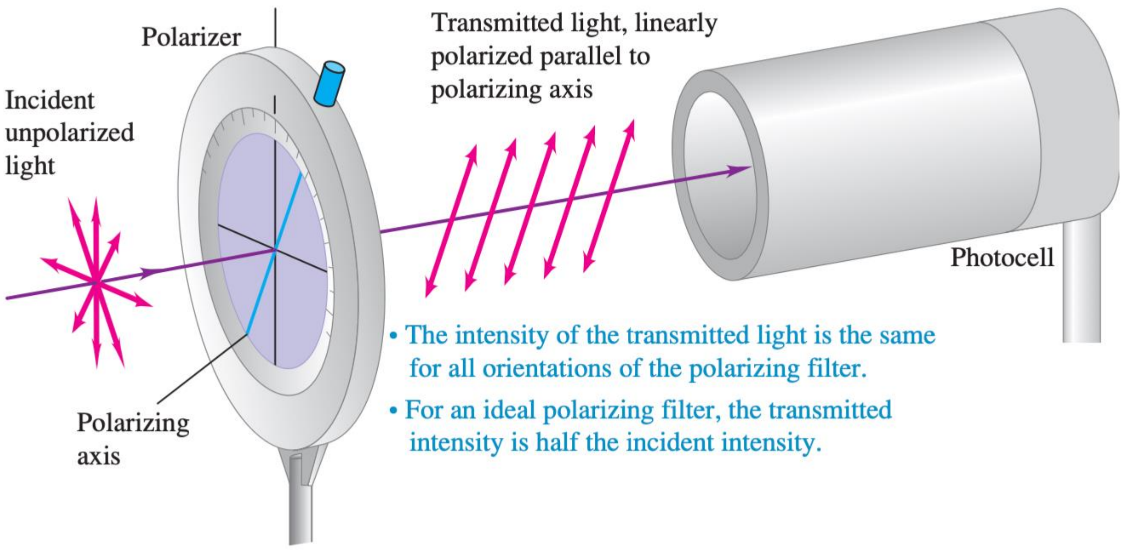
(a) (b)





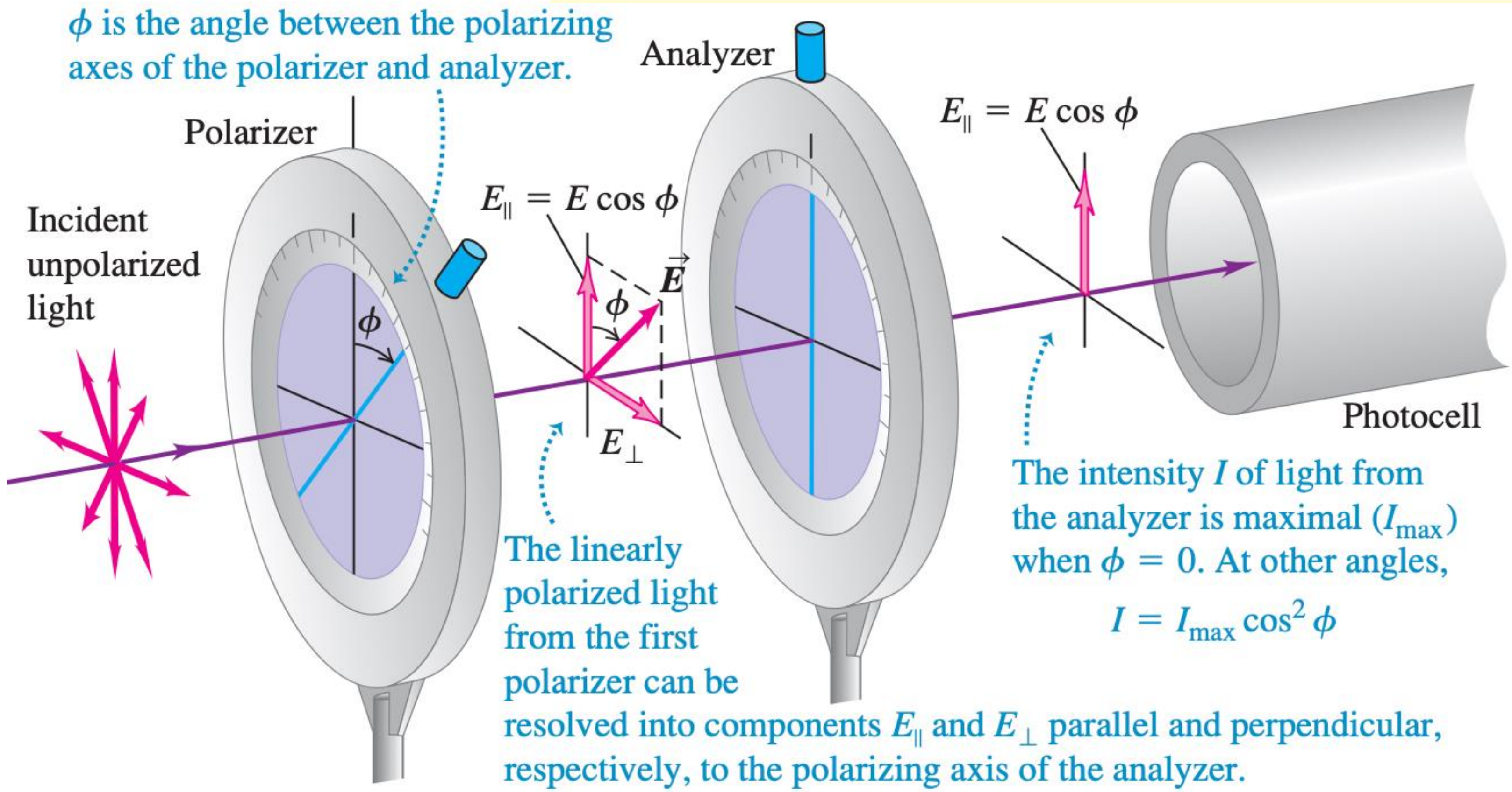
33-5 Polarization



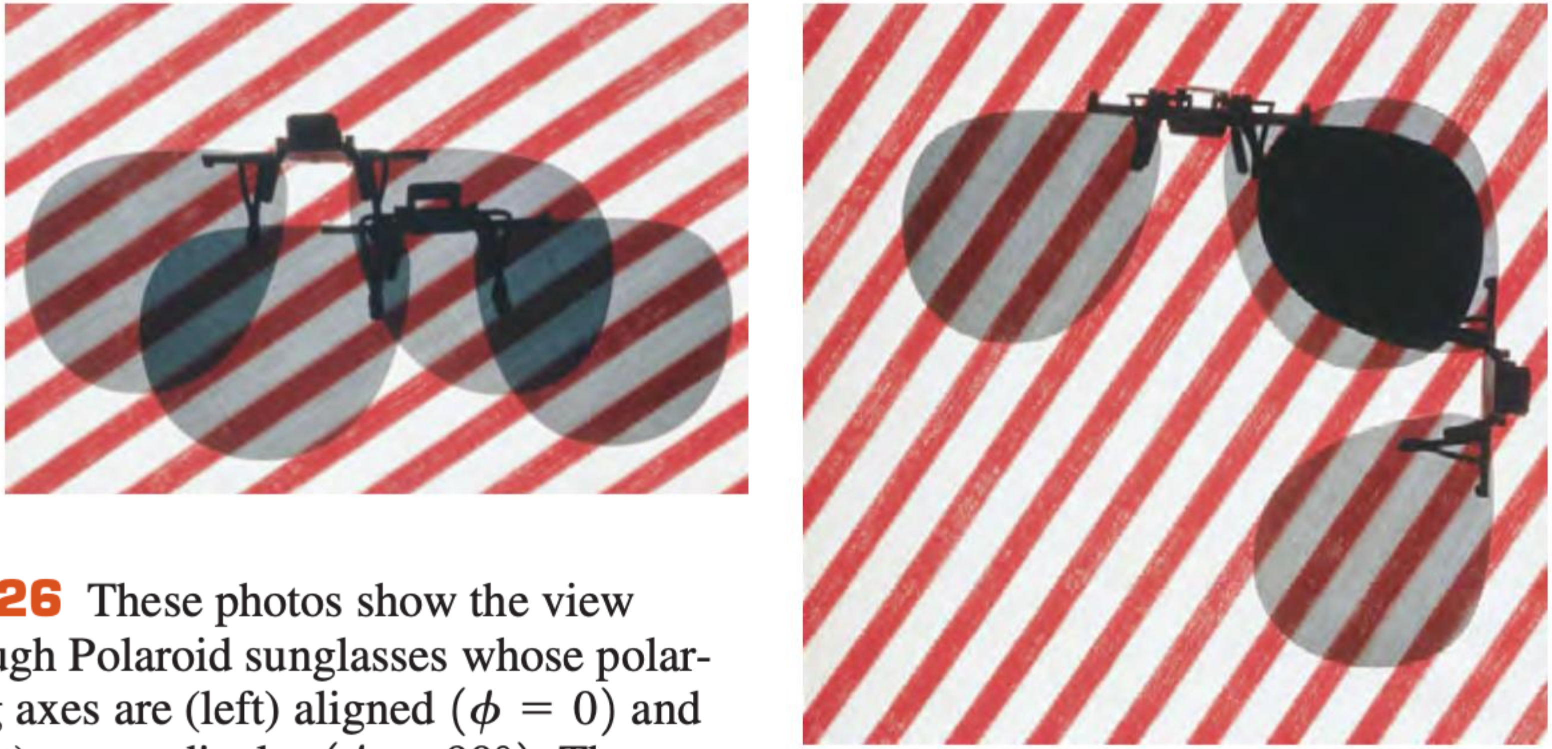


33-5 Polarization

$$I = I_{max} \cos^2 \phi$$ (Malus's law, polarized light passing through an analyzer)



33-5 Polarization



33.26 These photos show the view through Polaroid sunglasses whose polarizing axes are (left) aligned ($\phi = 0$) and (right) perpendicular ($\phi = 90°$). The transmitted intensity is greatest when the axes are aligned; it is zero when the axes are perpendicular.

Sample Problem

Example 33.5 **Two polarizers in combination**

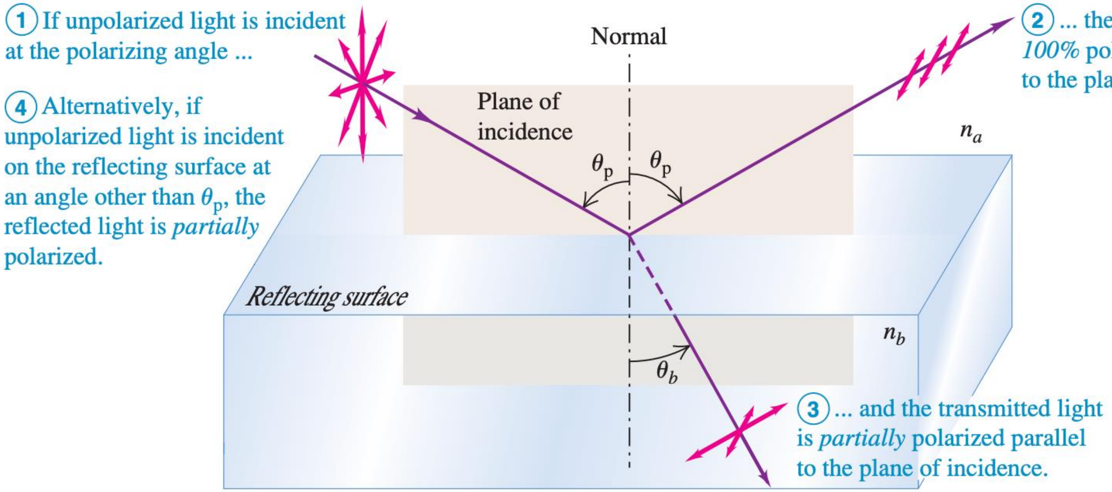
In Fig. 33.25 the incident unpolarized light has intensity I_0. Find the intensities transmitted by the first and second polarizers if the angle between the axes of the two filters is 30°.

EXECUTE: The incident light is unpolarized, so the intensity of the linearly polarized light transmitted by the first polarizer is $I_0/2$. From Eq. (33.7) with $\phi = 30°$, the second polarizer reduces the intensity by a further factor of $\cos^2 30° = \frac{3}{4}$. Thus the intensity transmitted by the second polarizer is

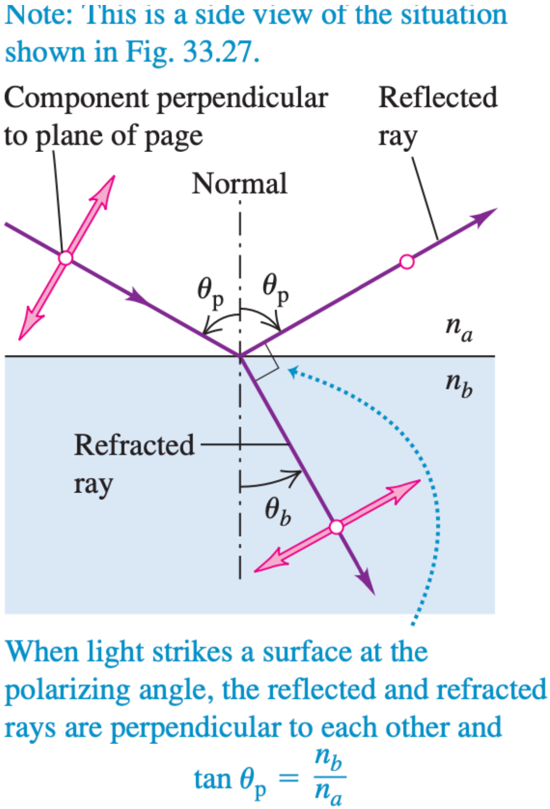
$$\left(\frac{I_0}{2}\right)\left(\tfrac{3}{4}\right) = \tfrac{3}{8}I_0$$

33-5 Polarization

33.27 When light is incident on a reflecting surface at the polarizing angle, the reflected light is linearly polarized.



$$\tan\theta_p = \frac{n_b}{n_a} \qquad \text{(Brewster's law for the polarizing angle)}$$



Sample Problem

Example 33.6 Reflection from a swimming pool's surface

Sunlight reflects off the smooth surface of a swimming pool. (a) For what angle of reflection is the reflected light completely polarized? (b) What is the corresponding angle of refraction? (c) At night, an underwater floodlight is turned on in the pool. Repeat parts (a) and (b) for rays from the floodlight that strike the surface from below.

EXECUTE: (a) During the day (shown in the upper part of Fig. 33.29) the light moves in air toward water, so $n_a = 1.00$ (air) and $n_b = 1.33$ (water). From Eq. (33.8),

$$\theta_p = \arctan\frac{n_b}{n_a} = \arctan\frac{1.33}{1.00} = 53.1°$$

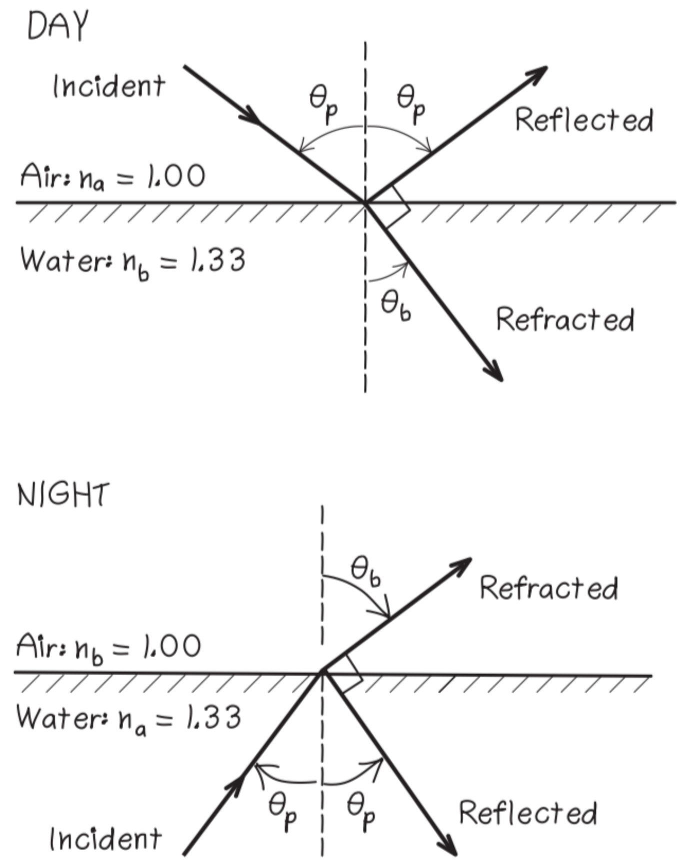
(b) The incident light is at the polarizing angle, so the reflected and refracted rays are perpendicular; hence

$$\theta_b = 90° - \theta_p = 90° - 53.1° = 36.9°$$

(c) At night (shown in the lower part of Fig. 33.29) the light moves in water toward air, so now $n_a = 1.33$ and $n_b = 1.00$. Again using Eq. (33.8), we have

$$\theta_p = \arctan\frac{1.00}{1.33} = 36.9°$$

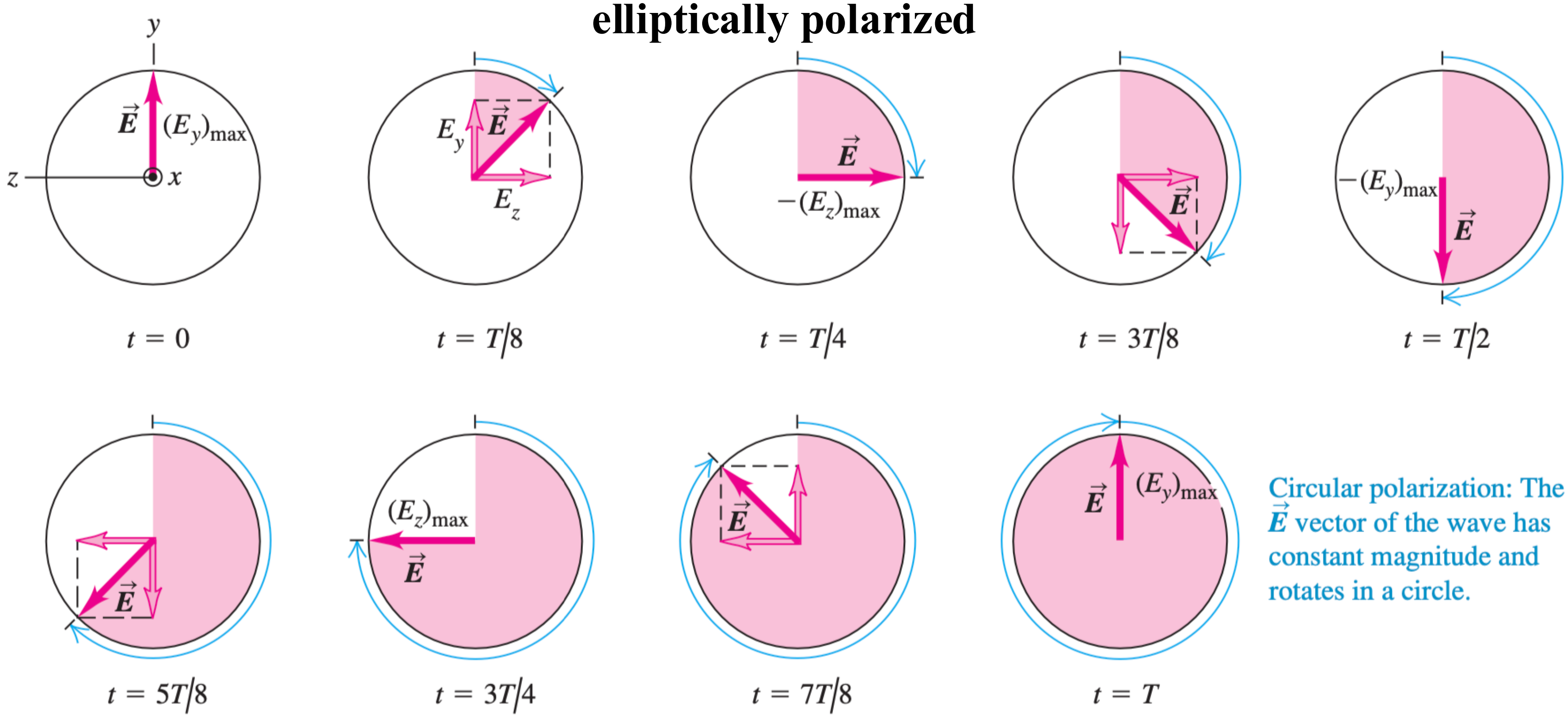
$$\theta_b = 90° - 36.9° = 53.1°$$



33-5 Polarization

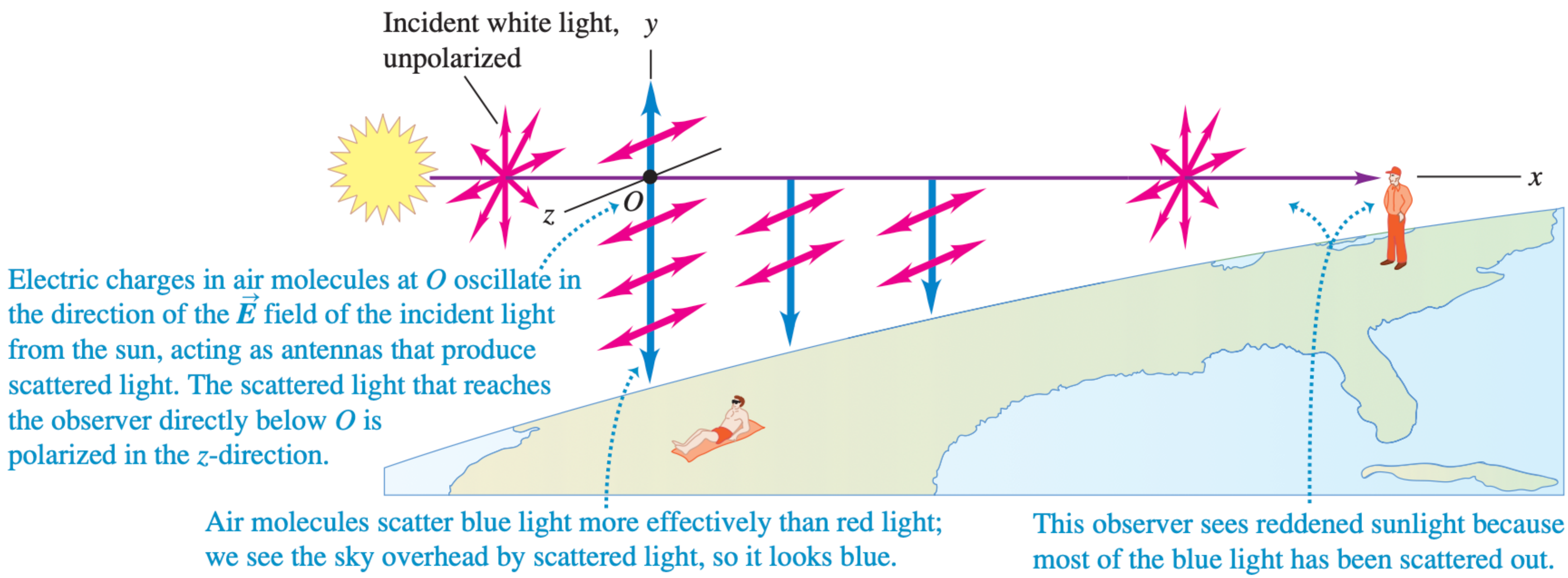
33.30 Circular polarization of an electromagnetic wave moving toward you parallel to the x-axis. The y-component of $\vec{E}$ lags the z-component by a quarter-cycle. This phase difference results in right circular polarization.

elliptically polarized



33-6 Scattering of Light

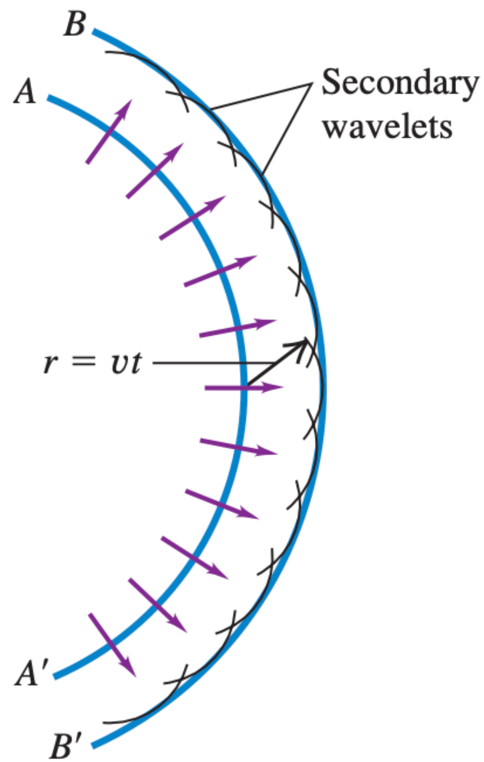
33.32 When the sunbathing observer on the left looks up, he sees blue, polarized sunlight that has been scattered by air molecules. The observer on the right sees reddened, unpolarized light when he looks at the sun.



33-6 Scattering of Light

Light of *all* wavelengths is eventually scattered out of the cloud, so the cloud looks white

33-7 Huygens's Principle

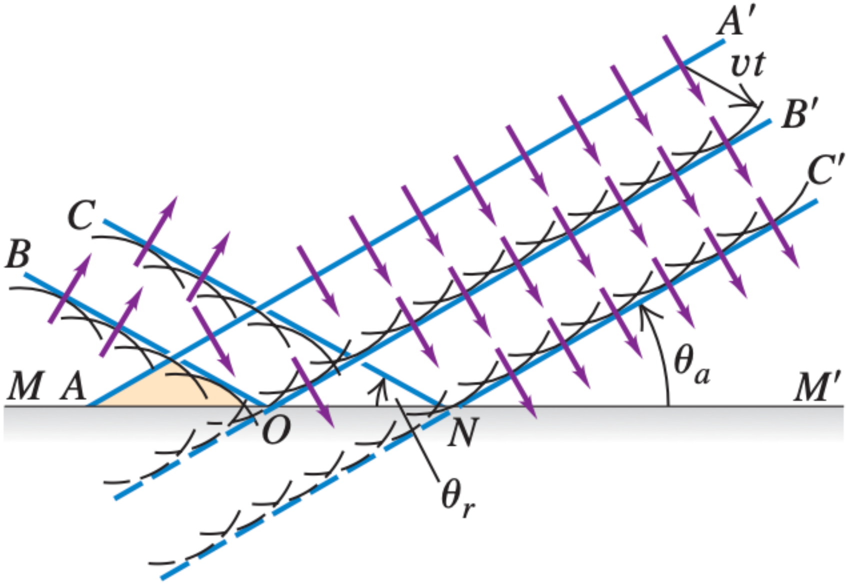


Every point of a wave front may be considered the source of secondary wavelets that spread out in all directions with a speed equal to the speed of propagation of the wave.

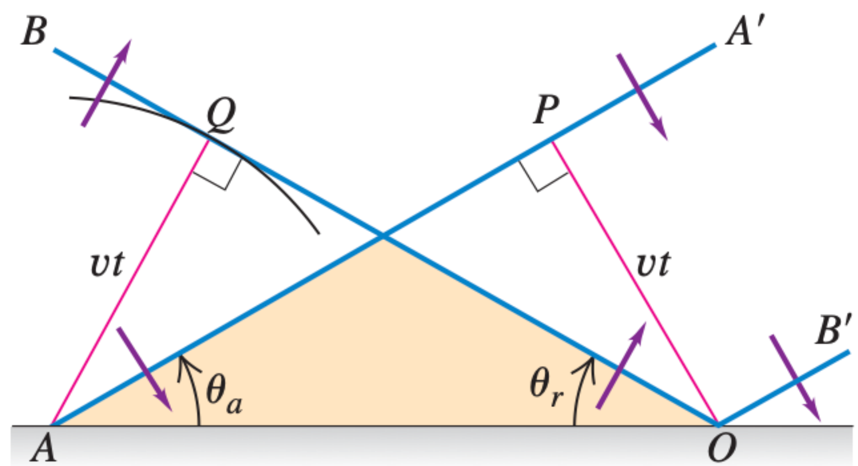
33-7 Huygens's Principle

Law of reflection from Huygens's principle

(a) Successive positions of a plane wave AA' as it is reflected from a plane surface



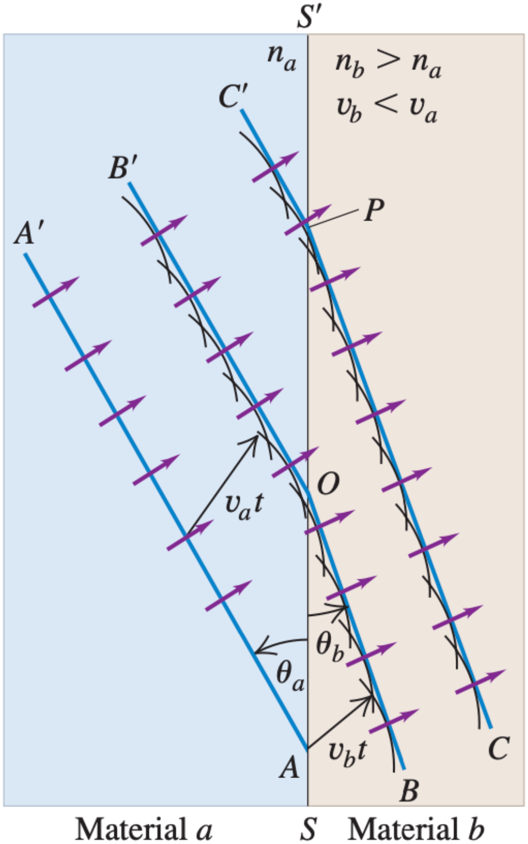
(b) Magnified portion of **(a)**



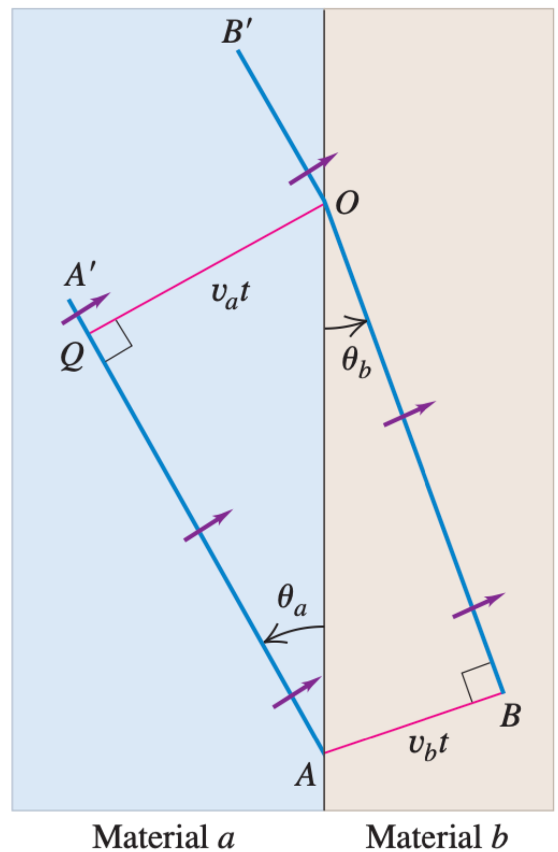
33-7 Huygens's Principle

Law of reflection from Huygens's principle

(a) Successive positions of a plane wave AA' as it is refracted by a plane surface



(b) Magnified portion of **(a)**



33-7 Huygens's Principle