

# PHYS1001B College Physics IB

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

# Introduction

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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

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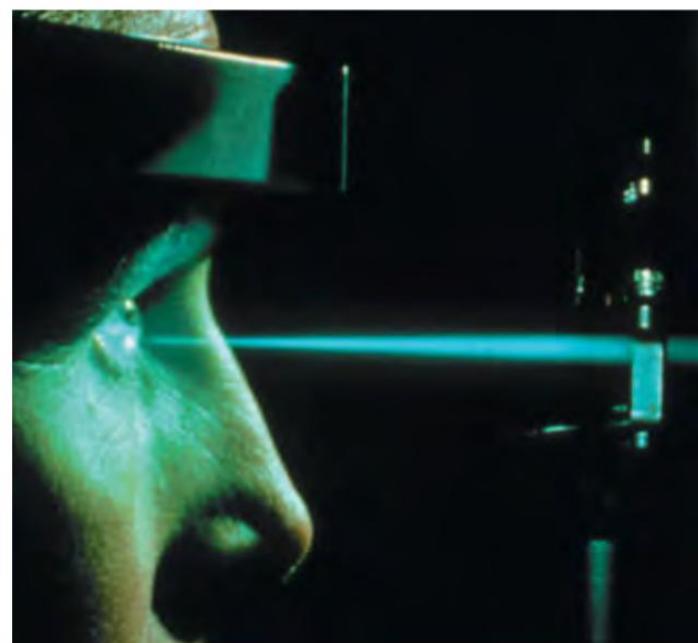
- ▶ 33-1 The Nature of Light
- ▶ 33-2 Reflection and Refraction
- ▶ 33-3 Total Internal Reflection
- ▶ 33-4 Dispersion
- ▶ 33-5 Polarization
- ▶ 33-6 Scattering of Light
- ▶ 33-7 Huygens's Principle

# 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.

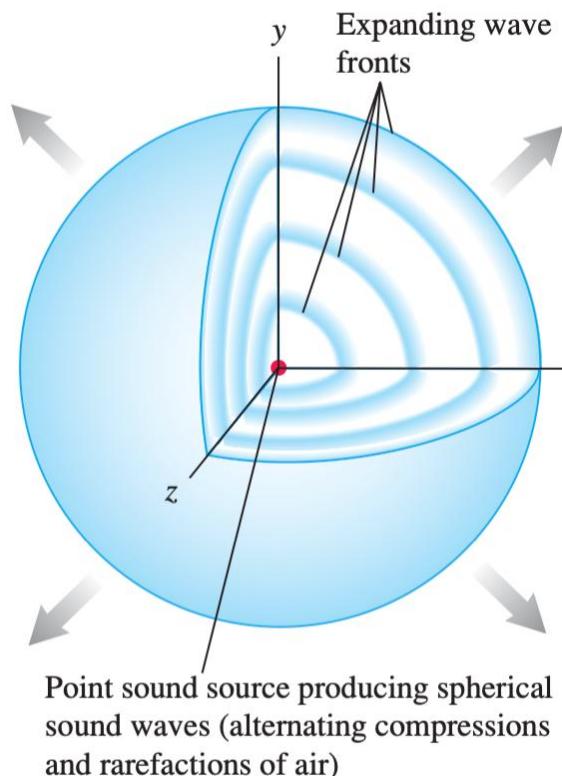


**33.2** Ophthalmic surgeons use lasers for repairing detached retinas and for cauterizing blood vessels in retinopathy. Pulses of blue-green light from an argon laser are ideal for this purpose, since they pass harmlessly through the transparent part of the eye but are absorbed by red pigments in the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



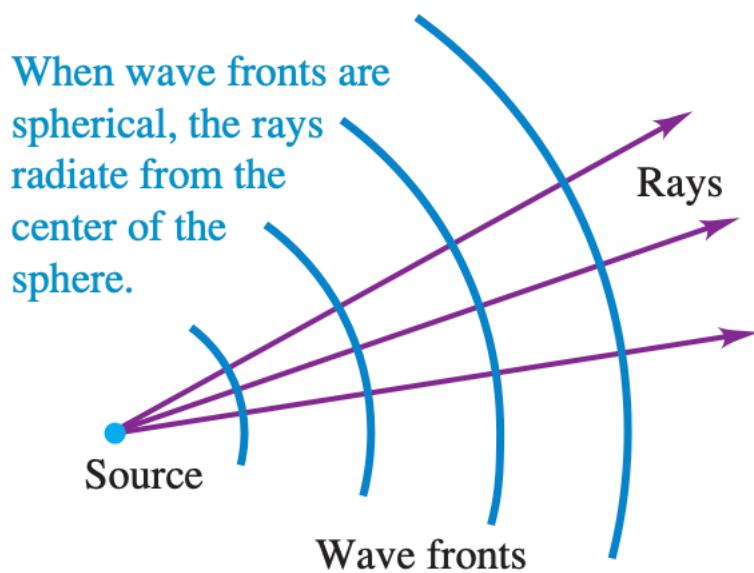
# 33-1 The Nature of Light

- Source: electric charges in accelerated motion.
- *wave* properties vs *particle* property
- the speed of light in vacuum  $3.00 \times 10^8$  m/s



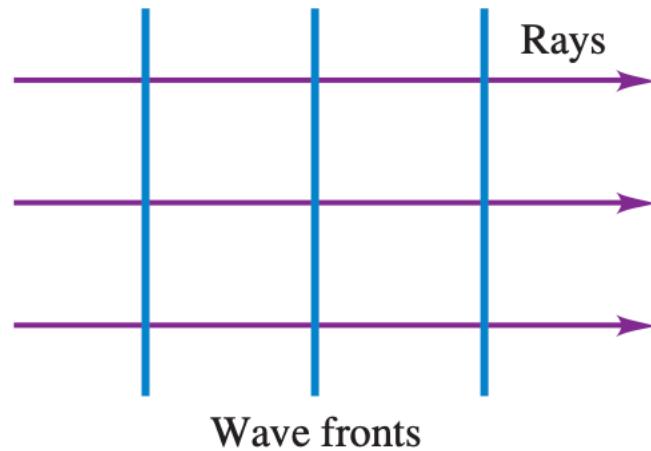
# 33-1 The Nature of Light

(a)



(b)

When wave fronts are planar, the rays are perpendicular to the wave fronts and parallel to each other.

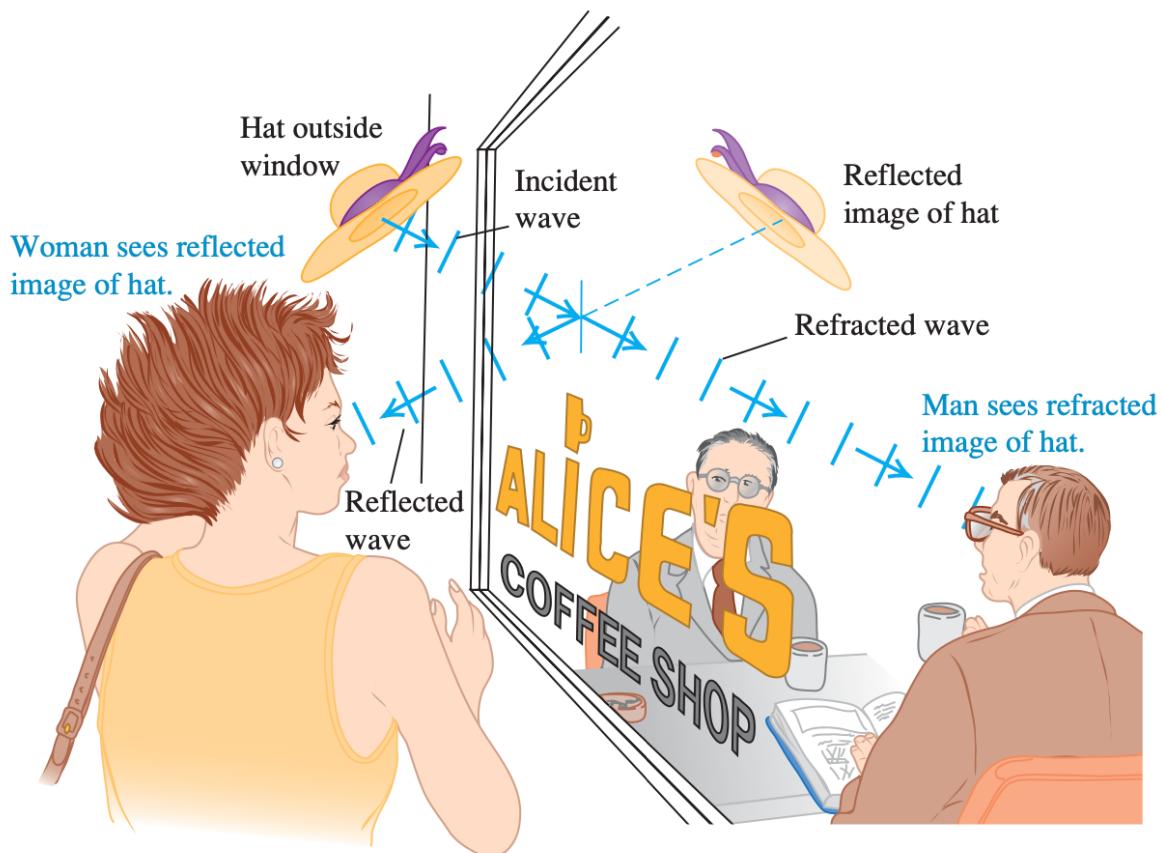


Ray description is adequate: geometric optics Ch 33 Ch 34

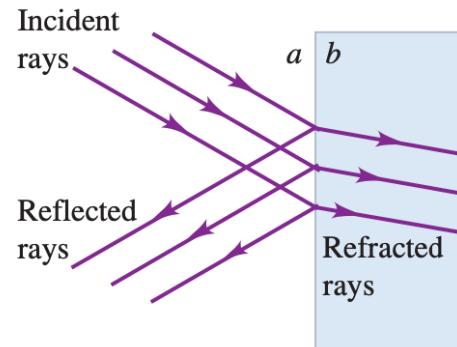
Require consideration of wave behavior: physical optics Ch 35 Ch 36

# 33-2 Reflection and Refraction

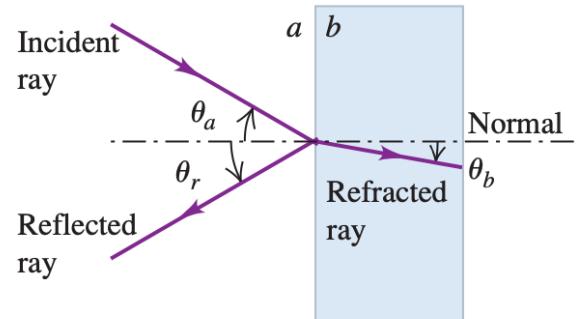
(a) Plane waves reflected and refracted from a window



(b) The waves in the outside air and glass represented by rays



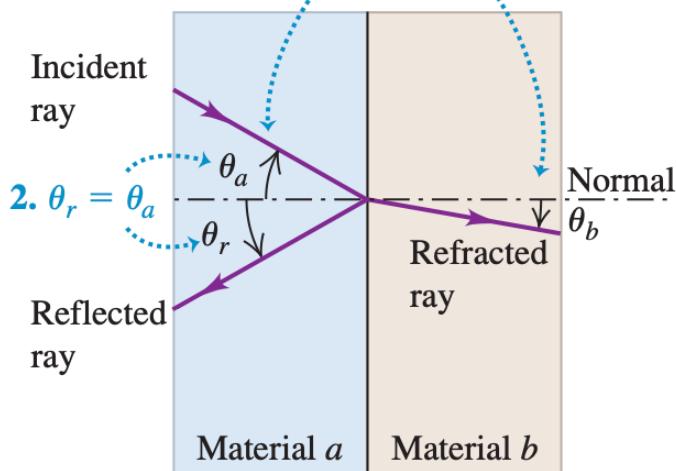
(c) The representation simplified to show just one set of rays



# 33-2 Reflection and Refraction

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

Angles  $\theta_a$ ,  $\theta_b$ , and  $\theta_r$  are measured from the normal.



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

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

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

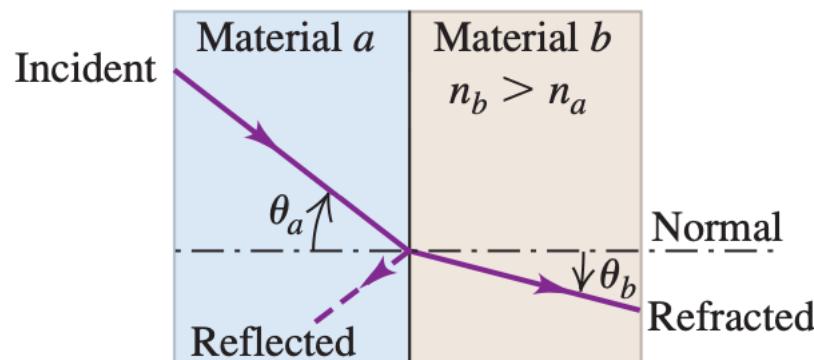
$$n_a \sin \theta_a = n_b \sin \theta_b \quad (\text{law of refraction})$$

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

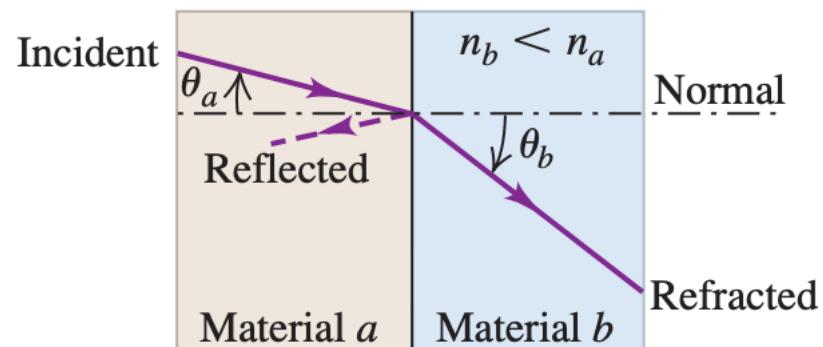
the ratio of the speed of light  $c$  in vacuum to the speed  $v$  in the material

# 33-2 Reflection and Refraction

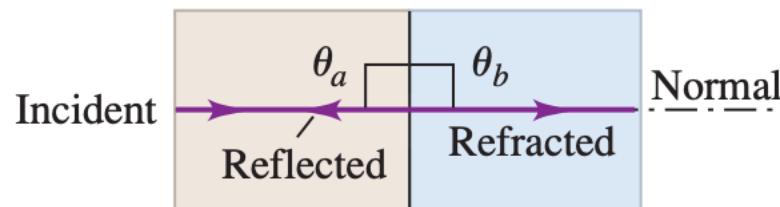
(a) A ray entering a material of *larger* index of refraction bends *toward* the normal.



(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.

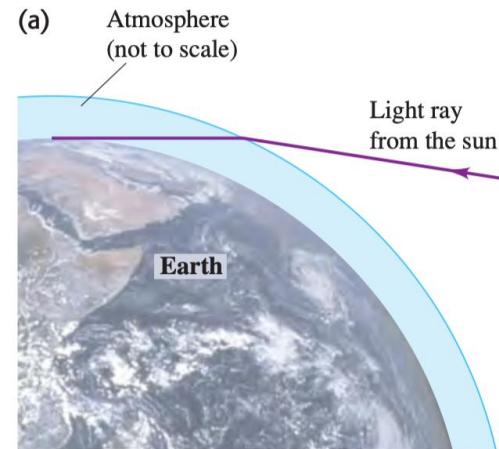
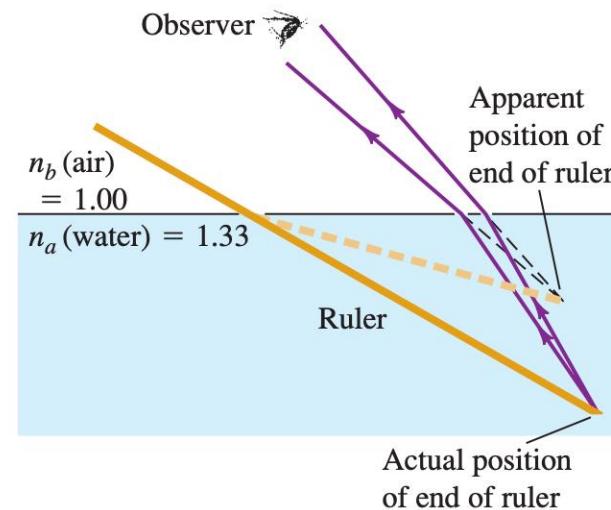


# 33-2 Reflection and Refraction

(a) A straight ruler half-immersed in water



(b) Why the ruler appears bent



# 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  $60.0^\circ$  with the normal; find the directions of the reflected and refracted rays.

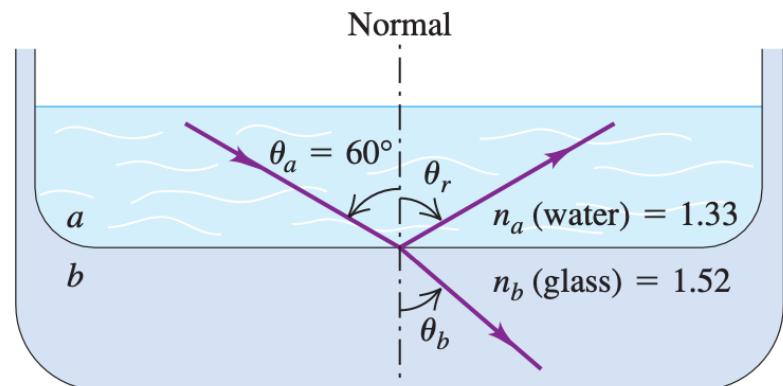
**EXECUTE:** According to Eq. (33.2), the angle the reflected ray makes with the normal is the same as that of the incident ray, so  $\theta_r = \theta_a = 60.0^\circ$ .

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

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

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

$$\theta_b = \arcsin(0.758) = 49.3^\circ$$



# 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  $\lambda_0$  in vacuum is the same as that in air, 633 nm. Then from Eq. (33.5),

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

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

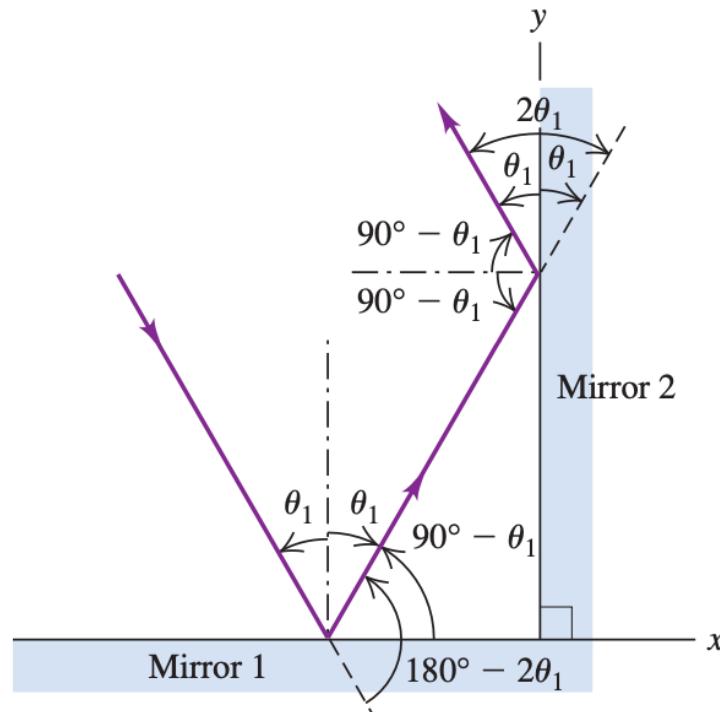
$$v = \frac{c}{n} = \frac{3.00 \times 10^8 \text{ m/s}}{1.34} = 2.25 \times 10^8 \text{ m/s}$$

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

# 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

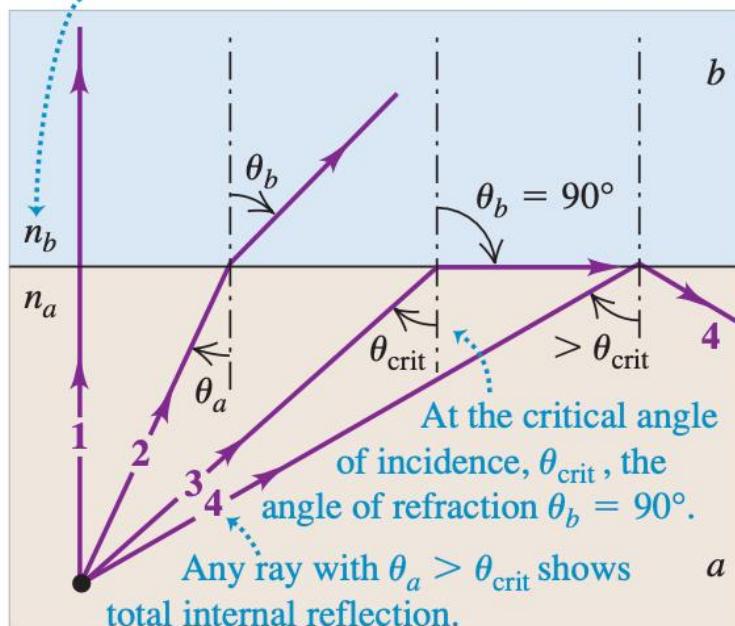
Two mirrors are perpendicular to each other. A ray traveling in a plane perpendicular to both mirrors is reflected from one mirror, then the other, as shown in Fig. 33.12. What is the ray's final direction relative to its original direction?

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

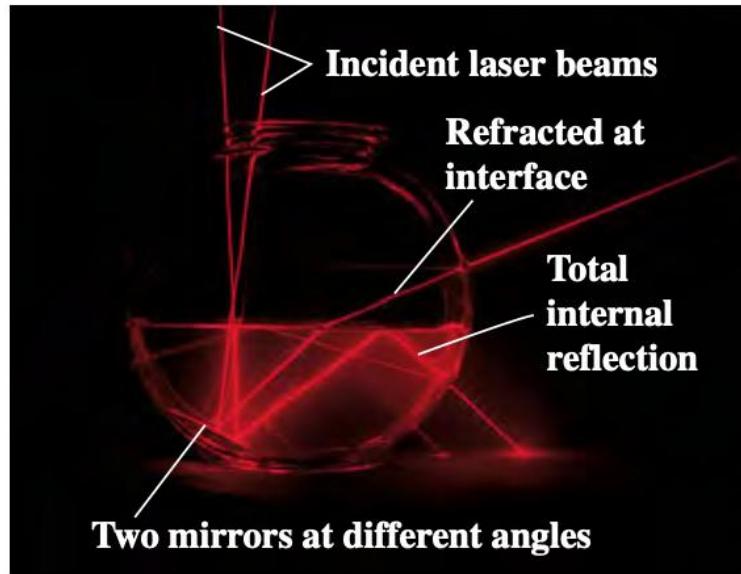
# 33-3 Total Internal Reflection

(a) Total internal reflection

Total internal reflection occurs only if  $n_b < n_a$ .

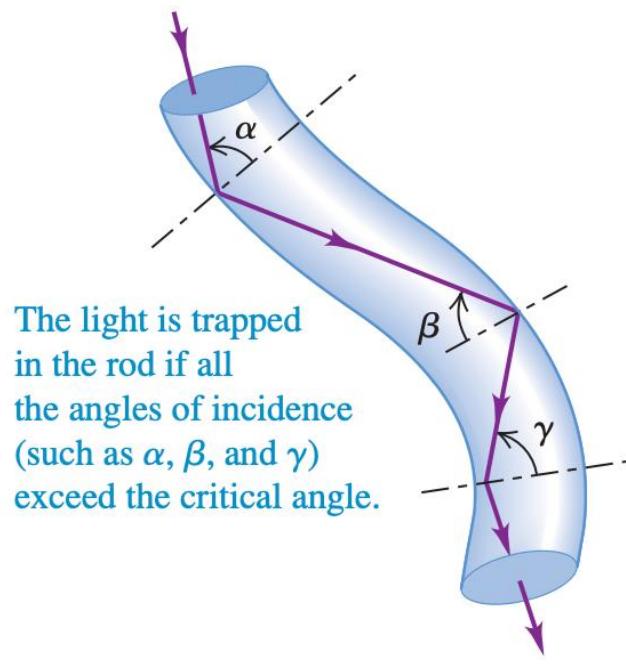


(b) Total internal reflection demonstrated with a laser, mirrors, and water in a fishbowl

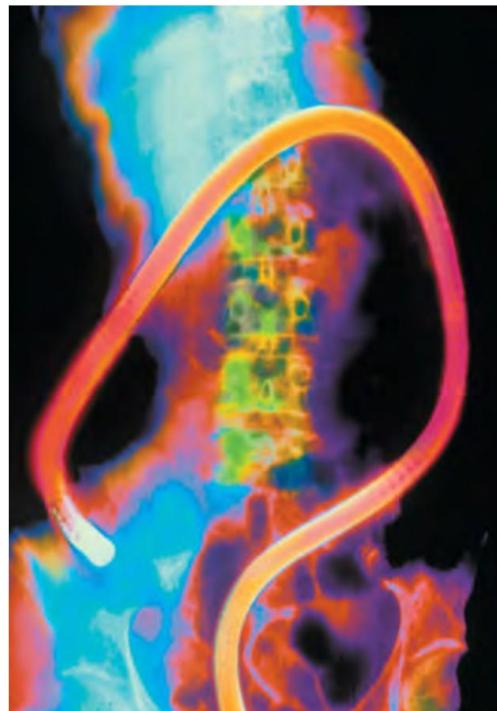


$$\sin \theta_{crit} = \frac{n_b}{n_a} \quad (\text{critical angle for total internal reflection})$$

# 33-3 Total Internal Reflection



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



Cut of diamond

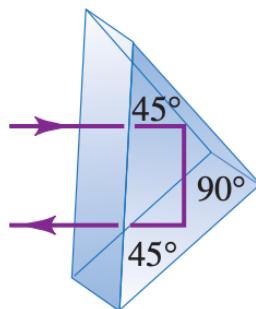
$$\sin \theta_{\text{crit}} = \frac{n_b}{n_a} \quad (\text{critical angle for total internal reflection})$$

# Sample Problem

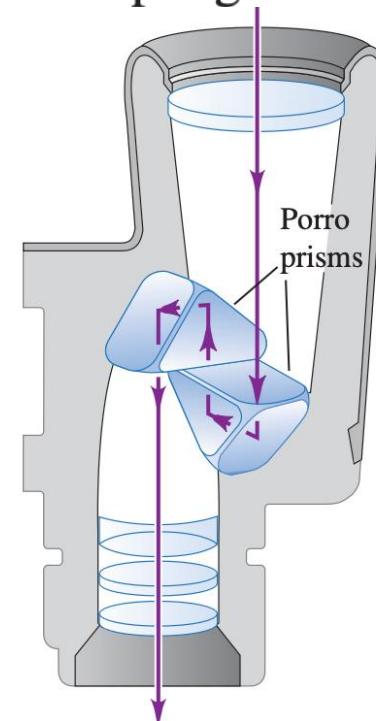
## Conceptual Example 33.4 A leaky periscope

A submarine periscope uses two totally reflecting  $45^\circ$ - $45^\circ$ - $90^\circ$  prisms with total internal reflection on the sides adjacent to the  $45^\circ$  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  $45^\circ$  faces (because, for a glass-air interface,  $\theta_{\text{crit}} = 41.1$ ).



# Sample Problem

## Conceptual Example 33.4 A leaky periscope

A submarine periscope uses two totally reflecting  $45^\circ$ - $45^\circ$ - $90^\circ$  prisms with total internal reflection on the sides adjacent to the  $45^\circ$  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

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

The  $45^\circ$  angle of incidence for a totally reflecting prism is *smaller* than this new  $61^\circ$  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.

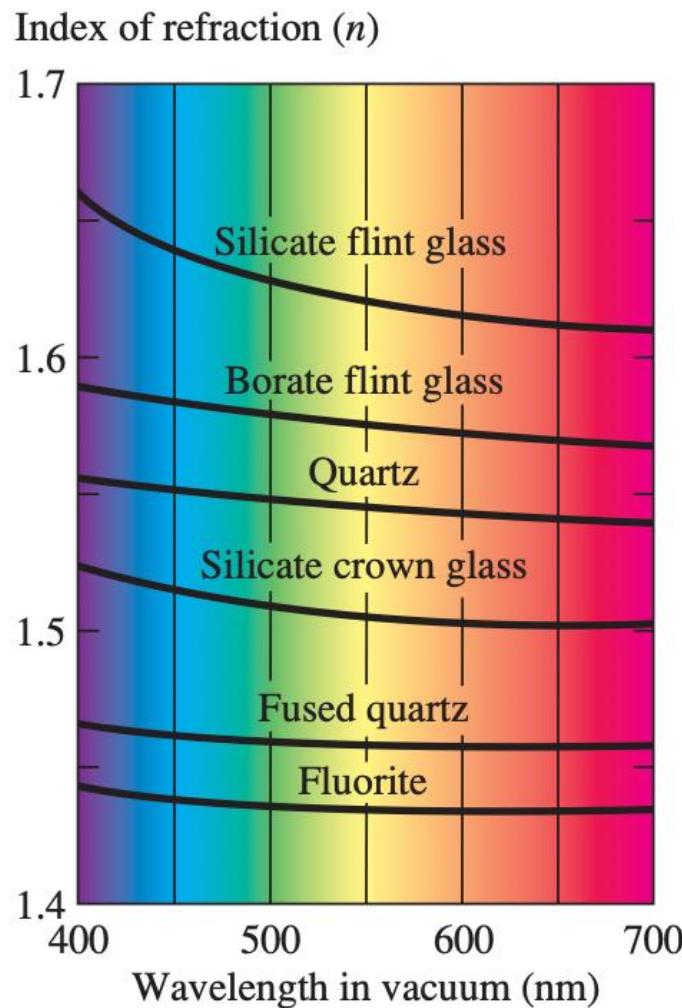
# Sample Problem

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**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  $70^\circ$ ; (ii) light propagating in glass ( $n = 1.52$ ) strikes a glass–water interface at an incident angle of  $70^\circ$ ; (iii) light propagating in water strikes a water–glass interface at an incident angle of  $70^\circ$ .



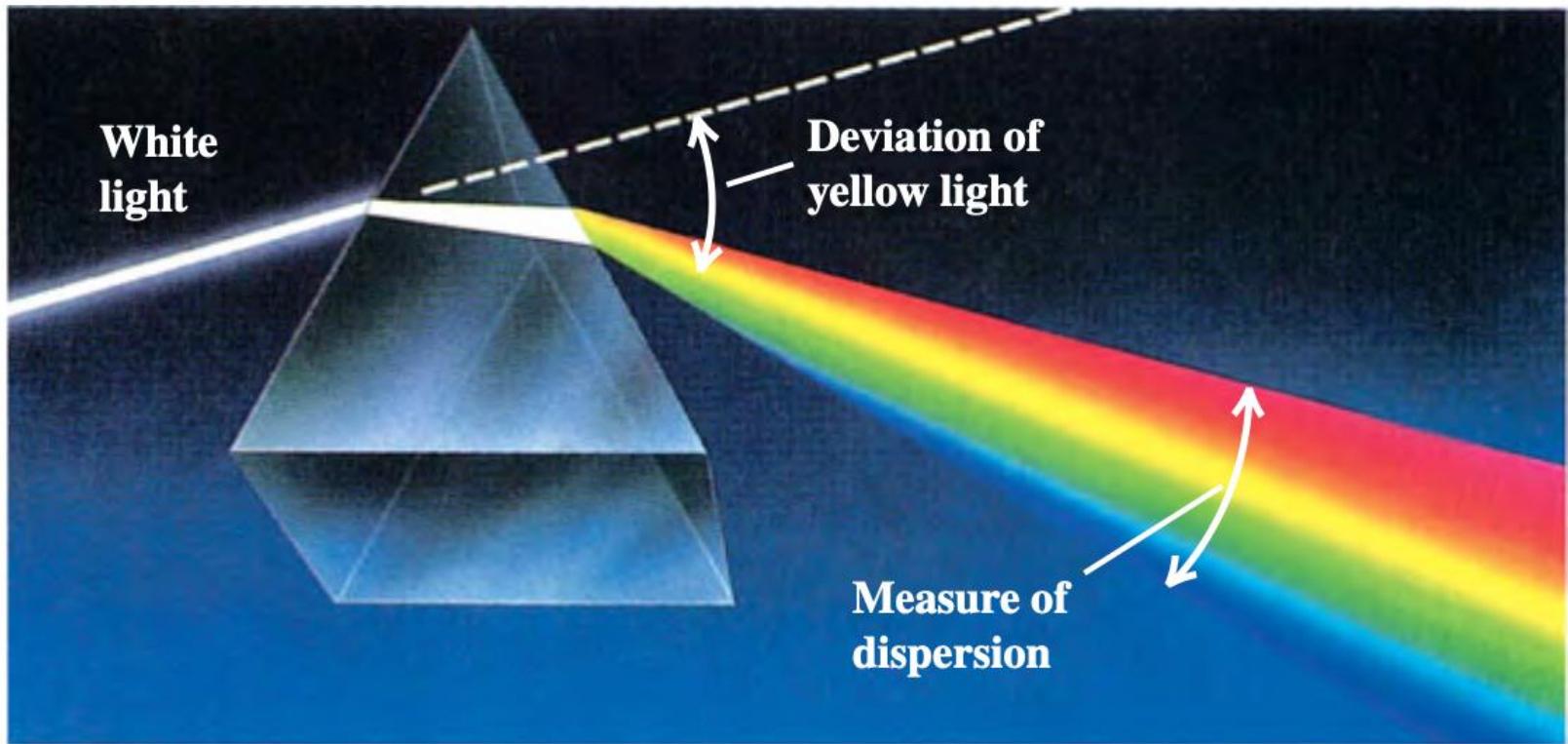
# 33-4 Dispersion



**33.18** Variation of index of refraction  $n$  with wavelength for different transparent materials. The horizontal axis shows the wavelength  $\lambda_0$  of the light *in vacuum*; the wavelength in the material is equal to  $\lambda = \lambda_0/n$ .

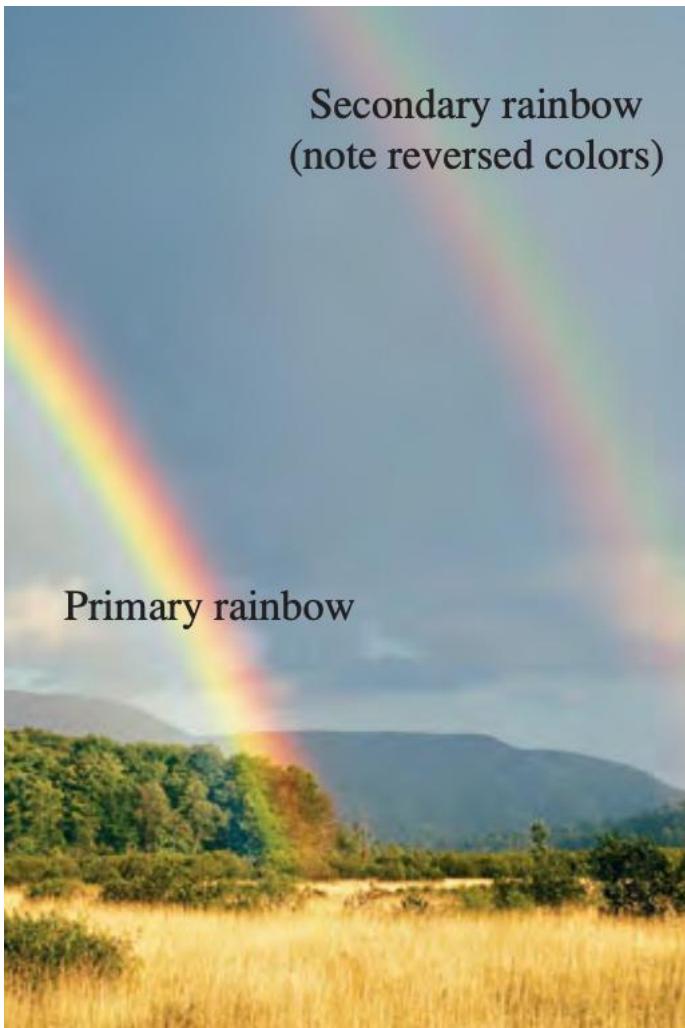
- Light of longer wavelength has greater speed than light of shorter wavelength.

## 33-4 Dispersion - Prism

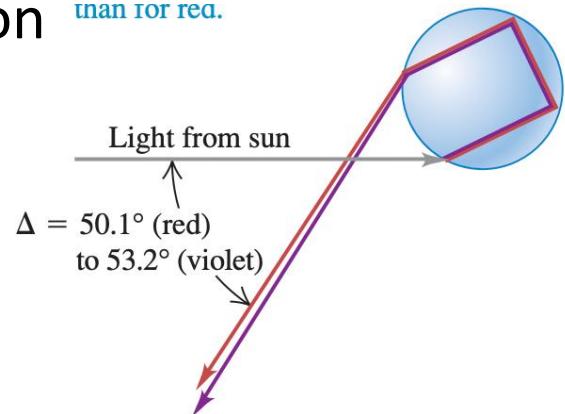


- The dependence of wave speed and index of refraction on wavelength is called **dispersion**.
- Violet light is deviated most, and red is deviated least

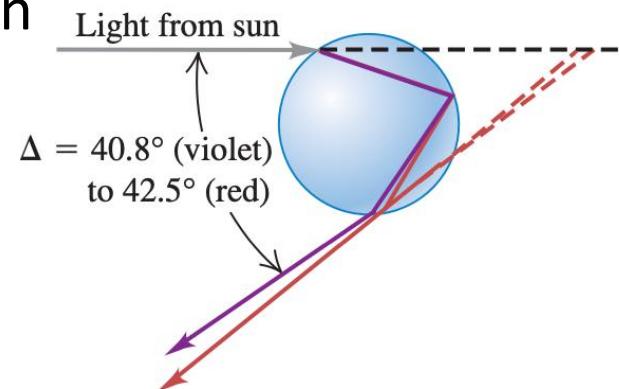
# 33-4 Dispersion - Rainbow



Secondary: Two refraction + two total internal reflection than for red.

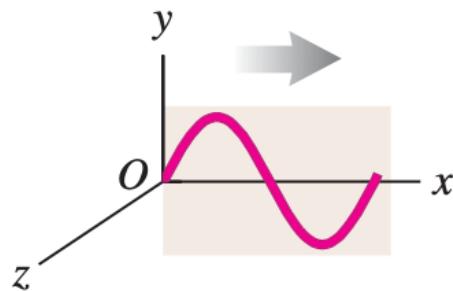


Primary: Two refraction + One total internal reflection

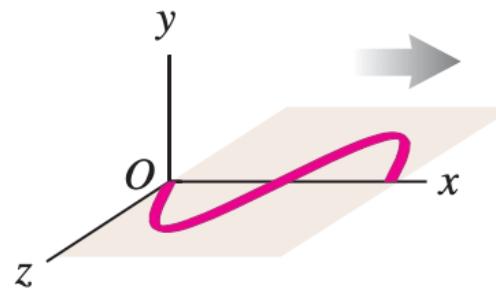


# 33-5 Polarization

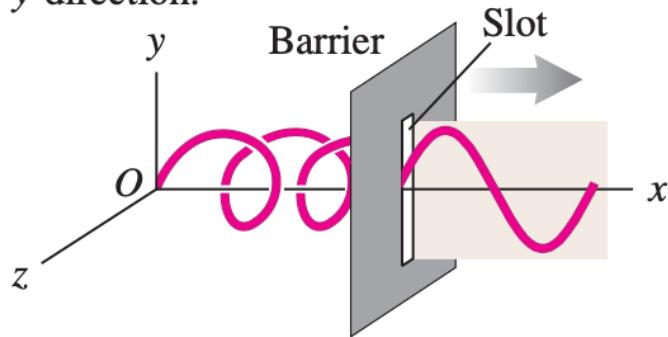
(a) Transverse wave linearly polarized in the  $y$ -direction



(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.



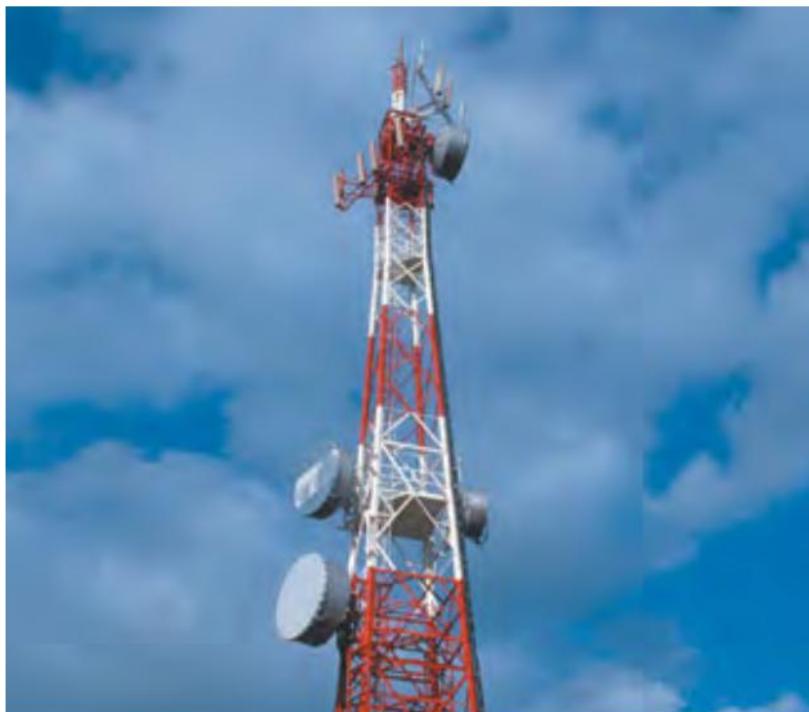
Light: EM wave

$$\vec{E}(x, t) = \hat{j}E_{\max} \cos(kx - \omega t)$$

$$\vec{B}(x, t) = \hat{k}B_{\max} \cos(kx - \omega t)$$

# 33-5 Polarization

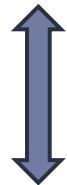
Broadcast Antenna



Light bulb

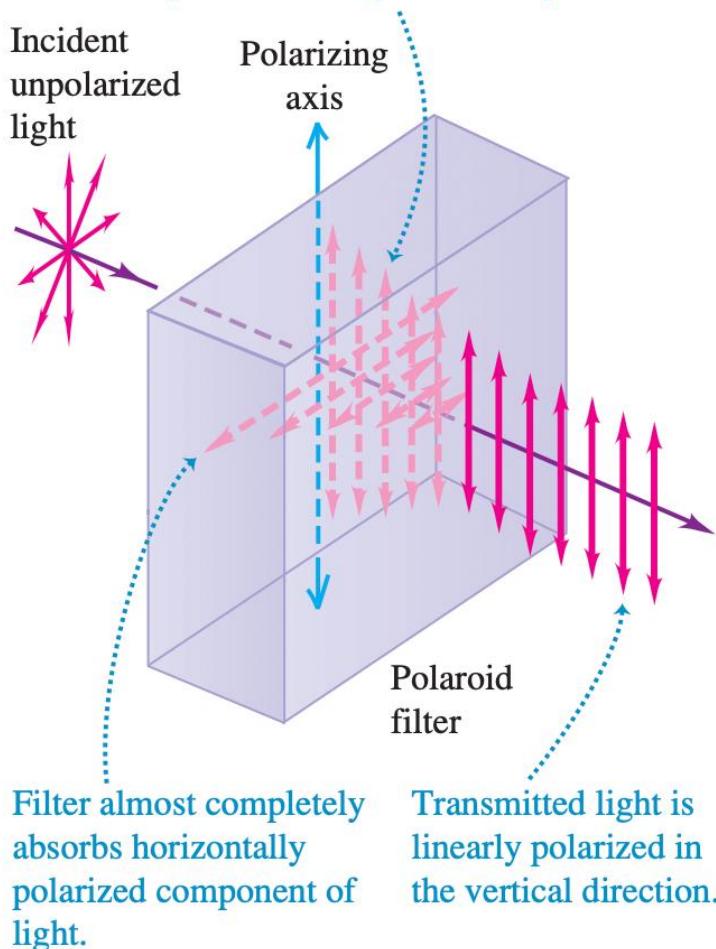


Electron motion  
polarization



# 33-5 Polarization

Filter only partially absorbs vertically polarized component of light.



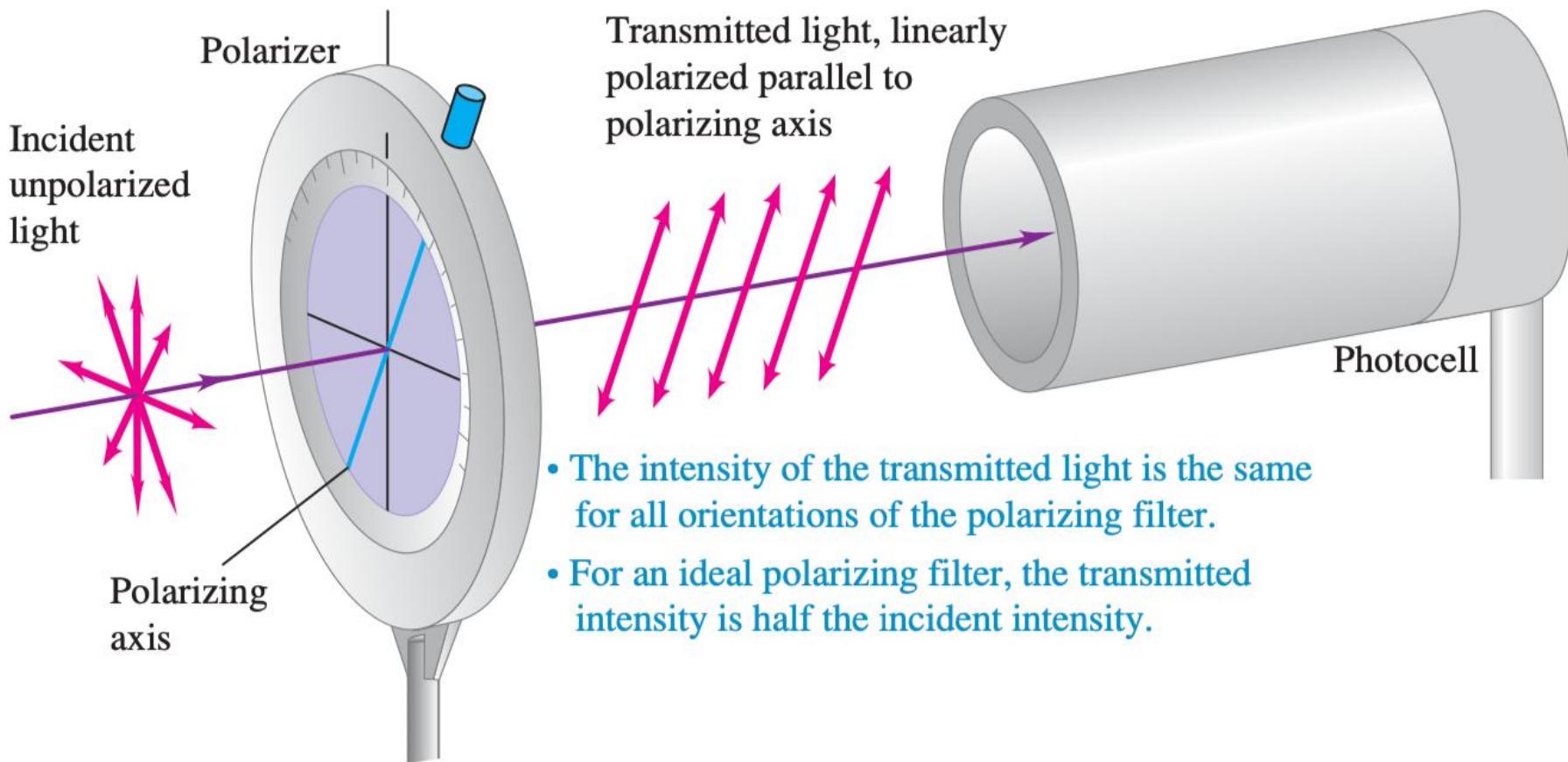
Malus's law

$$I = I_{\max} \cos^2 \phi$$

Unpolarized light passing through polarizer  
Intensity cut half.

$$I = I_0 \int_0^{2\pi} \cos^2 \theta \, d\theta = \frac{1}{2} I_0$$

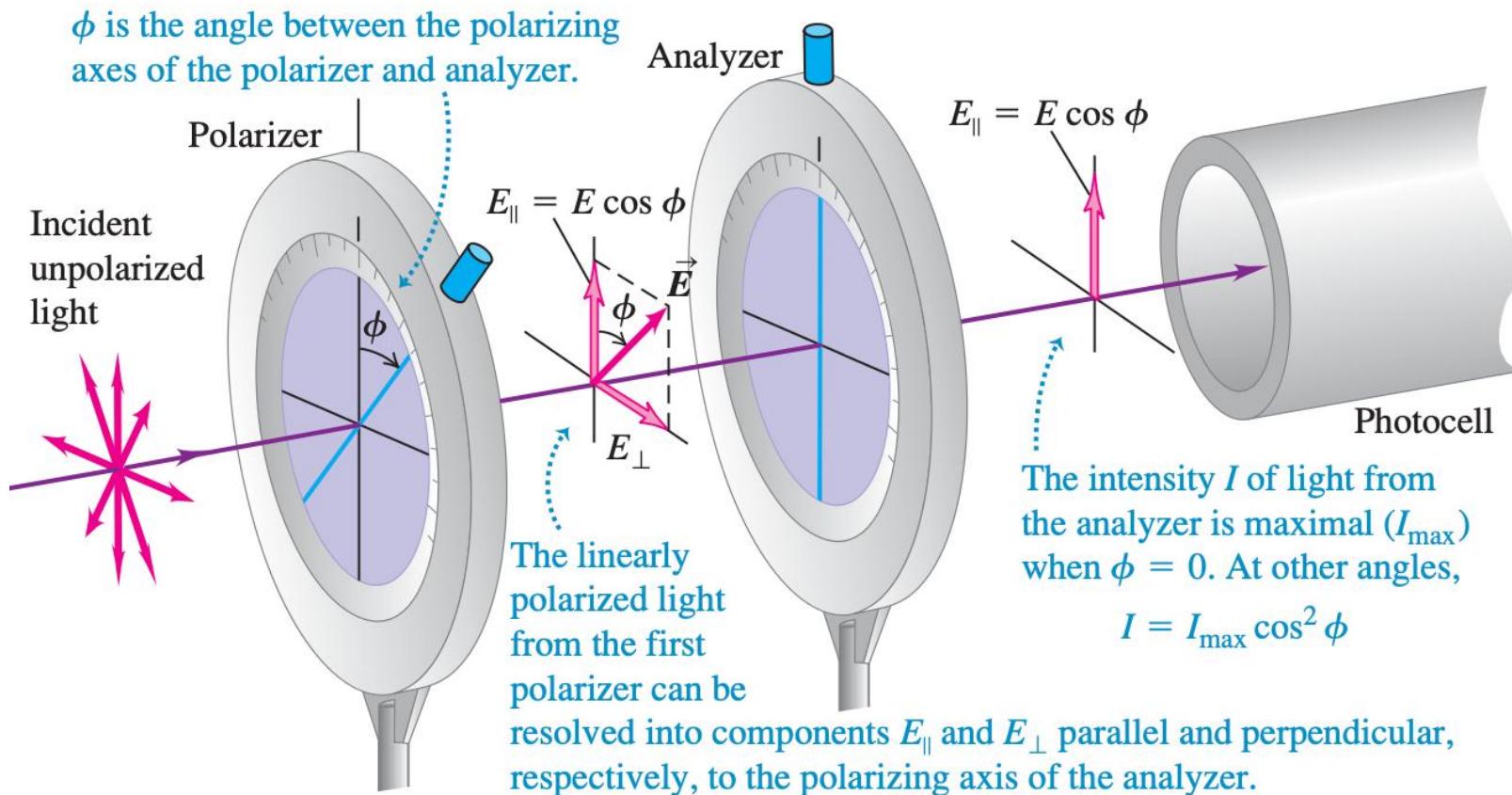
## 33-5 Polarization



## 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 ( $\phi = 90^\circ$ ). The transmitted intensity is greatest when the axes are aligned; it is zero when the axes are perpendicular.

90 degree: totally blocked

# 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  $30^\circ$ .

**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  $\phi = 30^\circ$ , the second polarizer reduces the intensity by a further factor of  $\cos^2 30^\circ = \frac{3}{4}$ . Thus the intensity transmitted by the second polarizer is

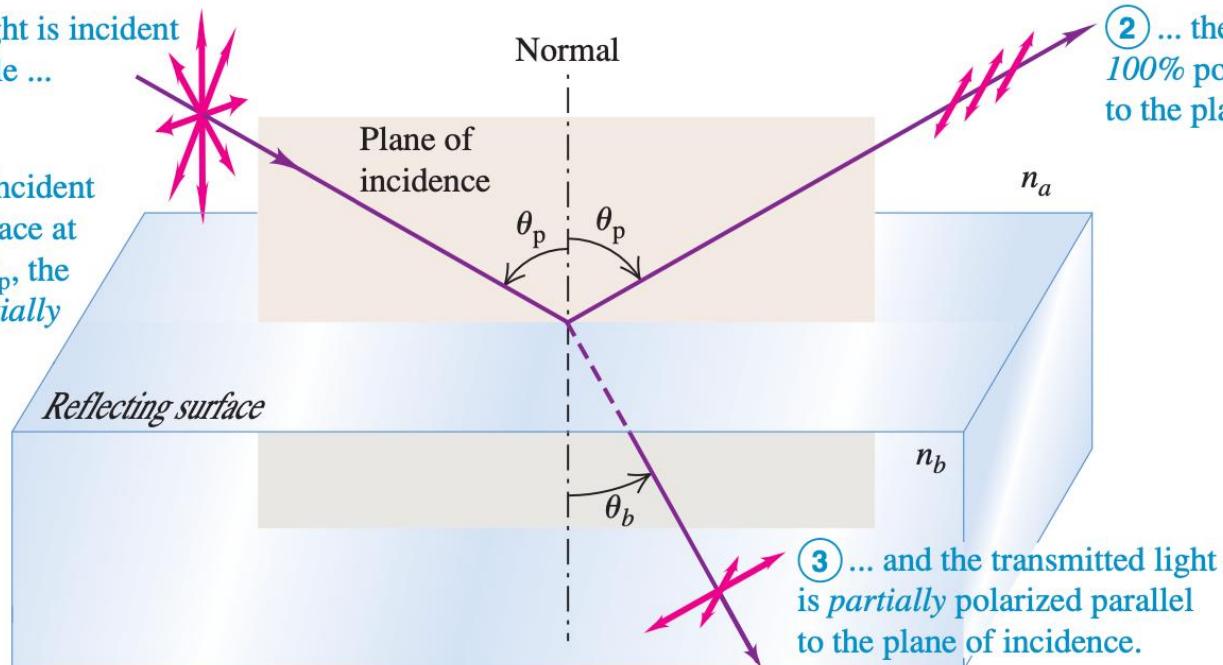
$$\left(\frac{I_0}{2}\right)\left(\frac{3}{4}\right) = \frac{3}{8}I_0$$

## 33-5 Polarization

Unpolarized light can be polarized by *reflection*

① If unpolarized light is incident at the polarizing angle ...

④ Alternatively, if unpolarized light is incident on the reflecting surface at an angle other than  $\theta_p$ , the reflected light is *partially* polarized.



② ... then the reflected light is 100% polarized perpendicular to the plane of incidence ...

③ ... and the transmitted light is *partially* polarized parallel to the plane of incidence.

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

# 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),

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

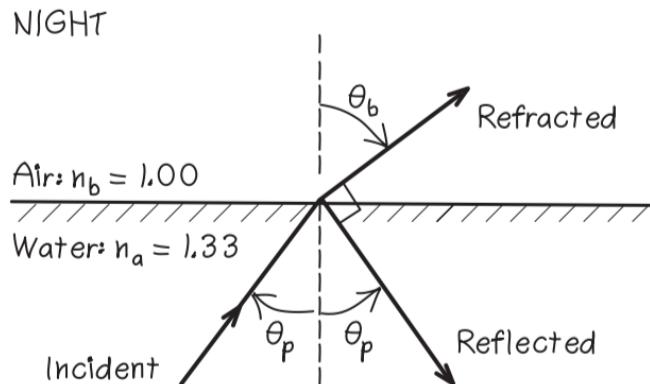
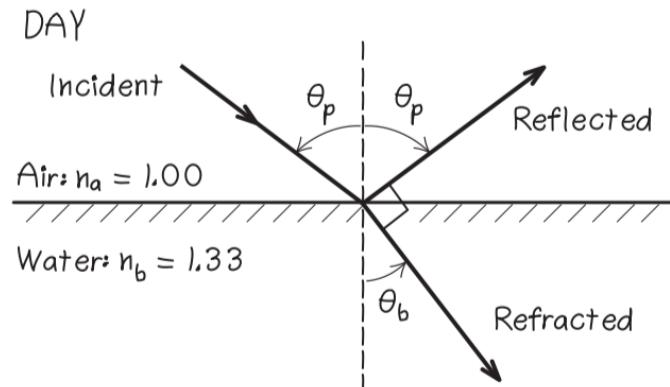
(b) The incident light is at the polarizing angle, so the reflected and refracted rays are perpendicular; hence

$$\theta_b = 90^\circ - \theta_p = 90^\circ - 53.1^\circ = 36.9^\circ$$

(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

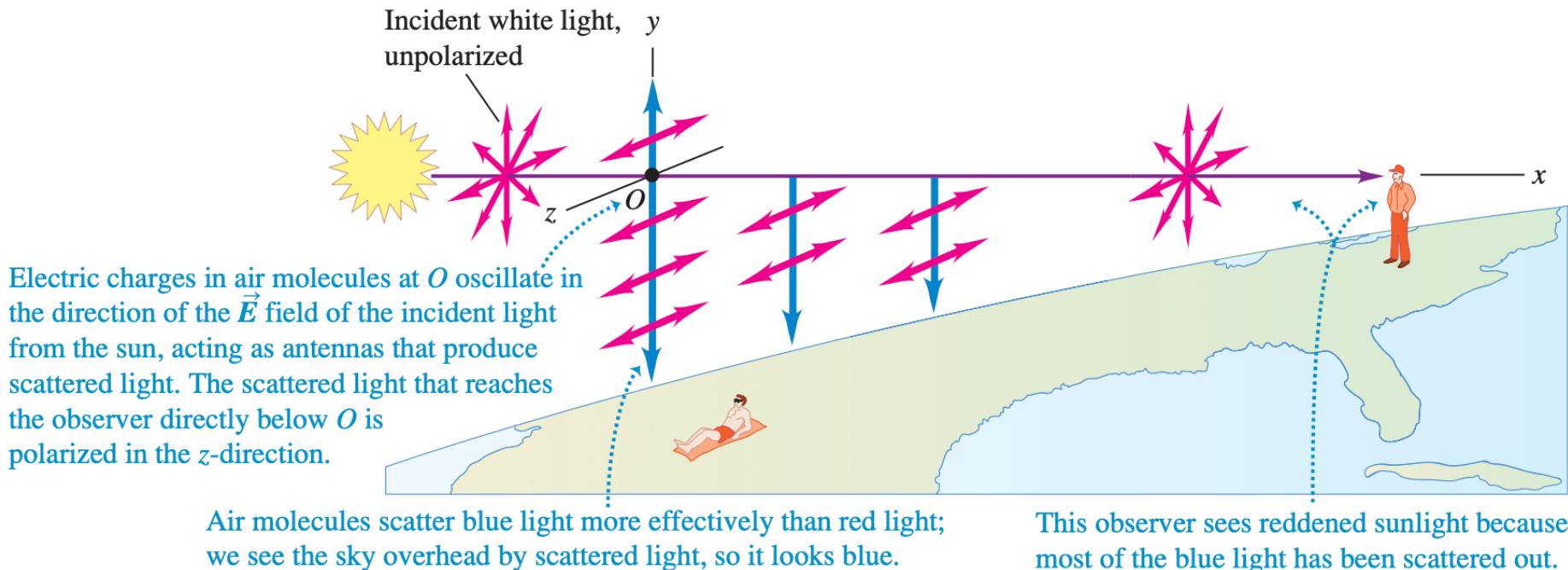
$$\theta_p = \arctan \frac{1.00}{1.33} = 36.9^\circ$$

$$\theta_b = 90^\circ - 36.9^\circ = 53.1^\circ$$



# 33-6 Scattering of Light

The sky is blue. Sunsets are red. Why?



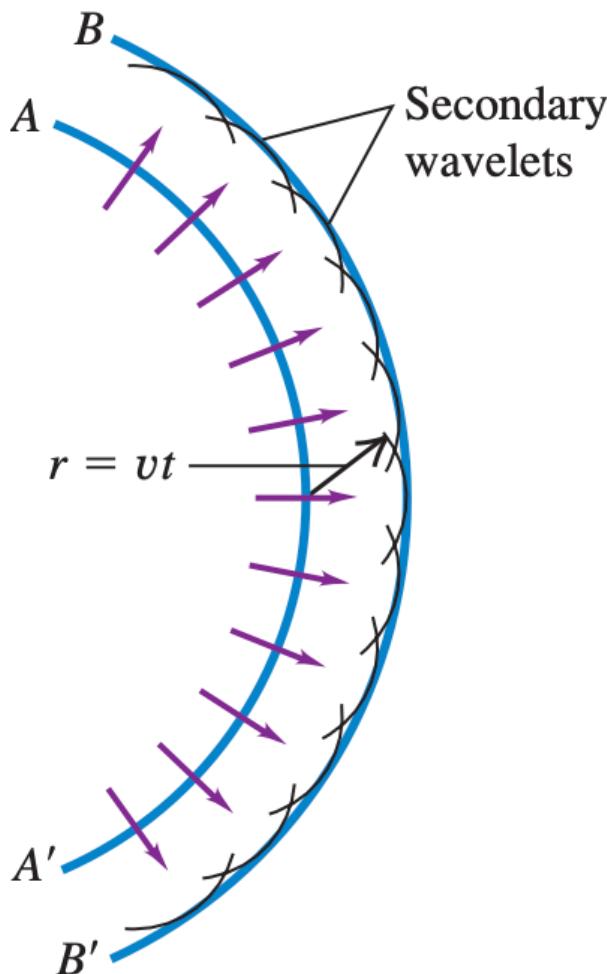
## 33-6 Scattering of Light

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

## 33-7 Huygen's Principle

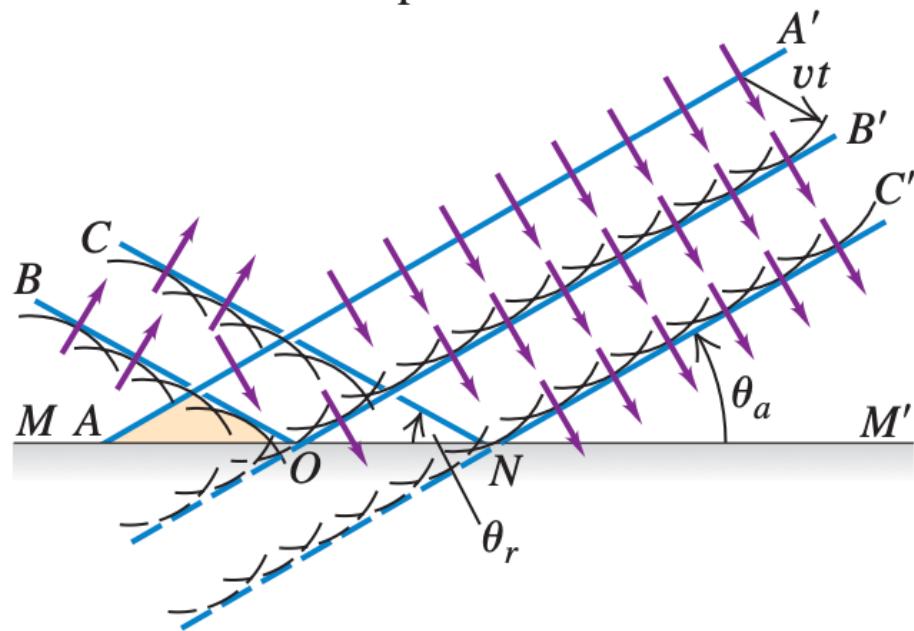


- How the law of reflection and refraction derived from wave nature of light?
- Every point of a wave front may be considered the source of secondary wavelets that spread out in all directions with a speed equal to the speed of propagation of the wave.

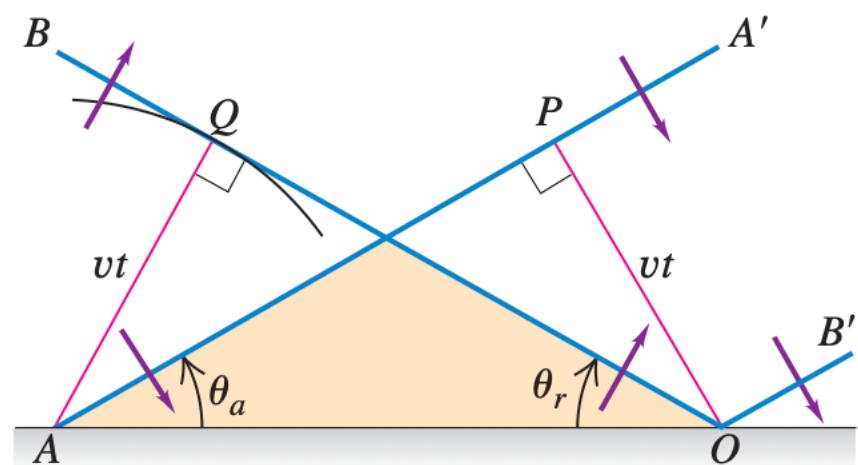
# 33-7 Huygen's Principle

Law of reflection from Huygens's principle

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



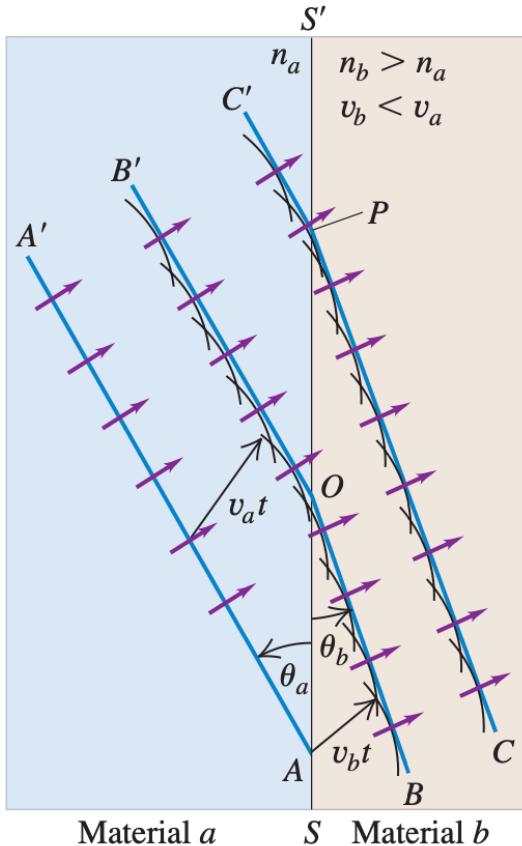
(b) Magnified portion of (a)



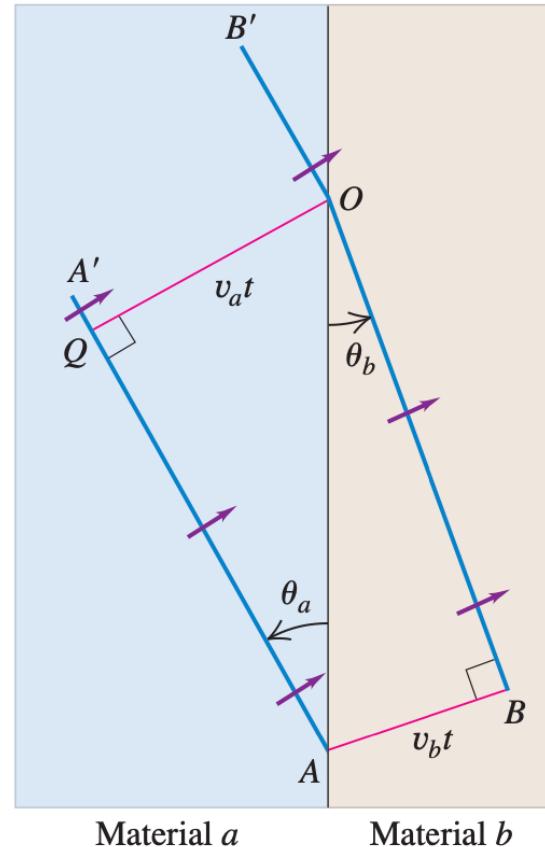
# 33-7 Huygen's Principle

## 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 Huygen's Principle



Mirages: The speed of light is slightly greater in the hotter air near the ground, the Huygens wavelets have slightly larger radii, the wave fronts tilt slightly.

