Chapter 33

The Nature and Propagation of Light

PowerPoint® Lectures for
University Physics, Twelfth Edition
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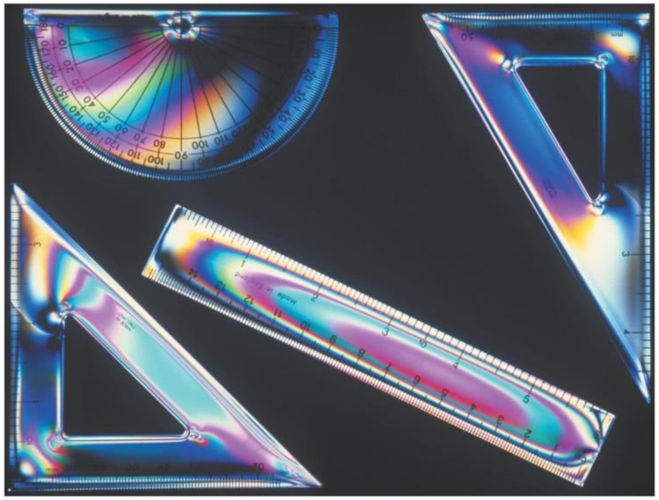
Goals for Chapter 33

- To overview light and its properties
- To study reflection and refraction
- To examine the unique phenomenon of total internal reflection
- To consider the polarization of light
- To see polarization by reflection
- To study Huygens’s Principle

Introduction

- A coating of oil on water or a delicate glass prism can create a rainbow. A rainstorm among open patches of daylight can cast a conventional rainbow. Both effects are beautiful and arise from the wavelength dependence of refraction angles.



- Eyeglasses or contact lenses both use refraction to correct imperfections in the eyeball's focus on the retina and allow vision correction.

“Light is a wave,” “Light is a particle”

- The wave–particle duality of light was not well understood until Albert Einstein won his Nobel Prize in the early 20th century. It was a tenacious understanding of light that led to quantum mechanics and modern physics.
- Consider Figures 33.1 and 33.2 below. Black-body and laser radiation look so different but are brother and sister.

The branch of physics called **optics** deals with the behavior of light and other electromagnetic waves. Until the time of Isaac Newton (1642–1727), most scientists thought that light consisted of streams of particles (called *corpuscles*) emitted by light sources. Maxwell's theory and Hertz's experiments showed conclusively that light is indeed an electromagnetic wave

The Two Personalities of Light

The wave picture of light is not the whole story. Emission and absorption of light reveal a particle aspect, in that the energy carried by light waves is packaged in discrete bundles called *photons* or *quanta.* These apparently contradictory wave and particle properties have been reconciled since 1930 with the development of quantum electrodynamics, a comprehensive theory that includes *both* wave and particle properties

1. The *propagation* of light is best described by a wave model
2. But understanding emission and absorption requires a particle approach.

The fundamental sources of all electromagnetic radiation are electric charges in accelerated motion. All bodies emit electromagnetic radiation as a result of thermal motion of their molecules; this radiation, called *thermal radiation,* is a mixture of different wavelengths. At sufficiently high temperatures, all matter emits enough visible light to be self-luminous; a very hot body appears “red-hot” or “white-hot.” Light is also produced during electrical discharges through ionized gases.

In most light sources, light is emitted independently by different atoms within the source; in a *laser,* by contrast, atoms are induced to emit light in a cooperative, coherent fashion. The result is a very narrow beam of radiation that can be enormously intense and that is much more nearly *monochromatic,* or single frequency,than light from any other source.

Waves, Wave Fronts, and Rays

We often use the concept of a **wave front** to describe wave propagation. More generally, we define a wave front as *the locus of all adjacent points at which the phase of vibration of a physical quantity associated with the wave is the same.* That is, at any instant, all points on a wave front are at the same part of the cycle of their variation.

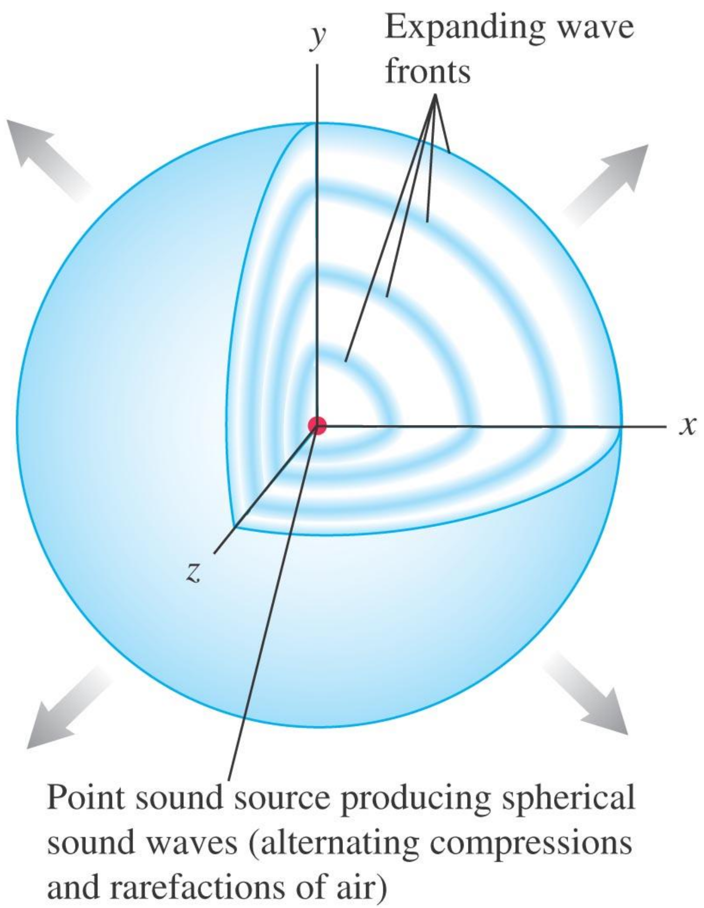
For example, when electromagnetic waves are radiated by a small light source, we can represent the wave fronts as spherical surfaces concentric with the source. Far away from the source, where the radii of the spheres have become very large, a section of a spherical surface can be considered as a plane wave

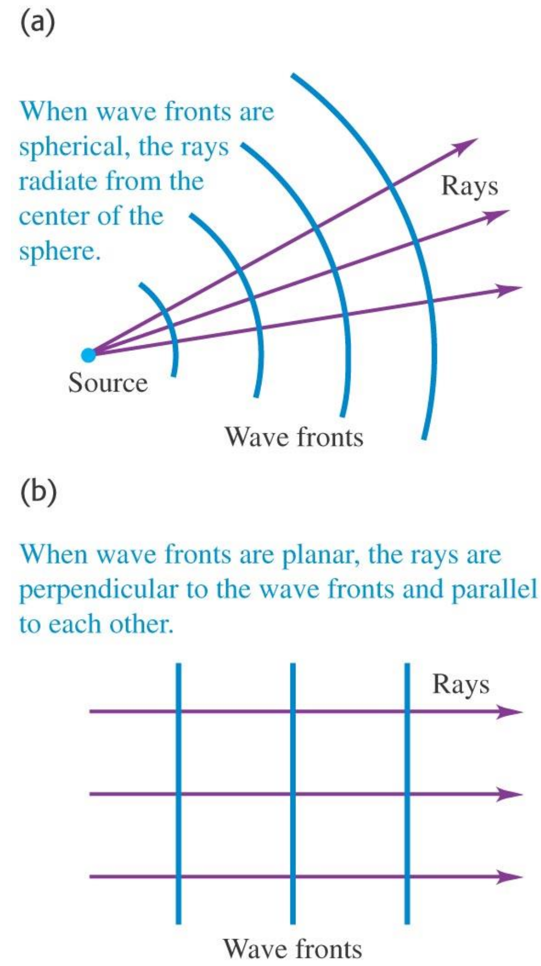
To describe the directions in which light propagates, it’s often convenient to represent a light wave by **rays** rather than by wave fronts. Rays were used to describe light long before its wave nature was firmly established. In a particle theory of light, rays are the paths of the articles. From the wave viewpoint *a ray is an imaginary line along the direction of travel of the wave.*

The branch of optics for which the ray description is adequate is called **geometric optics;** the branch dealing specifically with wave behavior is called **physical optics.**

Wave fronts and rays

- Light is actually a nearly uncountable number of electromagnetic wave fronts, but analysis of refraction or reflection are made possible by treating light as a ray.

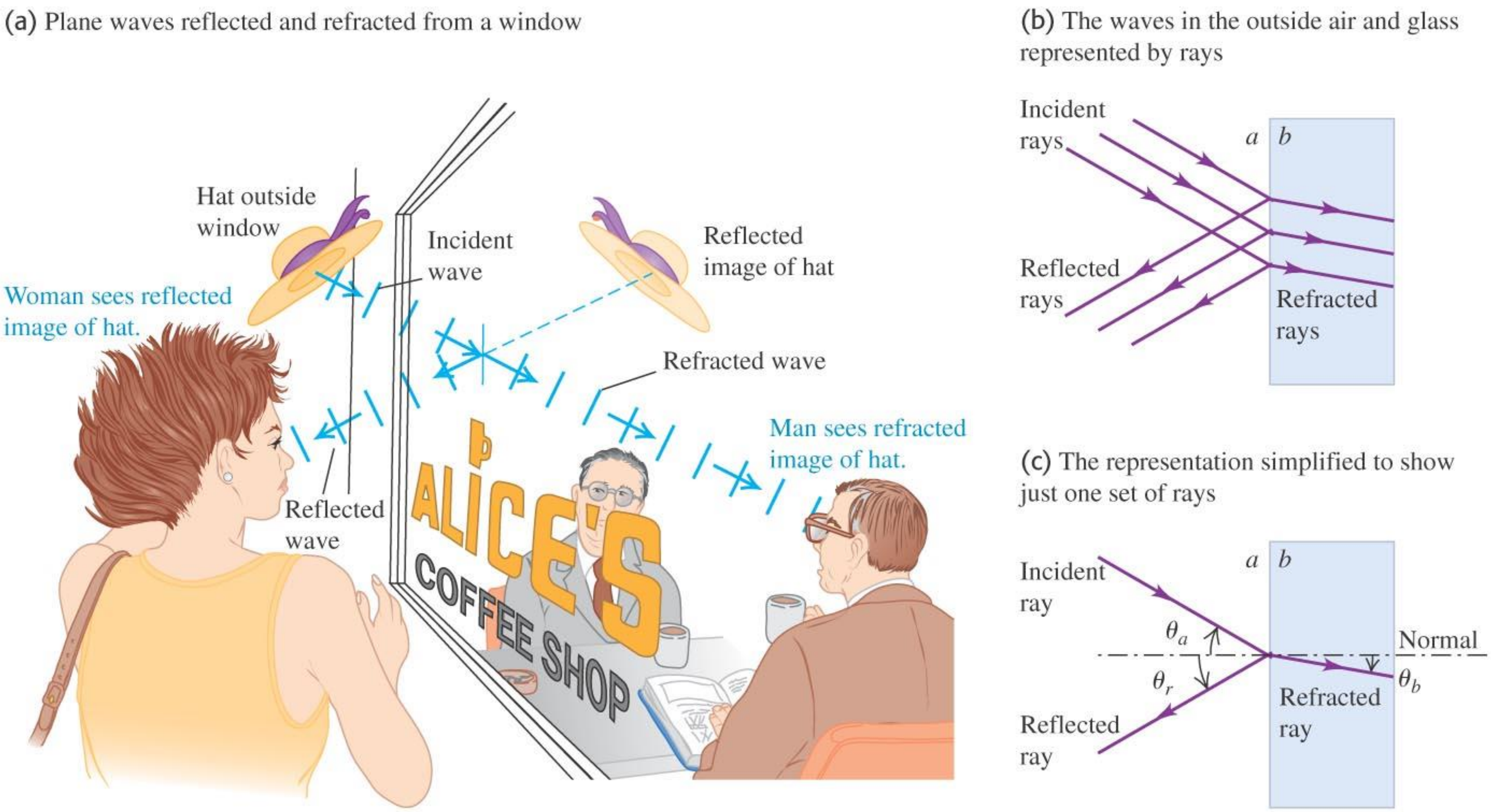




When a light wave strikes a smooth interface separating two transparent materials (such as air and glass or water and glass), the wave is in general partly *reflected* and partly *refracted* (transmitted) into the second material,

Reflection and refraction

- Figure 33.5 illustrates both reflection and refraction at once. The storefront window both shows the passersby their reflections and allows them to see inside.



We describe the directions of the incident, reflected, and refracted (transmitted) rays at a smooth interface between two optical materials in terms of the angles they make with the *normal* (perpendicular) to the surface at the point of incidence

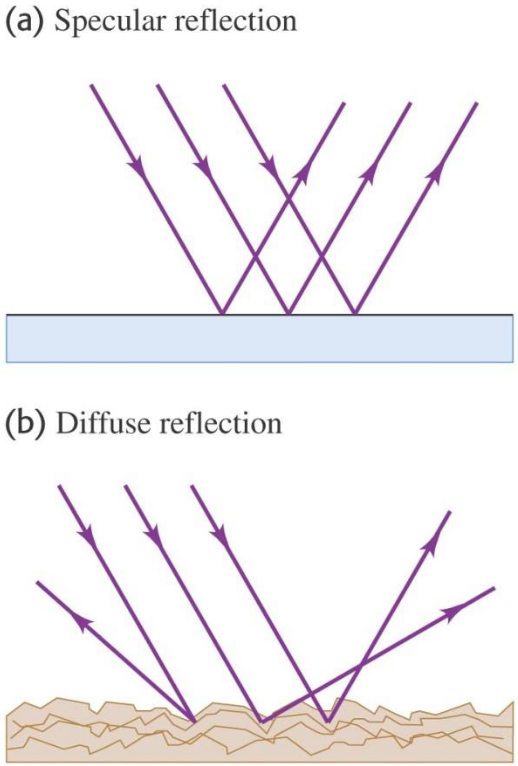
The **index of refraction** of an optical material (also called the **refractive index**), denoted by n, plays a central role in geometric optics. It is the ratio of the speed of light c in vacuum to the speed v in the material:

$$n = \frac{c}{v} \qquad \text{(index of refraction)} \qquad (33.1)$$

Light always travels *more slowly* in a material than in vacuum, so the value of n in anything other than vacuum is always greater than unity. For vacuum, $n = 1$.

We will consider specular reflections

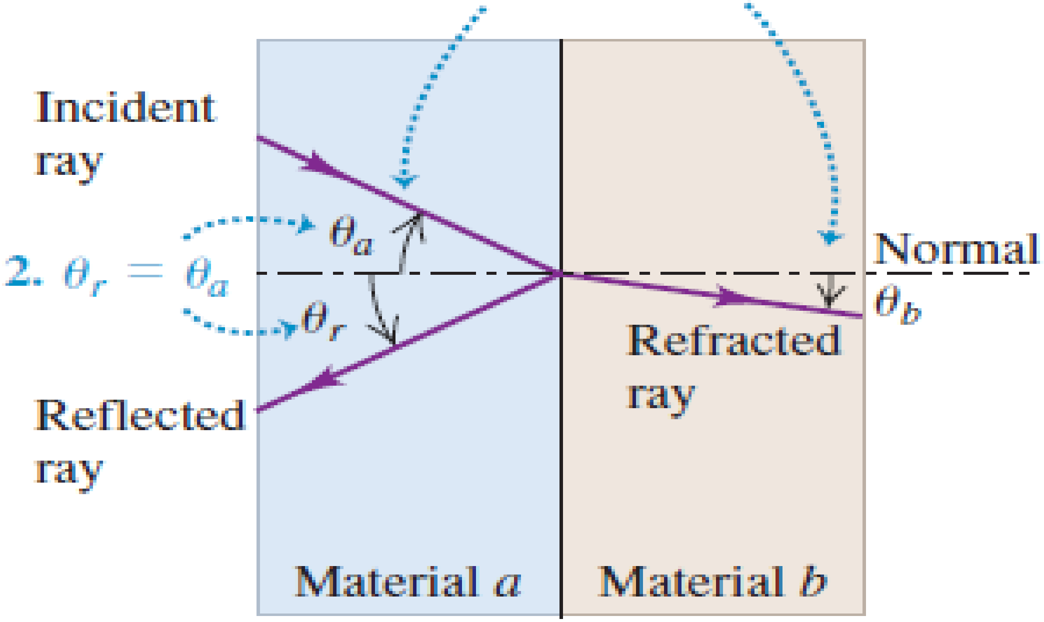
- A real surface will scatter and reflect light. Diffuse reflection is the rule, not the exception. We will use specular reflection as we used the ray approximation, to make a very difficult problem manageable.
- Consider Figure 33.6.



33.7 The laws of reflection and refraction.

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

Angles θ_a, θ_b, and θ_r are measured *from the normal*.



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

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

1. **The incident, reflected, and refracted rays and the normal to the surface all lie in the same plane.** The plane of the three rays and the normal, called the **plane of incidence,** is perpendicular to the plane of the boundary surface between the two materials. We always draw ray diagrams so that the incident, reflected, and refracted rays are in the plane of the diagram.

2. The angle of reflection θ_r is equal to the angle of incidence θ_a for all wavelengths and for any pair of materials. That is, in Fig. 33.5c,

$$\theta_r = \theta_a \qquad \text{(law of reflection)} \qquad (33.2)$$

This relationship, together with the observation that the incident and reflected rays and the normal all lie in the same plane, is called the **law of reflection.**

3. For monochromatic light and for a given pair of materials, a and b, on opposite sides of the interface, **the ratio of the sines of the angles θ_a and θ_b, where both angles are measured from the normal to the surface, is equal to the inverse ratio of the two indexes of refraction:**

$$\frac{\sin\theta_a}{\sin\theta_b} = \frac{n_b}{n_a} \tag{33.3}$$

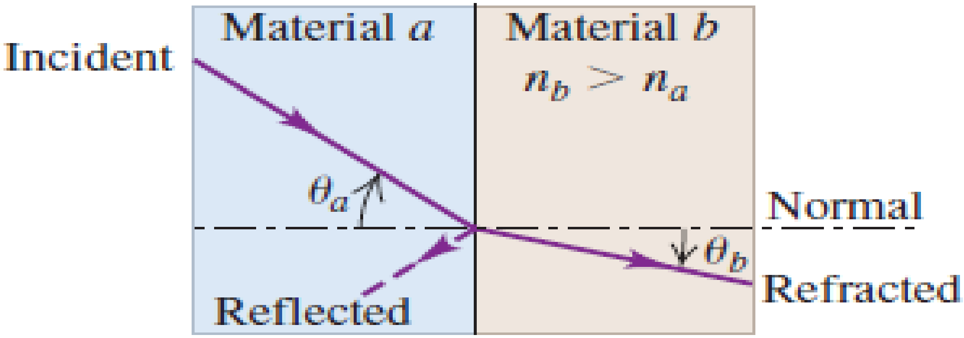
or

$$n_a \sin\theta_a = n_b \sin\theta_b \qquad \text{(law of refraction)} \tag{33.4}$$

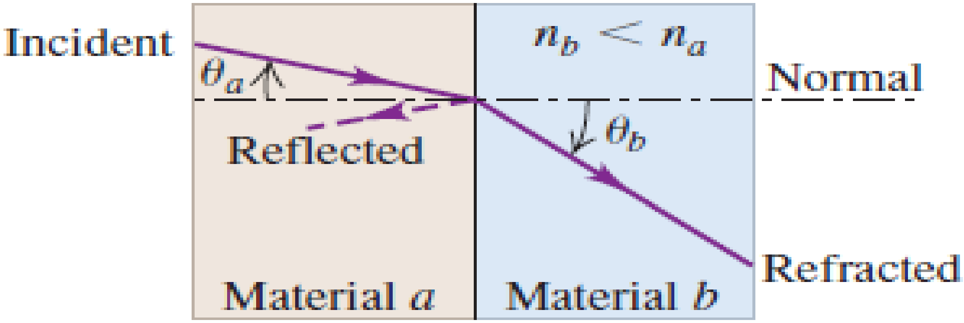
This experimental result, together with the observation that the incident and refracted rays and the normal all lie in the same plane, is called the **law of refraction** or **Snell's law,** While these results were first observed experimentally, they can be derived theoretically from a wave description of light.

33.8 Refraction and reflection in three cases. (a) Material b has a larger index of refraction than material a. (b) Material b has a smaller index of refraction than material a. (c) The incident light ray is normal to the interface between the materials.

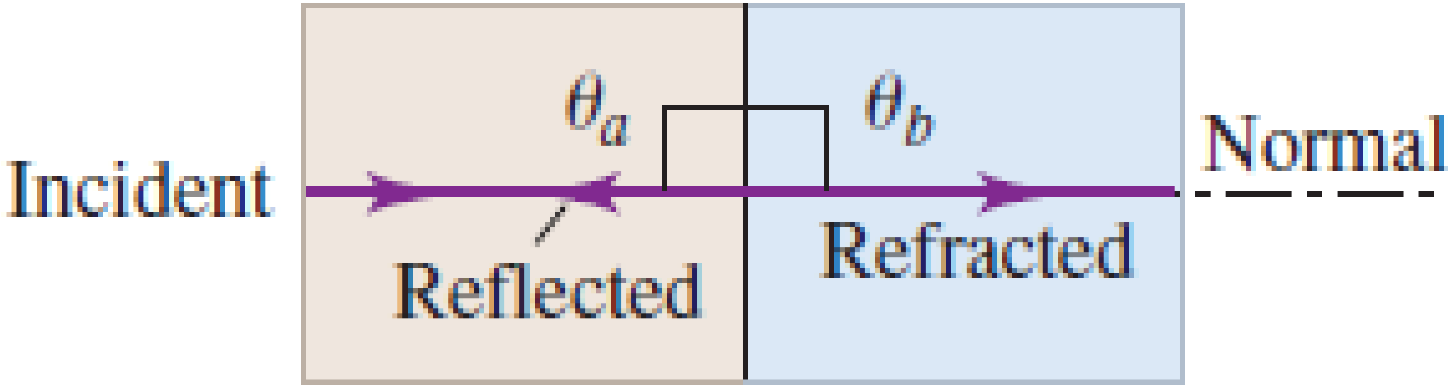
(a) A ray entering a material of *larger* index of refraction bends *toward* the normal.



(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.



Equations (33.3) and (33.4) show that when a ray passes from one material (a) into another material (b) having a larger index of refraction ($n_b > n_a$) and hence a slower wave speed, the angle θ_b with the normal is *smaller* in the second material than the angle θ_a in the first; hence the ray is bent *toward* the normal (Fig. 33.8a). When the second material has a *smaller* index of refraction than the first material ($n_b < n_a$) and hence a faster wave speed, the ray is bent *away from* the normal (Fig. 33.8b).

No matter what the materials on either side of the interface, in the case of *normal* incidence the transmitted ray is not bent at all

The laws of reflection and refraction apply regardless of which side of the interface the incident ray comes from. Furthermore, the path of a refracted ray is *reversible;* Since reflected and incident rays make the same angle with the normal, the path of a reflected ray is also reversible. That's why when you see someone's eyes in a mirror, they can also see you.

The *intensities* of the reflected and refracted rays depend on the angle of incidence, the two indexes of refraction, and the polarization (that is, the direction of the electric-field vector) of the incident ray. The fraction reflected is smallest at normal incidence ($\theta_a = 0°$), where it is about 4% for an air–glass interface. This fraction increases with increasing angle of incidence to 100% at grazing incidence, when $\theta_a = 90°$.

It's possible to use Maxwell's equations to predict the amplitude, intensity, phase, and polarization states of the reflected and refracted waves. Such an analysis is beyond our scope, however.

Table 33.1 Index of Refraction for Yellow Sodium Light, $\lambda_0 = 589$ nm

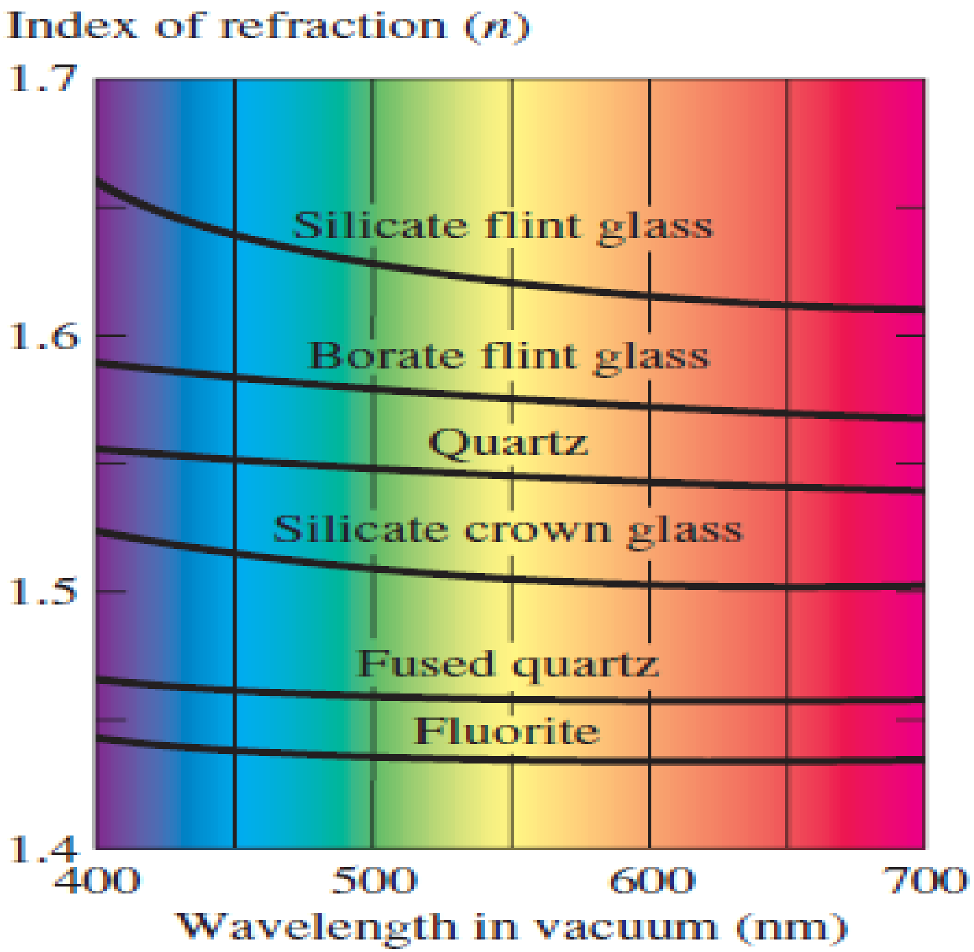
Substance	Index of Refraction, n
Solids	
Ice (H_2O)	1.309
Fluorite (CaF_2)	1.434
Polystyrene	1.49
Rock salt (NaCl)	1.544
Quartz (SiO_2)	1.544
Zircon ($ZrO_2 \cdot SiO_2$)	1.923
Diamond (C)	2.417
Fabulite ($SrTiO_3$)	2.409
Rutile (TiO_2)	2.62
Glasses (typical values)	
Crown	1.52
Light flint	1.58
Medium flint	1.62
Dense flint	1.66
Lanthanum flint	1.80
Liquids at 20°C	
Methanol (CH_3OH)	1.329
Water (H_2O)	1.333
Ethanol (C_2H_5OH)	1.36
Carbon tetrachloride (CCl_4)	1.460
Turpentine	1.472
Glycerine	1.473
Benzene	1.501
Carbon disulfide (CS_2)	1.628

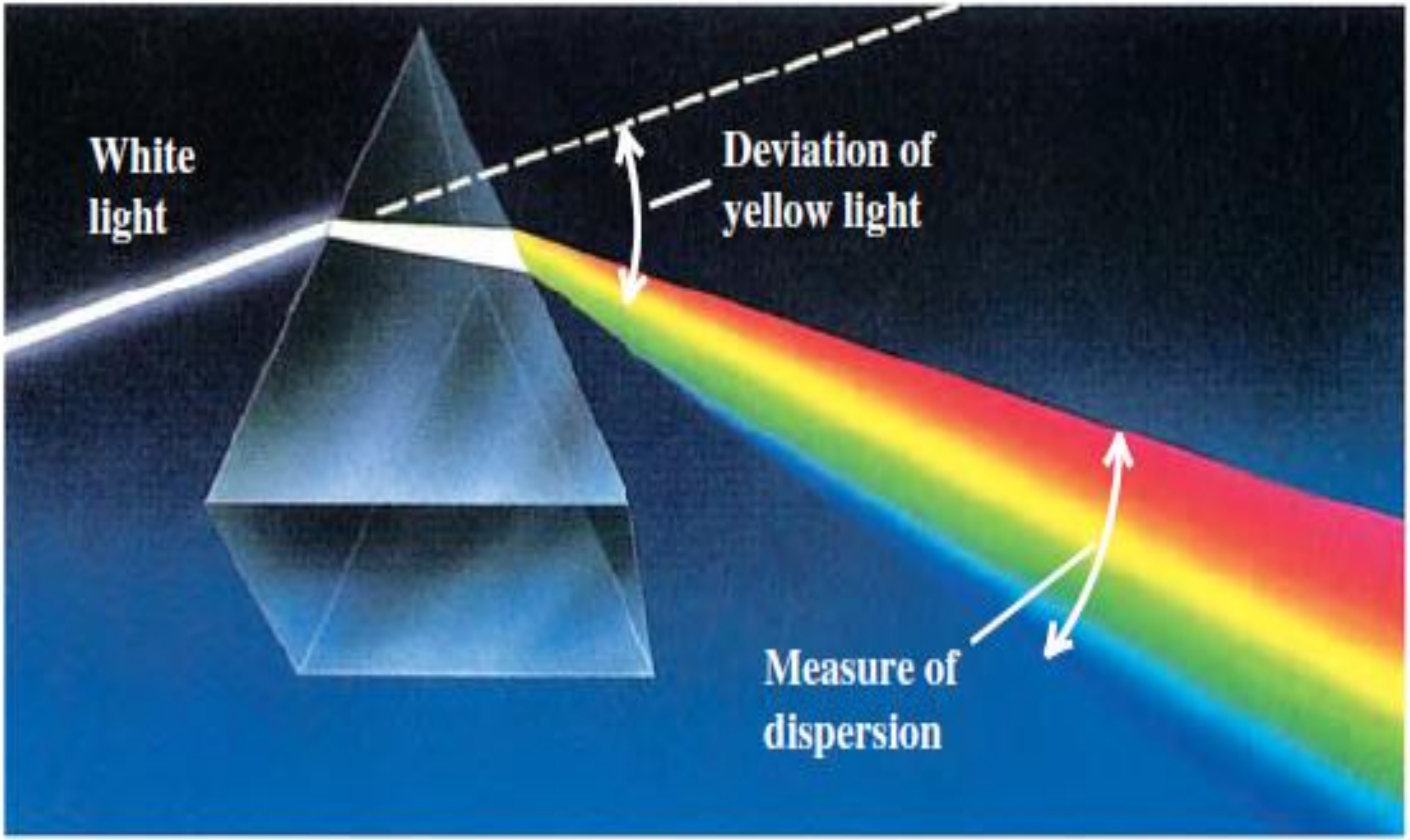
The index of refraction depends not only on the substance but also on the wavelength of the light. The dependence on wavelength is called *dispersion;* we will consider it in Section 33.4. Indexes of refraction for several solids and liquids are given in Table 33.1 for a particular wavelength of yellow light.

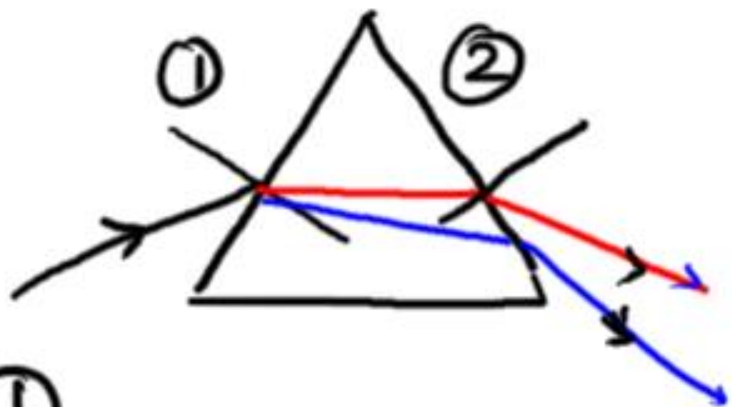
33.4 Dispersion

Ordinary white light is a superposition of waves with wavelengths extending throughout the visible spectrum. The speed of light *in vacuum* is the same for all wavelengths, but the speed in a material substance is different for different wavelengths. Therefore the index of refraction of a material depends on wavelength. The dependence of wave speed and index of refraction on wavelength is called **dispersion.**

33.18 Variation of index of refraction n with wavelength for different transparent materials. The horizontal axis shows the wavelength λ_0 of the light *in vacuum;* the wavelength in the material is equal to $\lambda = \lambda_0/n$.




White
light
Deviation of
yellow light
Measure of
dispersion



Surface 1

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

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

$$\sin\theta_r = \frac{\sin\theta_a}{n_r}$$

①

$n_b > n_r \therefore \theta_b < \theta_r$

θ_b is closer to the normal.

②

$\sin\theta_a = n_b \sin\theta_b$; $\sin\theta_a = n_r \sin\theta_r$

At surface ②, $\theta_r < \theta_b$ (incident) ; $n_r < n_b \therefore \theta_a\text{blue} > \theta_{red}$

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First, the frequency f of the wave does not change when passing from one material to another. That is, the number of wave cycles arriving per unit time must equal the number leaving per unit time; this is a statement that the boundary surface cannot create or destroy waves.

Second, the wavelength λ of the wave *is* different in general in different materials. This is because in any material, $v = \lambda f$; since f is the same in any material as in vacuum and v is always less than the wave speed c in vacuum, λ is also correspondingly reduced. Thus the wavelength λ of light in a material is *less than* the wavelength λ_0 of the same light in vacuum. From the above discussion, $f = c/\lambda_0 = v/\lambda$. Combining this with Eq. (33.1), $n = c/v$, we find

$$\lambda = \frac{\lambda_0}{n} \qquad \text{(wavelength of light in a material)} \qquad (33.5)$$

When a wave passes from one material into a second material with larger index of refraction, so that $n_b > n_a$, the wave speed decreases. The wavelength $\lambda_b = \lambda_0/n_b$ in the second material is then shorter than the wavelength $\lambda_a = \lambda_0/n_a$ in the first material. If instead the second material has a smaller index of refraction than the first material, so that $n_b < n_a$, then the wave speed increases. Then the wavelength λ_b in the second material is longer than the wavelength λ_a in the first material. This makes intuitive sense; the waves get "squeezed" (the wavelength gets shorter) if the wave speed decreases and get "stretched" (the wavelength gets longer) if the wave speed increases.

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),

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

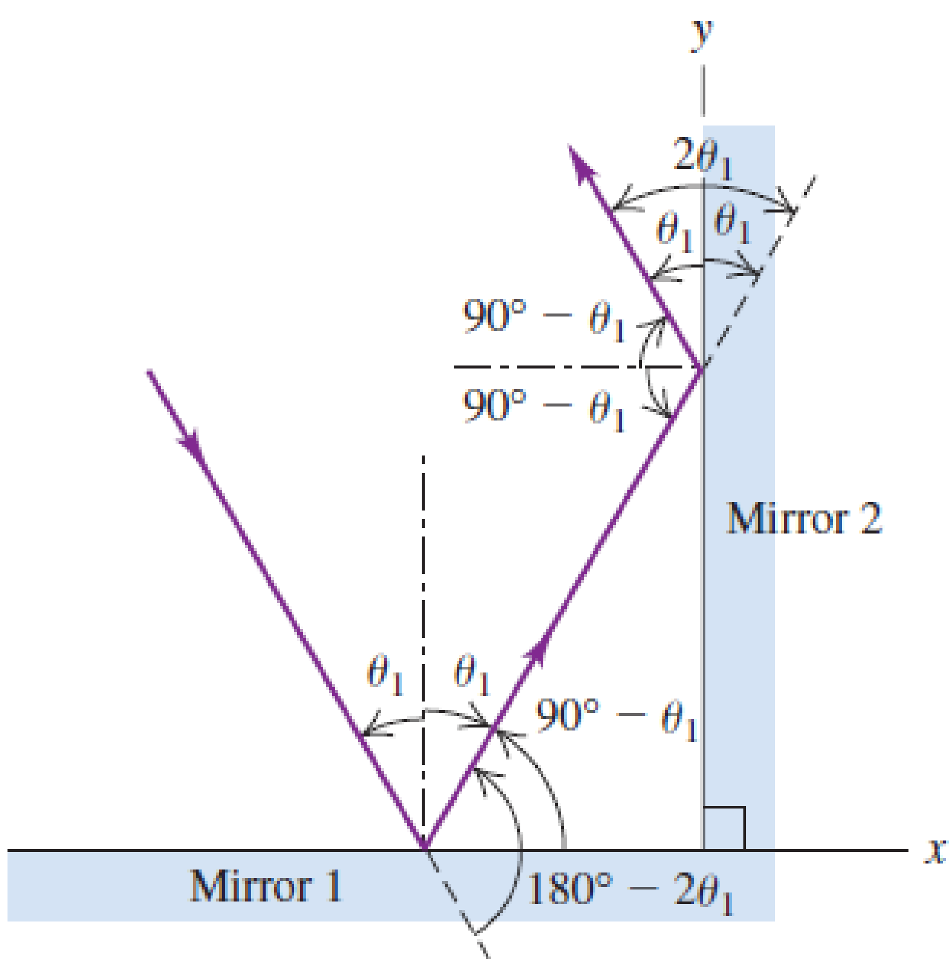
This is about the same index of refraction as for water. Then, using $n = c/v$ and $v = \lambda f$, we find

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

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

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?

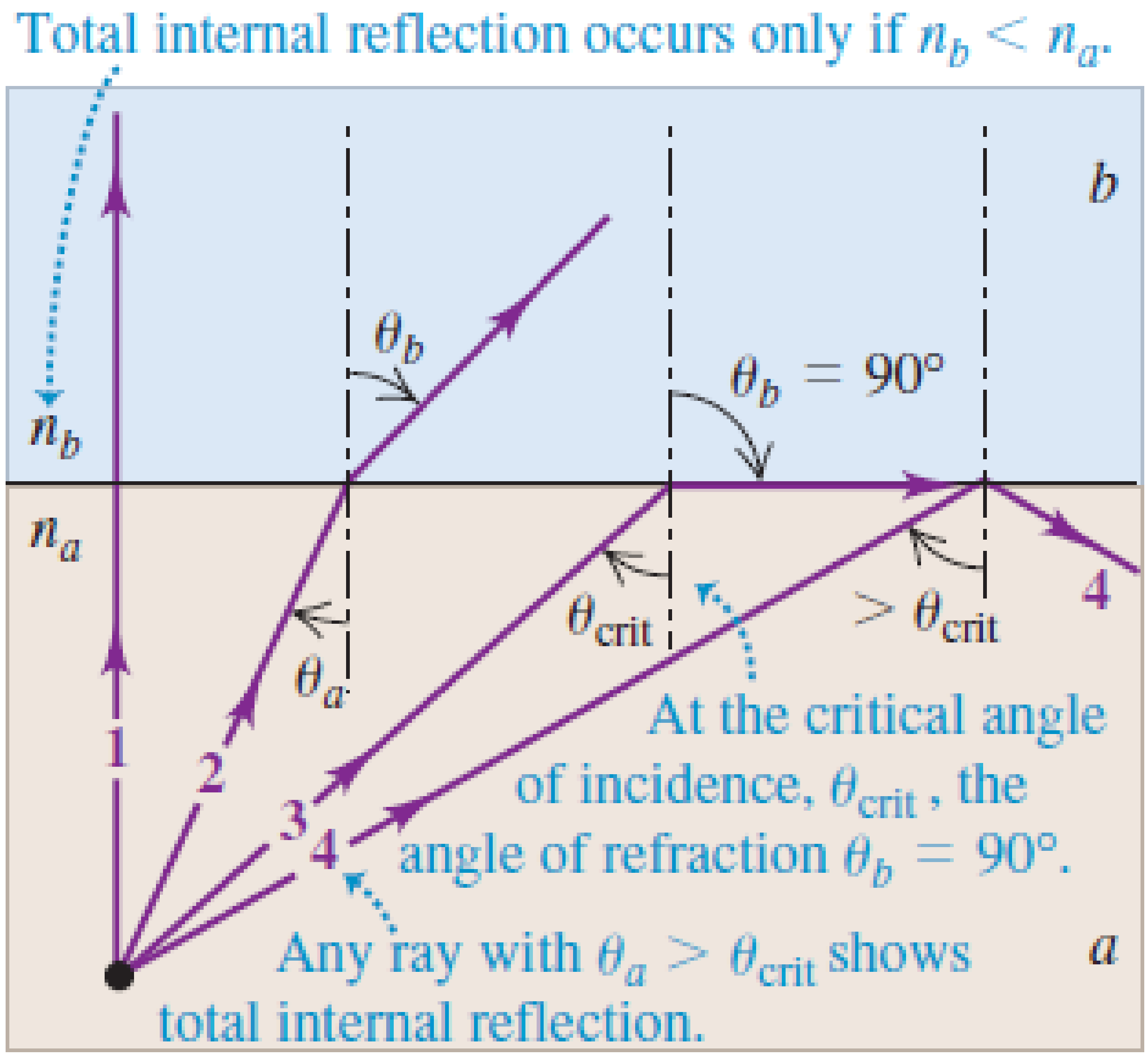
33.12 A ray moving in the *xy*-plane. The first reflection changes the sign of the *y*-component of its velocity, and the second reflection changes the sign of the *x*-component. For a different ray with a *z*-component of velocity, a third mirror (perpendicular to the two shown) could be used to change the sign of that component.



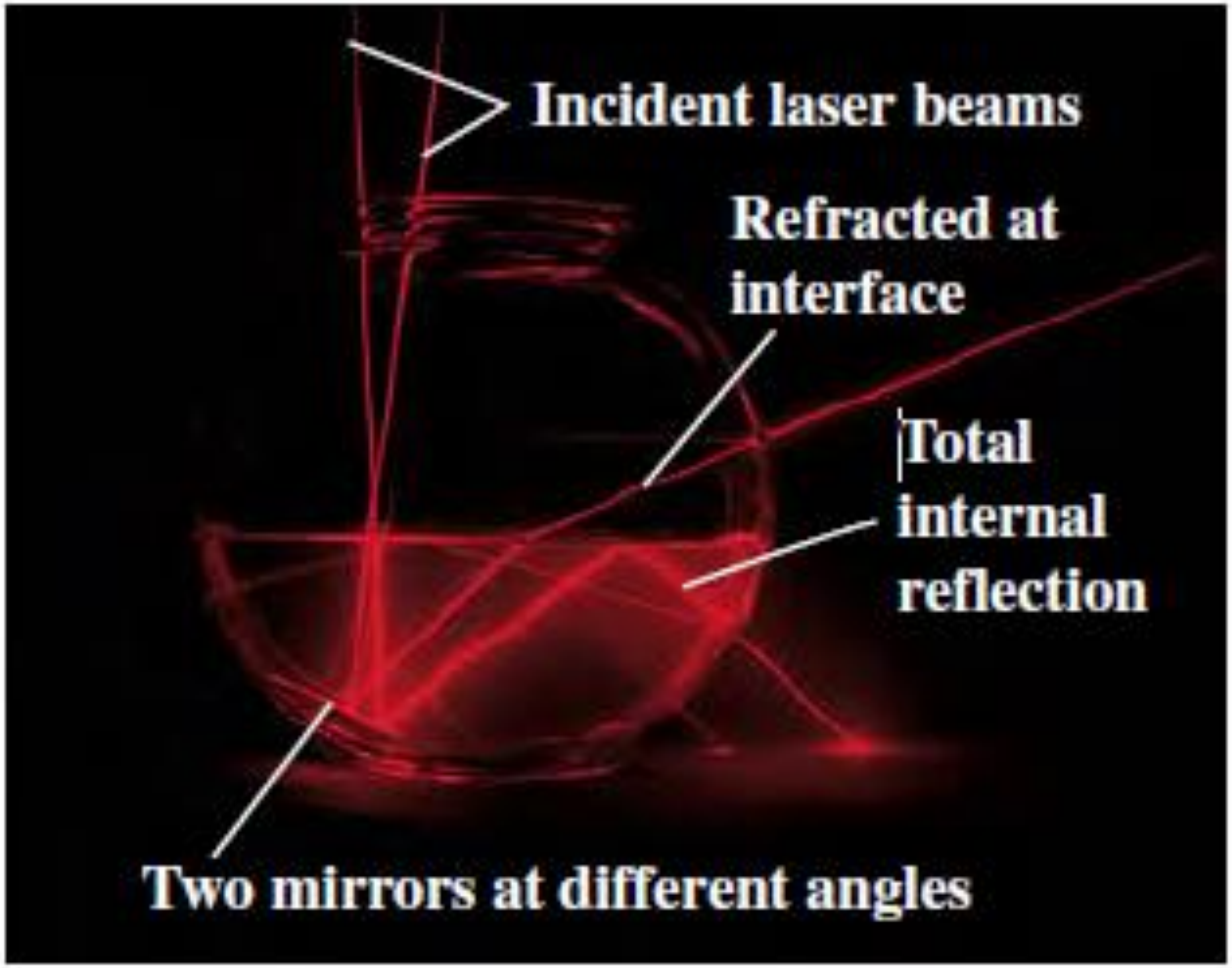
33.3 Total Internal Reflection

We have described how light is partially reflected and partially transmitted at an interface between two materials with different indexes of refraction. Under certain circumstances, however, *all* of the light can be reflected back from the interface, with none of it being transmitted, even though the second material is transparent. Figure 33.13a shows how this can occur. Several rays are shown radiating from a point source in material *a* with index of refraction *na*.

(a) Total internal reflection



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



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

We can find the critical angle for two given materials a and b by setting $\theta_b = 90°$ ($\sin\theta_b = 1$) in Snell's law. We then have

$$\sin\theta_{crit} = \frac{n_b}{n_a} \qquad \text{(critical angle for total internal reflection)} \qquad (33.6)$$

Total internal reflection will occur if the angle of incidence θ_a is larger than or equal to θ_{crit}.

Applications of Total Internal Reflection

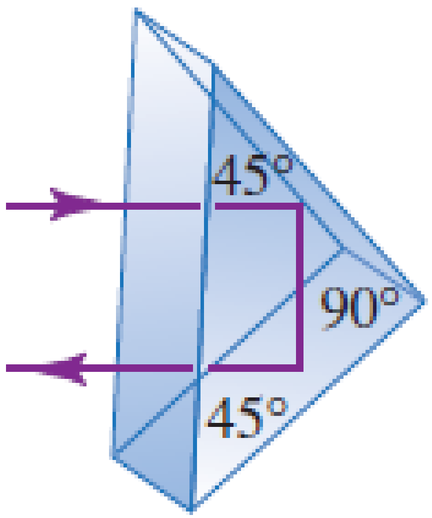
Total internal reflection finds numerous uses in optical technology. As an example, consider glass with index of refraction $n = 1.52$. If light propagating within this glass encounters a glass–air interface, the critical angle is

$$\sin\theta_{\text{crit}} = \frac{1}{1.52} = 0.658 \qquad \theta_{\text{crit}} = 41.1^\circ$$

The light will be *totally reflected* if it strikes the glass–air surface at an angle of 41.1° or larger. Because the critical angle is slightly smaller than 45°, it is possible to use a prism with angles of 45°–45°–90° as a totally reflecting surface. As reflectors, totally reflecting prisms have some advantages over metallic surfaces such as ordinary coated-glass mirrors. While no metallic surface reflects 100% of the light incident on it, light can be *totally* reflected by a prism. These reflecting properties of a prism are permanent and unaffected by tarnishing.

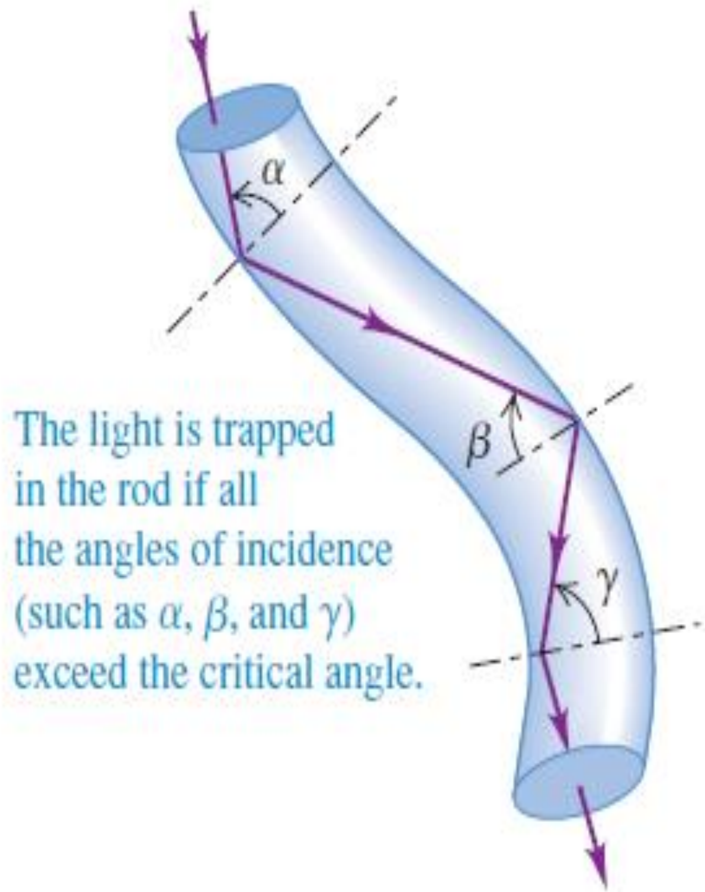
33.14 (a) Total internal reflection in a Porro prism. (b) A combination of two Porro prisms in binoculars.

(a) Total internal reflection in a Porro prism



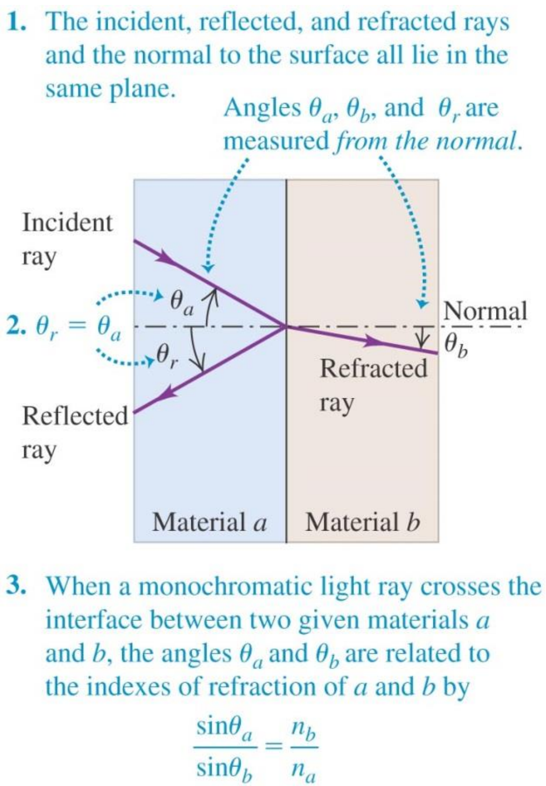
If the incident beam is oriented as shown, total internal reflection occurs on the 45° faces (because, for a glass–air interface, $\theta_{crit} = 41.1$).

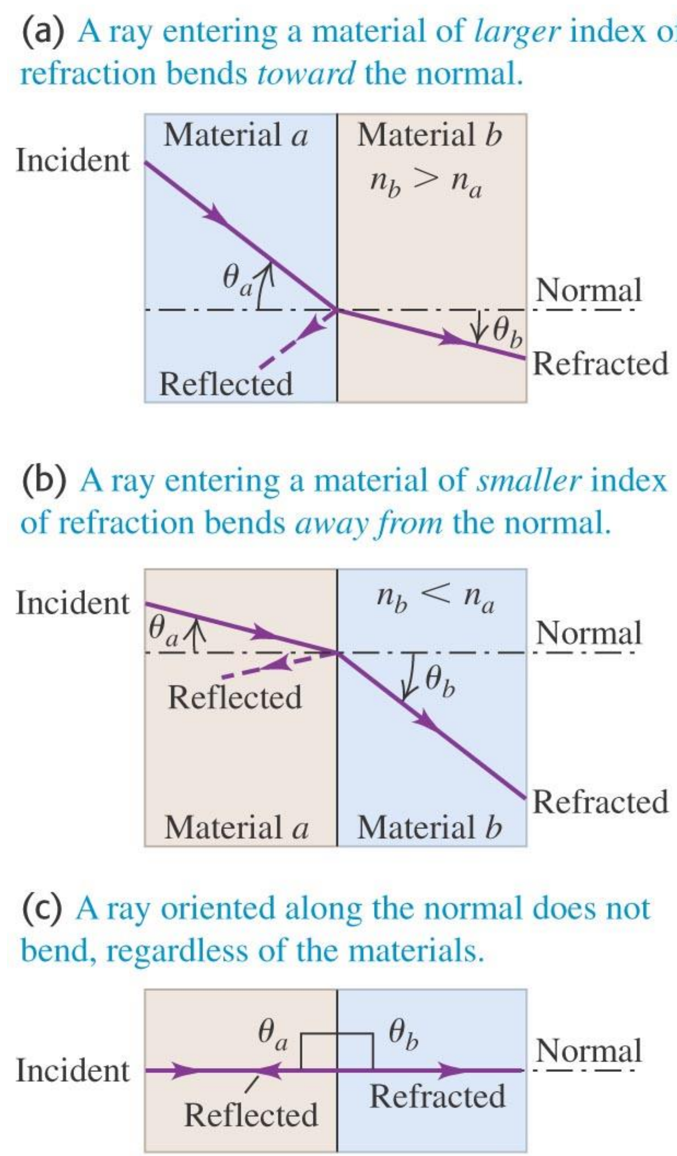
33.15 A transparent rod with refractive index greater than that of the surrounding material.



Laws of reflection and refraction

- Angle of incidence = angle of reflection.
- Snell's Law of Refraction considers the slowing of light in a medium other than vacuum … the index of refraction.
- Consider Figures 33.7 and 33.8.



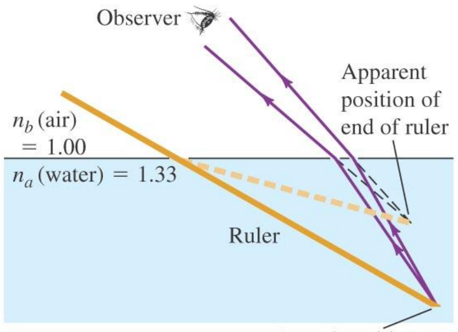


Why should the ruler appear to be bent?

- The difference in index of refraction for air and water causes your eye to be deceived. Your brain follows rays back to the origin they would have had if not bent.
- Consider Figure 33.9.

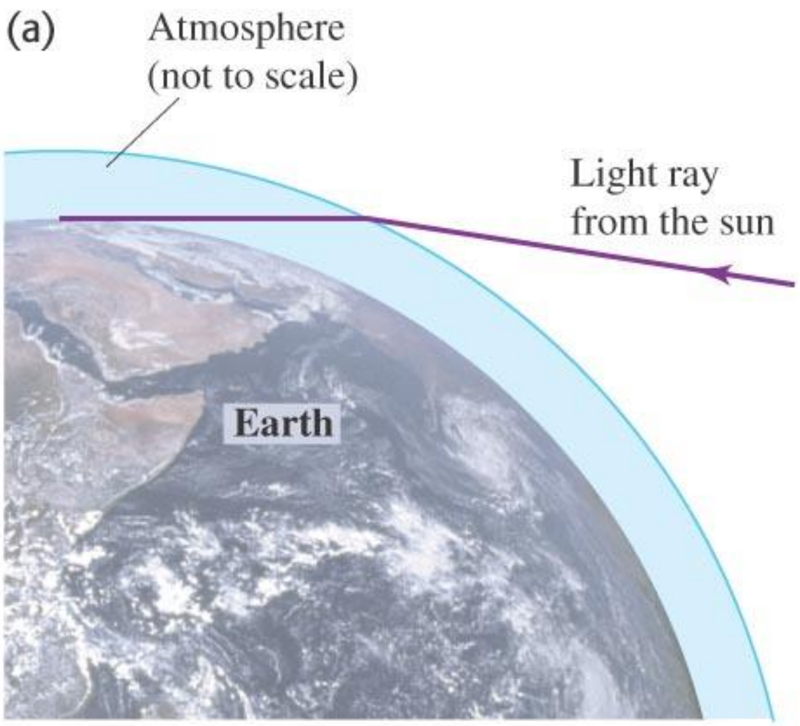
(a) A straight ruler half-immersed in water

(b) Why the ruler appears bent



Why should sunsets be orange and red?

- The light path at sunset is much longer than at noon when the sun is directly overhead.
- Consider Figure 33.10.



Tabulated indexes of refraction

Table 33.1 Index of Refraction for Yellow Sodium Light $\lambda_0 = 589$ nm

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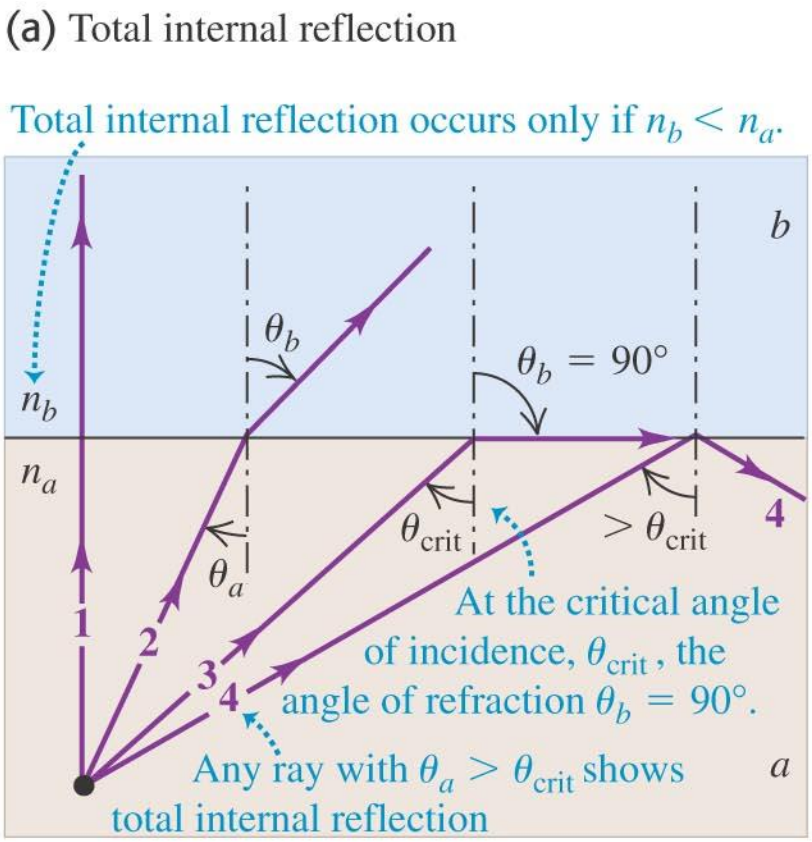
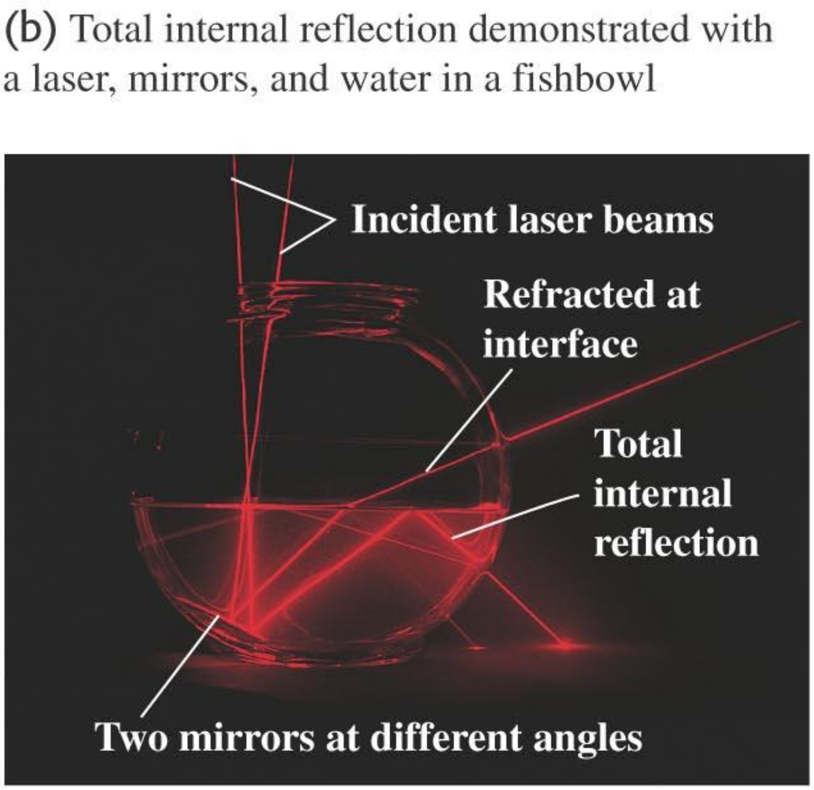
Dense flint	1.66
Lanthanum flint	1.80
Liquids at 20°C	
Methanol (CH_3OH)	1.329
Water (H_2O)	1.333
Ethanol (C_2H_5OH)	1.36
Carbon tetrachloride (CCl_4)	1.460
Turpentine	1.472
Glycerine	1.473
Benzene	1.501
Carbon disulfide (CS_2)	1.628

Total internal reflection I

- As the angle of incidence becomes more and more acute, the light ceases to be transmitted, only reflected.
- Consider Figure 33.13.

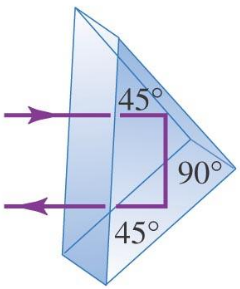




Total internal reflection II

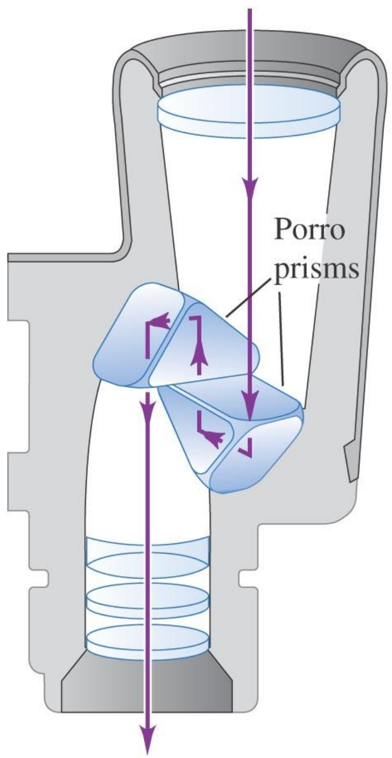
- Using clever arrangements of glass or plastic, the applications are mind boggling.

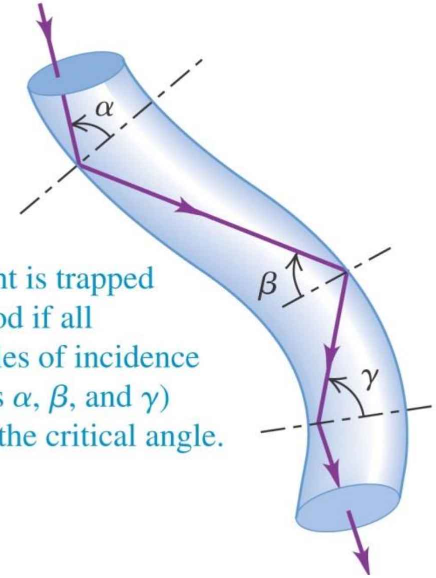
(a) Total internal reflection in a Porro prism



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

(b) Binoculars use Porro prisms to reflect the light to each eyepiece.





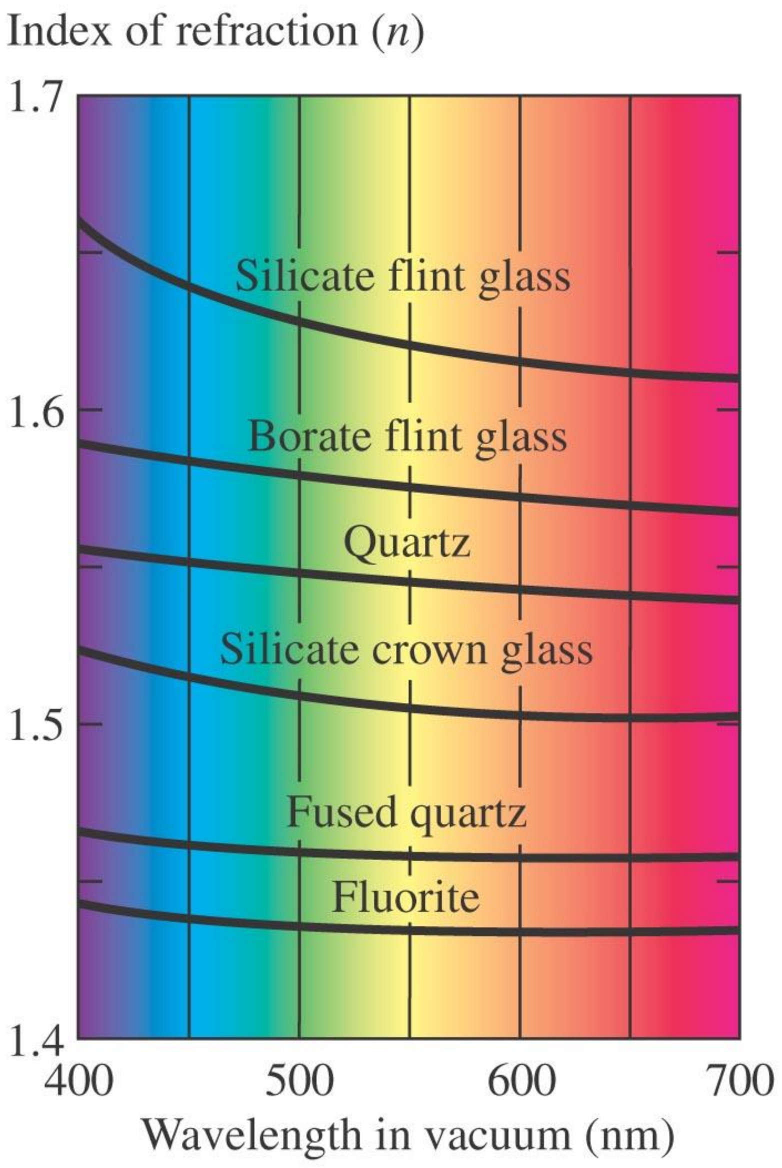
The light is trapped in the rod if all the angles of incidence (such as α, β, and γ) exceed the critical angle.

Total internal reflection III

- Diamonds sparkle as they do because their index of refraction is one of the highest a transparent material can have. Nearly all light that enters a surface ends up making many passes around the inside of the stone. The effect is only amplified by cutting the surfaces at sharp angles. See Figure 33.17.
- Follow Conceptual Example 33.4.

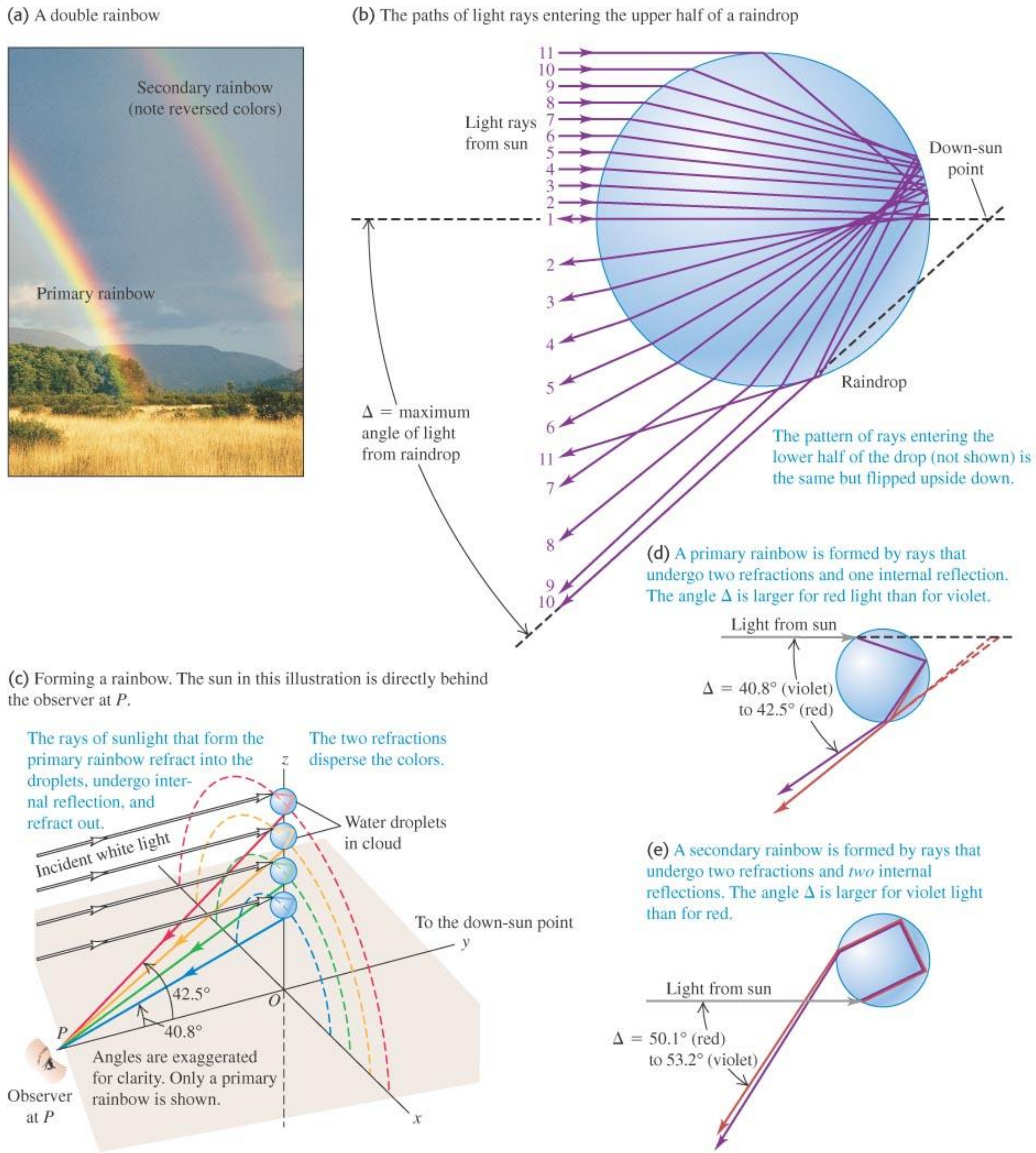
Dispersion

- From the discussion of the prism seen in earlier slides, we recall that light refraction is wavelength dependent. This effect is made more pronounced if the index of refraction is higher. "Making a rainbow" is actually more than just appreciation of beauty; applied to chemical systems, the dispersion of spectral lines can be a powerful identification tool.
- Refer to Figures 33.18 and 33.19 (not shown).



Special case—dispersion and atmospheric rainbows

- As a person looks into the sky and sees a rainbow, he or she is actually “receiving light signals” from a physical spread of water droplets over many meters (or hundreds of meters) of altitude in the atmosphere. The reds come from the higher droplets and the blues from the lower (as we have seen in the wavelength dependence of light refraction).



33.5 Polarization

Polarization is a characteristic of all transverse waves. This chapter is about light, but to introduce some basic polarization concepts, let's go back to the transverse waves on a string that we studied in Chapter 15. For a string that in equilibrium lies along the x-axis, the displacements may be along the y-direction, as in Fig. 33.21a. In this case the string always lies in the xy-plane. But the displacements might instead be along the z-axis, as in Fig. 33.21b; then the string always lies in the xz-plane.

When a wave has only *y*-displacements, we say that it is **linearly polarized** in the *y*-direction; a wave with only *z*-displacements is linearly polarized in the *z*-direction. For mechanical waves we can build a **polarizing filter,** or **polarizer,** that permits only waves with a certain polarization direction to pass. In Fig. 33.21c the string can slide vertically in the slot without friction, but no horizontal motion is possible. This filter passes waves that are polarized in the *y*-direction but blocks those that are polarized in the *z*-direction.

We always define the direction of polarization of an electromagnetic wave to be the direction of the *electric*-field vector ***E*** not the magnetic field, because many common electromagnetic-wave detectors respond to the electric forces on electrons in materials, not the magnetic forces. Thus the electromagnetic wave described by Eq. (32.17),

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

Polarizing Filters

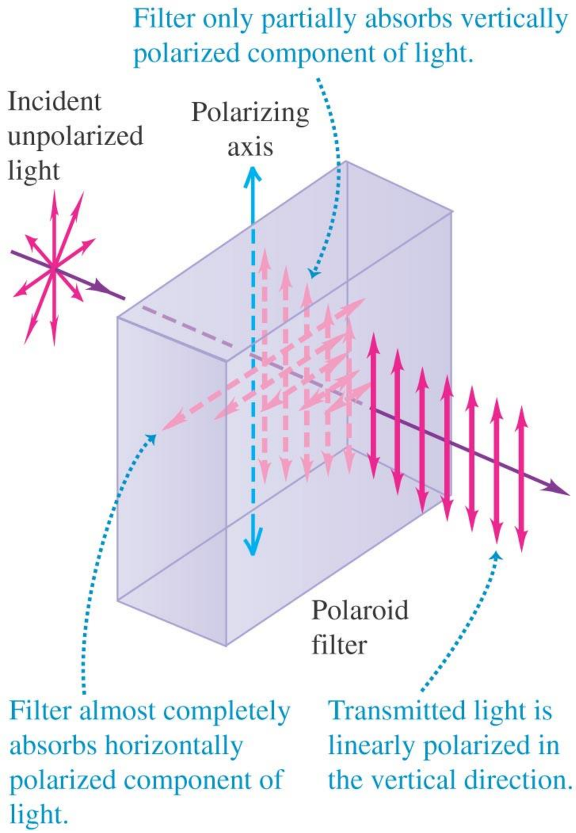
Waves emitted by a radio transmitter are usually linearly polarized. The vertical antennas that are used for radio broadcasting emit waves that, in a horizontal plane around the antenna, are polarized in the vertical direction (parallel to the antenna).

The situation is different for visible light. Light from incandescent light bulbs and fluorescent light fixtures is *not* polarized (Fig. 33.22b). The “antennas” that radiate light waves are the molecules that make up the sources. The waves emitted by any one molecule may be linearly polarized, like those from a radio antenna.

But any actual light source contains a tremendous number of molecules with random orientations, so the emitted light is a random mixture of waves linearly polarized in all possible transverse directions. Such light is called **unpolarized light** or **natural light.** To create polarized light from unpolarized natural light requires a filter

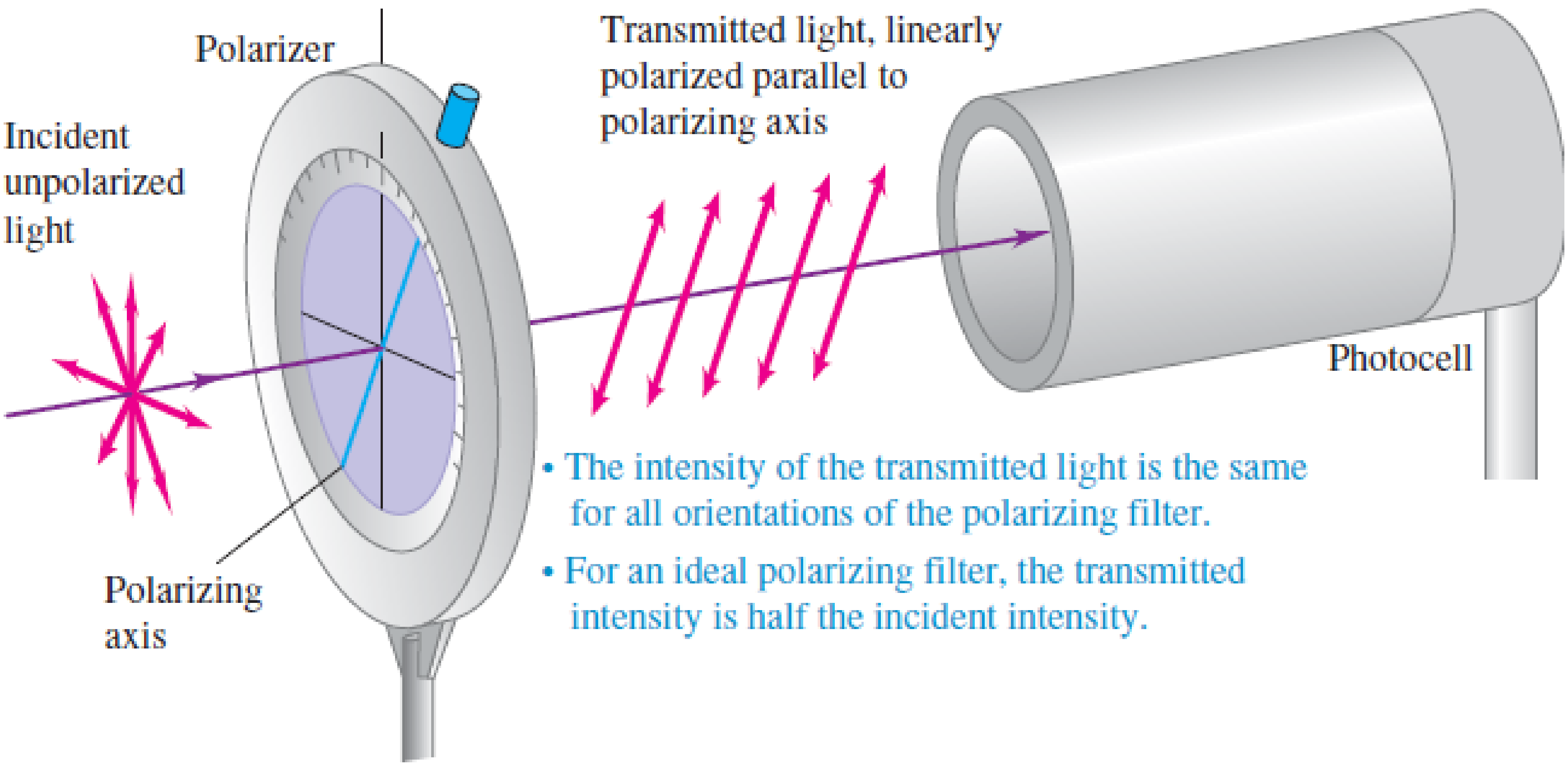
Selecting one orientation of the EM wave—the Polaroid

- A Polaroid filter is a polymer array that can be thought of like teeth in a comb. Hold the comb at arm's length with the teeth pointing down. Continue the mental cartoon and imagine waves oscillating straight up and down passing without resistance. Any "side-to-side" component and they would be blocked.



The most common polarizing filter for visible light is a material known by the trade name Polaroid, widely used for sunglasses and polarizing filters for camera lenses. Developed originally by the American scientist Edwin H. Land, this material incorporates substances that have **dichroism,** a selective absorption in which one of the polarized components is absorbed much more strongly than the other
(Fig. 33.23

A Polaroid filter transmits 80% or more of the intensity of a wave that is polarized parallel to a certain axis in the material, called the **polarizing axis,** but only 1% or less for waves that are polarized perpendicular to this axis. In one type of Polaroid filter, long-chain molecules within the filter are oriented with their axis perpendicular to the polarizing axis; these molecules preferentially absorb light that is polarized along their length, much like the conducting wires in a polarizing filter for microwaves.


Polarizer
Incident
unpolarized
light
Transmitted light, linearly
polarized parallel to
polarizing axis
Photocell
Polarizing
axis
• The intensity of the transmitted light is the same
for all orientations of the polarizing filter.
• For an ideal polarizing filter, the transmitted
intensity is half the incident intensity.

Using Polarizing Filters

An *ideal* polarizing filter (polarizer) passes 100% of the incident light that is polarized parallel to the filter's polarizing axis but completely blocks all light that is polarized perpendicular to this axis. Such a device is an unattainable idealization, but the concept is useful in clarifying the basic ideas. In the following discussion we will assume that all polarizing filters are ideal.

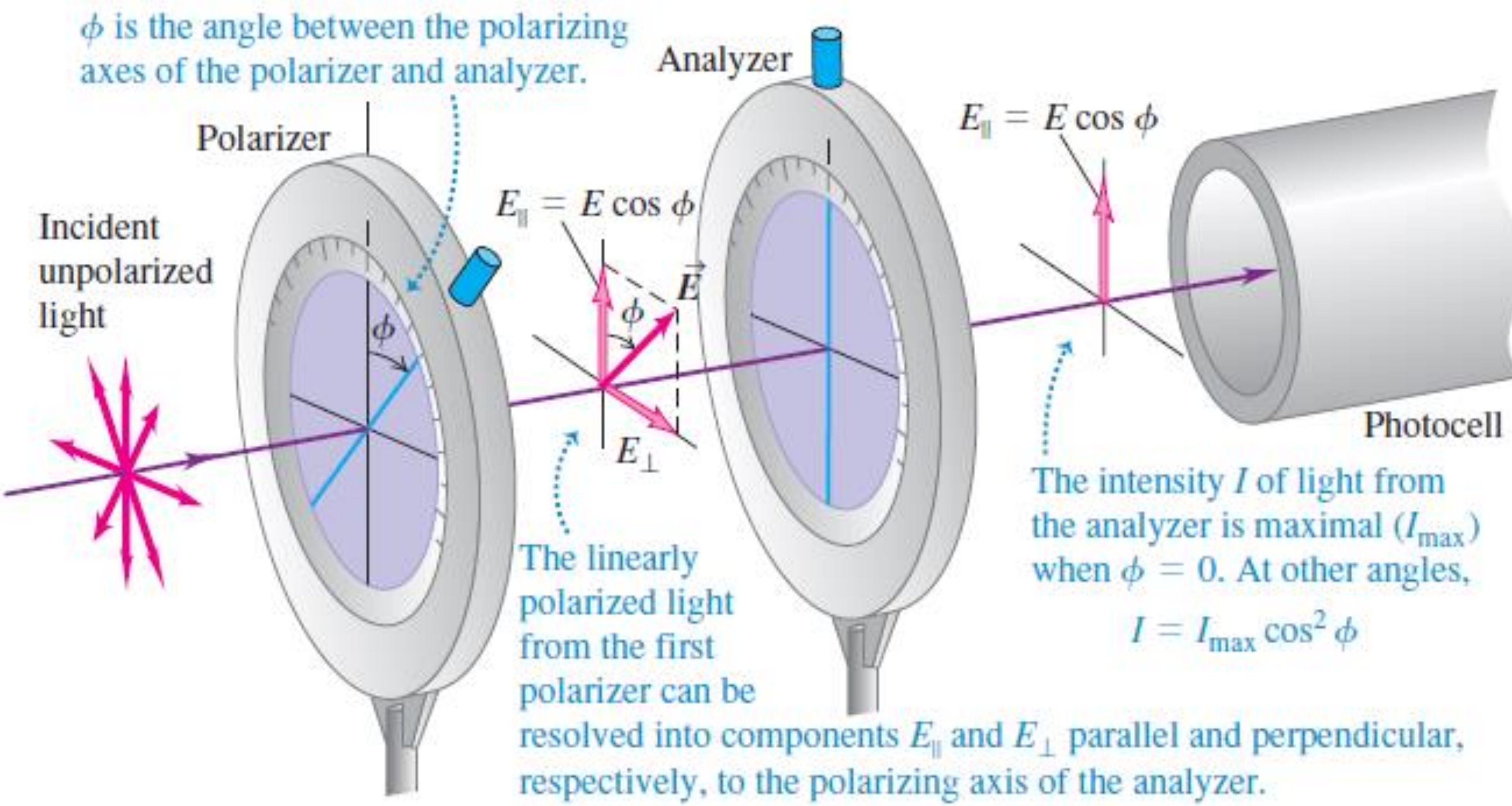
When unpolarized light is incident on an ideal polarizer as in Fig. 33.24, the intensity of the transmitted light is *exactly half* that of the incident unpolarized light, no matter how the polarizing axis is oriented. Here's why: We can resolve the field of the incident wave into a component parallel to the polarizing axis and a component perpendicular to it. Because the incident light is a random mixture of all states of polarization, these two components are, on average, equal. The ideal polarizer transmits only the component that is parallel to the polarizing axis, so half the incident intensity is transmitted.

The vector of the incident wave can be represented in terms of components parallel and perpendicular to the polarizer axis (shown in blue); only the component of parallel to the

polarizing axis is transmitted. Hence the light emerging from the polarizer is linearly polarized parallel to the polarizing axis.

What happens when the linearly polarized light emerging from a polarizer passes through a second polarizer, or *analyzer*, as in Fig. 33.25? Suppose the polarizing axis of the analyzer makes an angle ϕ with the polarizing axis of the first polarizer. We can resolve the linearly polarized light that is transmitted by the first polarizer into two components, as shown in Fig. 33.25, one parallel and the other perpendicular to the axis of the analyzer.

Only the parallel component, E cos (ϕ) with amplitude is transmitted by the analyzer. The transmitted intensity is greatest when $\phi = 0$ and it is zero when the polarizer and analyzer are *crossed* so that $\phi = 0$.


ϕ is the angle between the polarizing axes of the polarizer and analyzer.
Analyzer
Polarizer
Incident unpolarized light
$E_{\parallel} = E\cos\phi$
$\vec{E}$
ϕ
$E_{\perp}$
$E_{\parallel} = E\cos\phi$
Photocell
The intensity I of light from the analyzer is maximal (I_{max}) when $\phi = 0$. At other angles,
$I = I_{max}\cos^2\phi$
The linearly polarized light from the first polarizer can be resolved into components $E_{\parallel}$ and $E_{\perp}$ parallel and perpendicular, respectively, to the polarizing axis of the analyzer.

To find the transmitted intensity at intermediate values of the angle we recall from our energy discussion in Section 32.4 that the intensity of an electromagnetic wave is proportional to the *square* of the amplitude of the wave [see Eq. (32.29)]. The ratio of transmitted to incident *amplitude* is cos (ϕ) so the ratio of transmitted to incident *intensity* is $\cos^2$ (ϕ) Thus the intensity of the light transmitted through the analyzer is

$$I = I_{\max} \cos^2 \phi \qquad \text{(Malus's law, polarized light passing through an analyzer)} \qquad (33.7)$$

Where I_{max} is the maximum intensity of light transmitted (at $\phi = 0$ and I is the amount transmitted at angle ϕ. This relationship, discovered experimentally by Etienne Louis Malus in 1809, is called **Malus's law.** Malus's law applies *only* if the incident light passing through the analyzer is already linearly polarized.

Polarization by Reflection

Unpolarized light can be polarized, either partially or totally, by *reflection.* In Fig. 33.27, unpolarized natural light is incident on a reflecting surface between two transparent optical materials. For most angles of incidence, waves for which the electric-field vector is perpendicular to the plane of incidence (that is, parallel to the reflecting surface) are reflected more strongly than those for which lies in this plane. In this case the reflected light is *partially polarized* in the direction perpendicular to the plane of incidence.

But at one particular angle of incidence, called the **polarizing angle** θ_p the light for which E lies in the plane of incidence is *not reflected at all* but is completely refracted. At this same angle of incidence the light for which E is perpendicular to the plane of incidence is partially reflected and partially refracted.

The *reflected* light is therefore *completely* polarized perpendicular to the plane of incidence, as shown in Fig. 33.27. The *refracted* (transmitted) light is *partially* polarized parallel to this plane; the refracted light is a mixture of the component parallel to the plane of incidence, all of which is refracted, and the remainder the perpendicular component

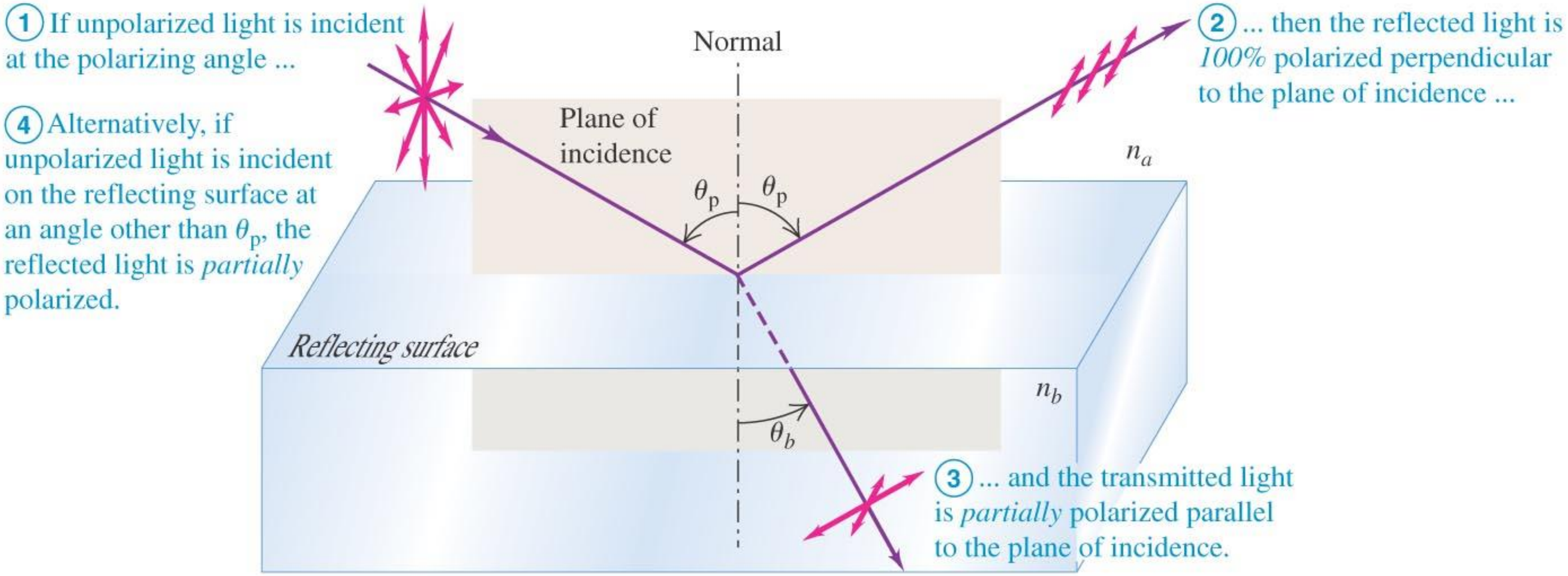
In 1812 the British scientist Sir David Brewster discovered that when the angle of incidence is equal to the polarizing angle θ_p, the reflected ray and the refracted ray are perpendicular to each other (Fig. 33.28). In this case the angle of refraction θ_b equals $90^\circ - \theta_p$. From the law of refraction,

$$n_a \sin\theta_p = n_b \sin\theta_b$$

$$n_a \sin\theta_p = n_b \sin(90^\circ - \theta_p) = n_b \cos\theta_p$$

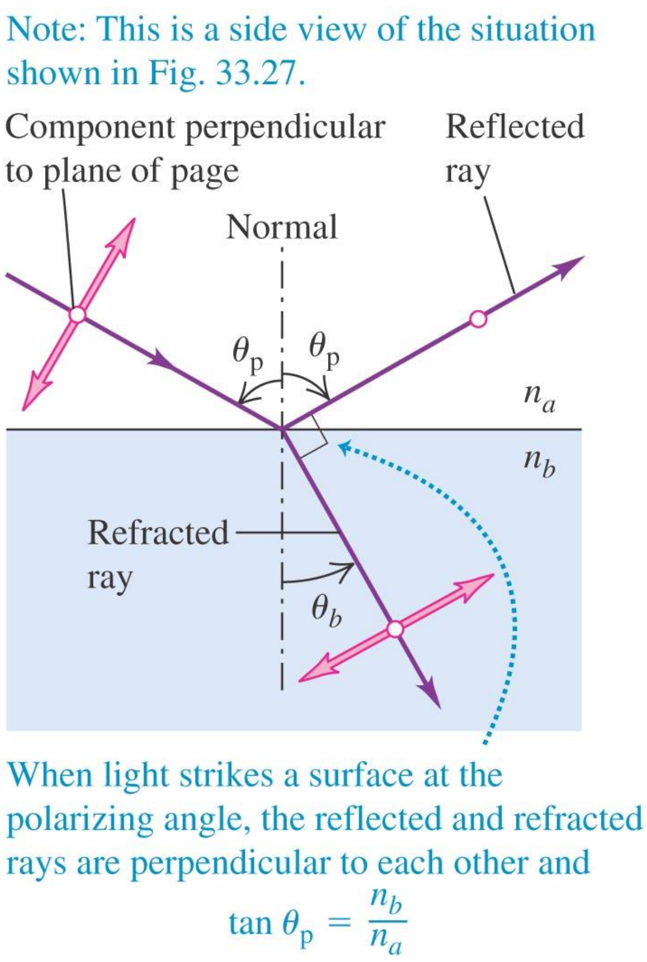
$$\tan\theta_p = \frac{n_b}{n_a} \qquad \text{(Brewster's law for the polarizing angle)} \qquad (33.8)$$

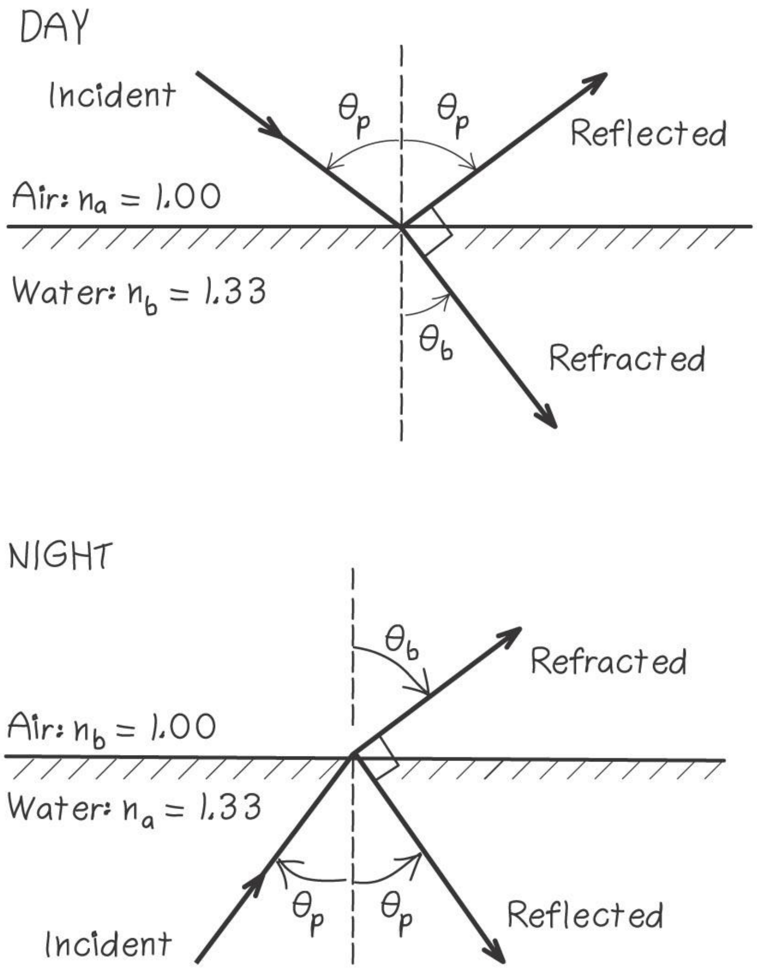
Polarization I



Polarization II

- .

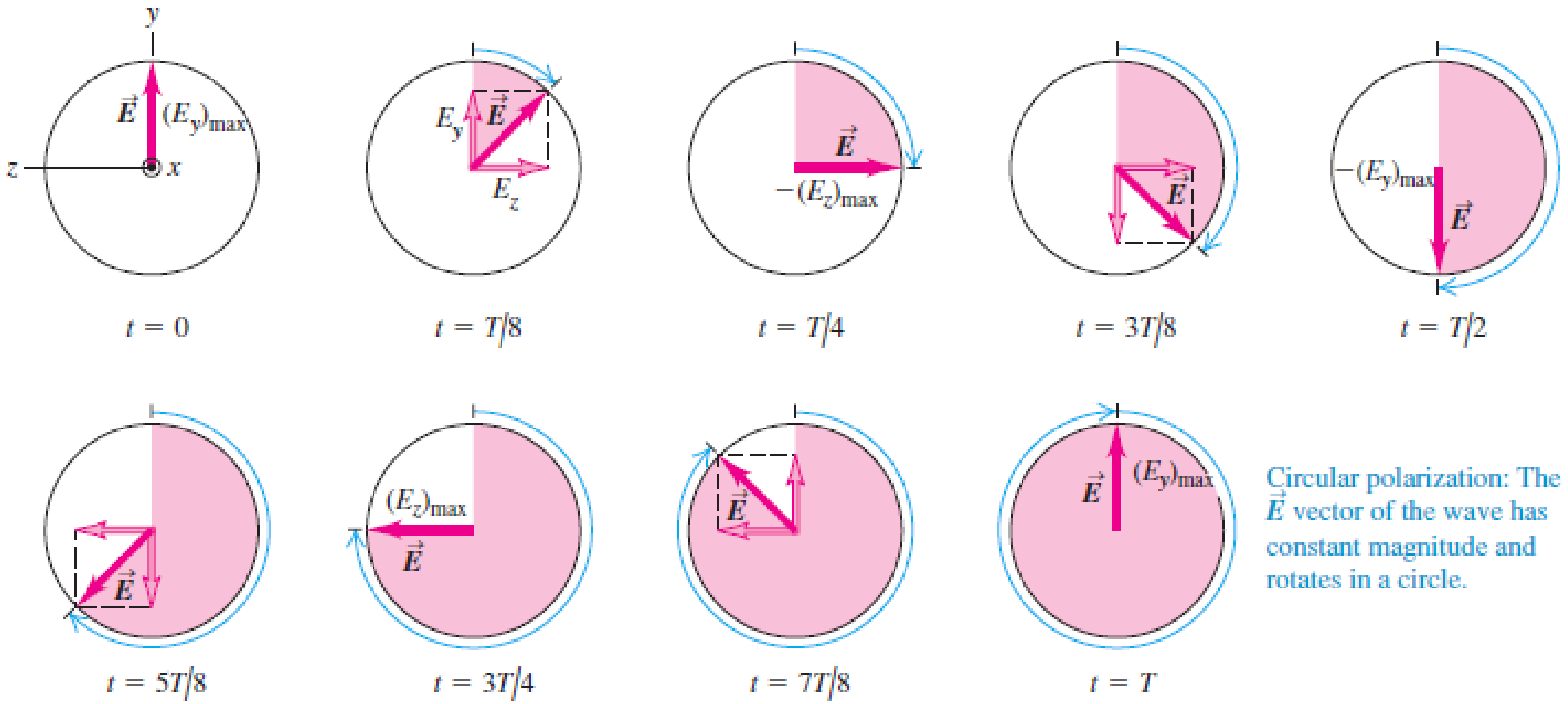




Polarization by reflection is the reason polarizing filters are widely used in sunglasses (Fig. 33.26). When sunlight is reflected from a horizontal surface, the plane of incidence is vertical, and the reflected light contains a preponderance of light that is polarized in the horizontal direction. When the reflection occurs at a smooth asphalt road surface or the surface of a lake, it causes unwanted glare. Vision can be improved by eliminating this glare. The manufacturer makes the polarizing axis of the lens material vertical, so very little of the horizontally polarized light reflected from the road is transmitted to the eyes. The glasses also reduce the overall intensity of the transmitted light to somewhat less than 50% of the intensity of the unpolarized incident light

Figure 33.30 shows the analogous situation for an electromagnetic wave. Two sinusoidal waves of equal amplitude, polarized in the and and with a quarter-cycle phase difference, are superposed. The result is a wave in which the vector at each point has a constant magnitude but *rotates* around the direction of propagation. The wave in Fig. 33.30 is propagating toward you and the vector appears to be rotating clockwise, so it is called a *right circularly polarized* electromagnetic wave. If instead the vector of a wave coming toward you appears to be rotating counterclockwise, it is called a *left circularly polarized* electromagnetic wave.

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.



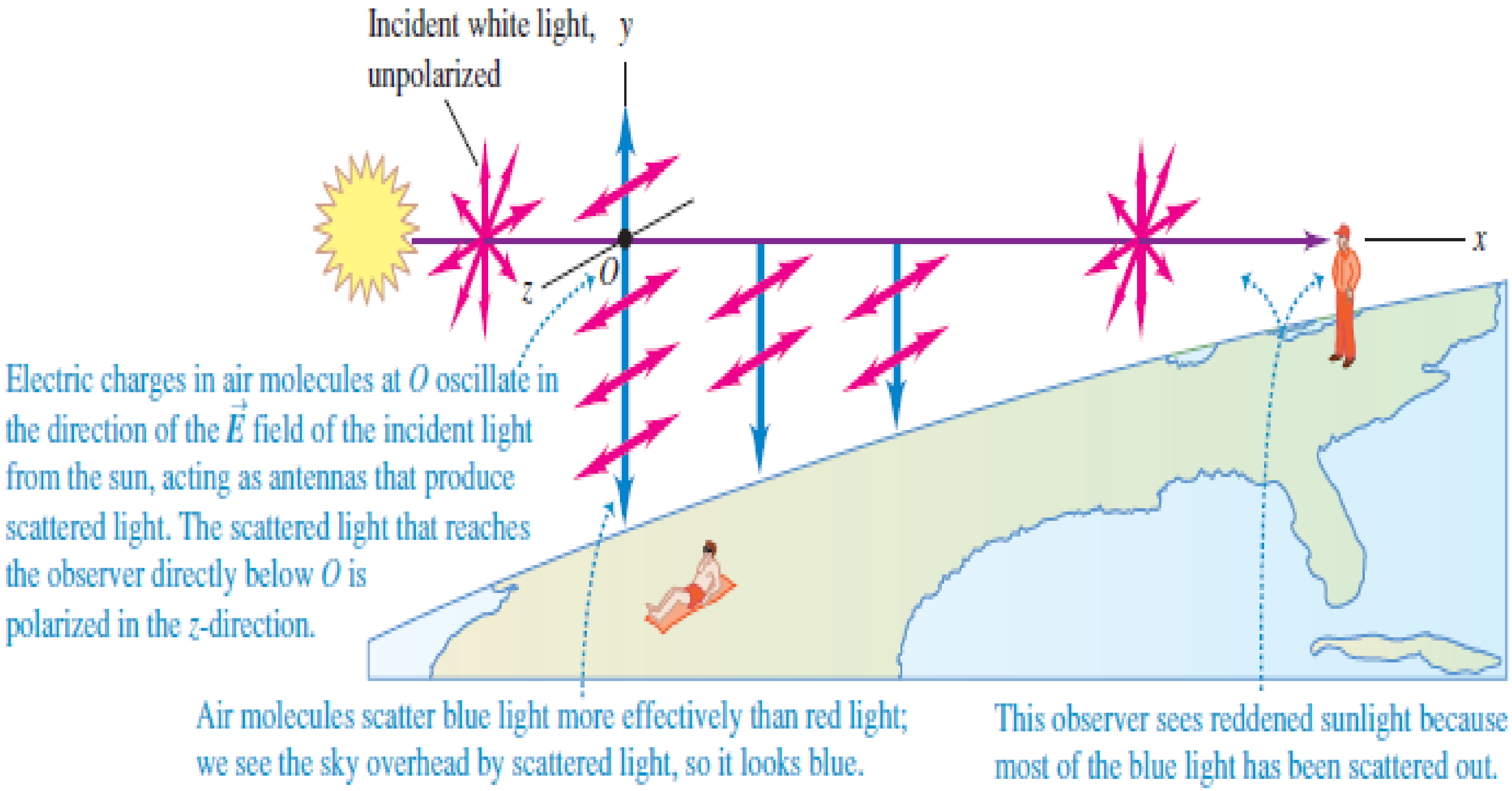
If the phase difference between the two component waves is something other than a quarter-cycle, or if the two component waves have different amplitudes, then each point on the string traces out not a circle but an *ellipse.* The resulting wave is said to be **elliptically polarized**

33.6 Scattering of Light

The sky is blue. Sunsets are red. Skylight is partially polarized; that’s why the sky looks darker from some angles than from others when it is viewed through Polaroid sunglasses. As we will see, a single phenomenon is responsible for all of these effects.

When you look at the daytime sky, the light that you see is sunlight that has been absorbed and then re-radiated in a variety of directions. This process is called **scattering.** (If the earth had no atmosphere, the sky would appear as black in the daytime as it does at night, just as it does to an astronaut in space or on the moon.)

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.

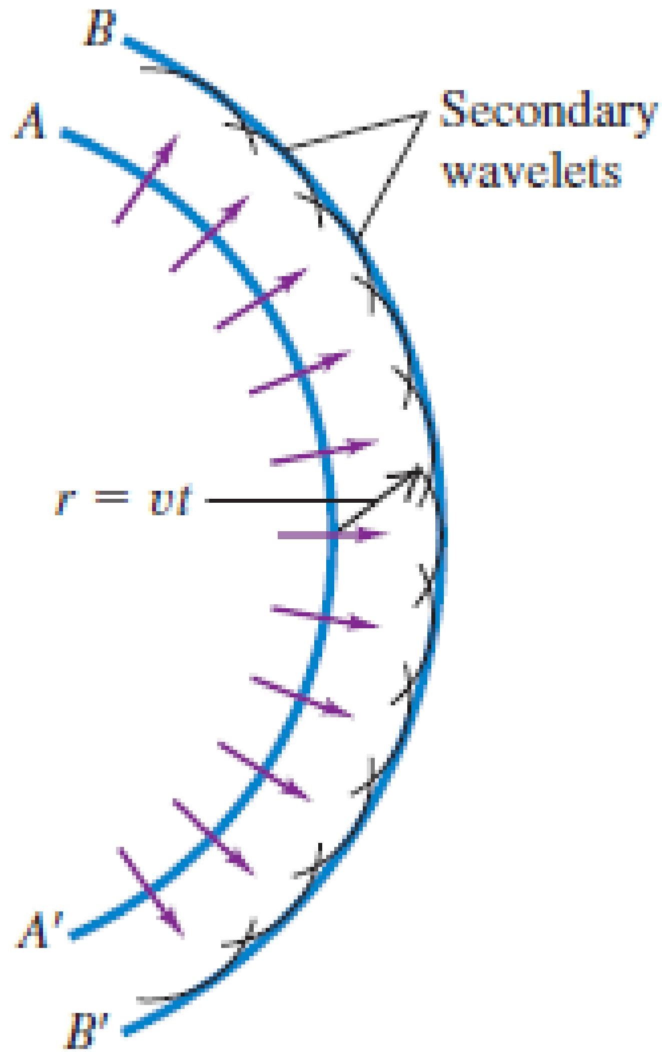


33.7 Huygens's Principle

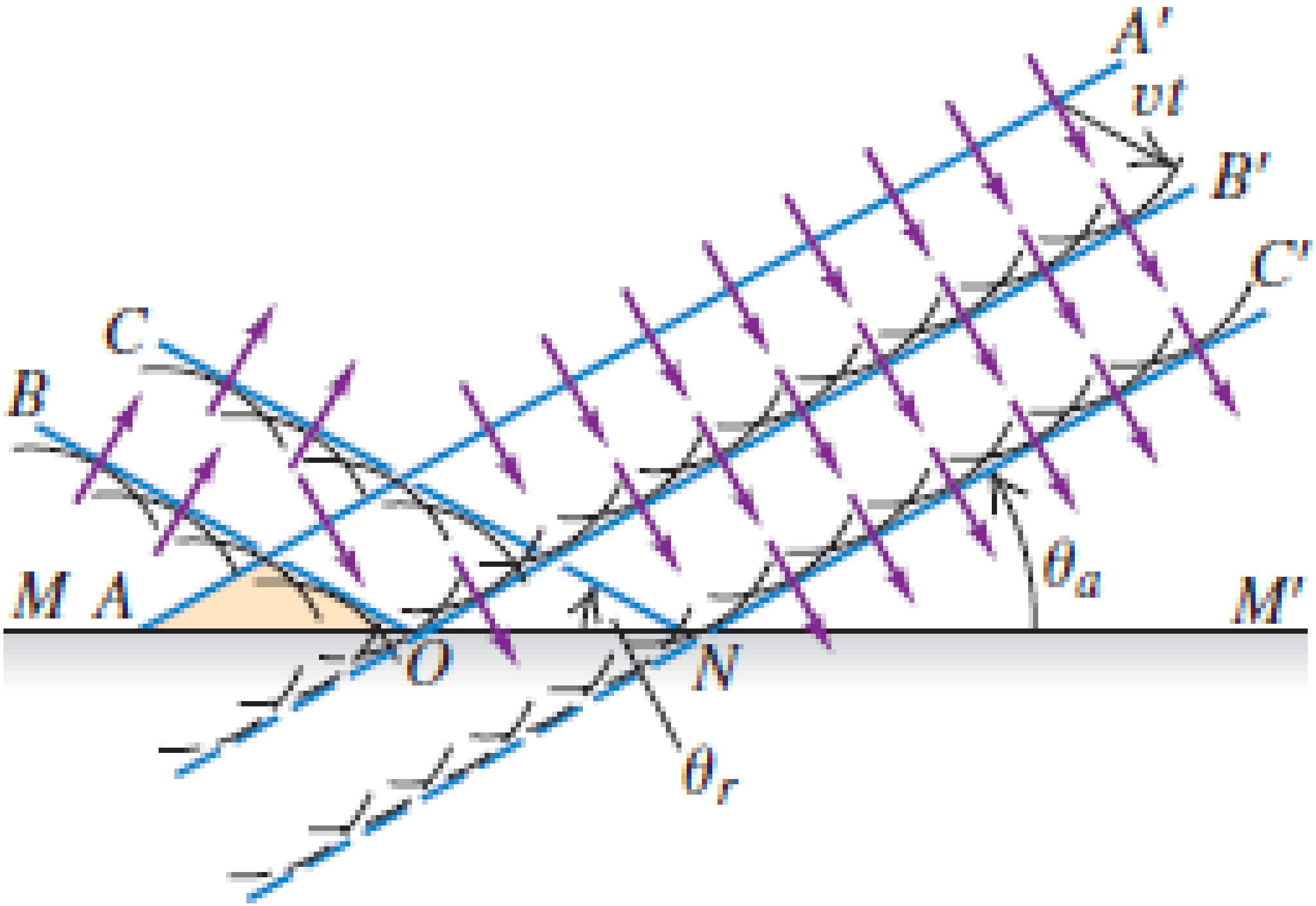
The laws of reflection and refraction of light rays that we introduced in Section 33.2 were discovered experimentally long before the wave nature of light was firmly established. However, we can *derive* these laws from wave considerations and show that they are consistent with the wave nature of light

We begin with a principle called **Huygens's principle.** This principle, stated originally by the Dutch scientist Christiaan Huygens in 1678, is a geometrical method for finding, from the known shape of a wave front at some instant, the shape of the wave front at some later time. Huygens assumed that **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.**

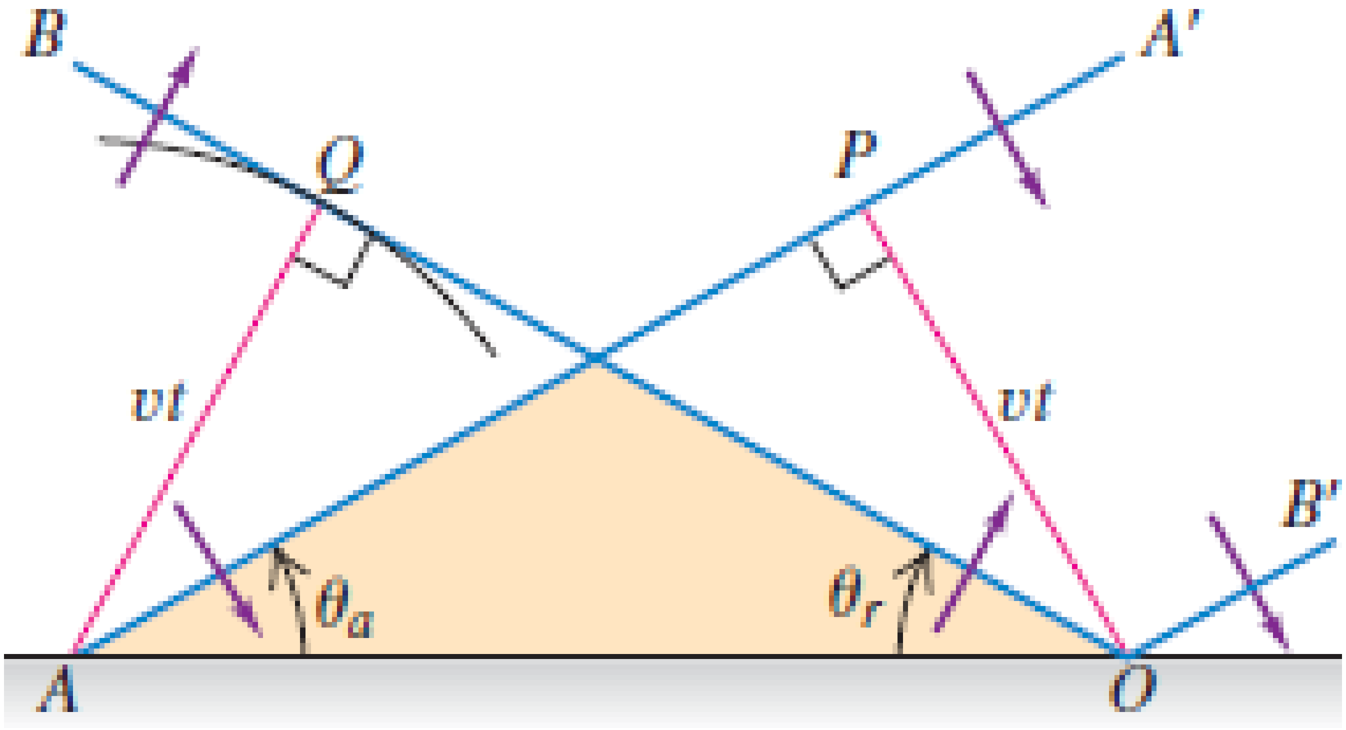
33.34 Applying Huygens's principle to wave front AA' to construct a new wave front BB'.



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

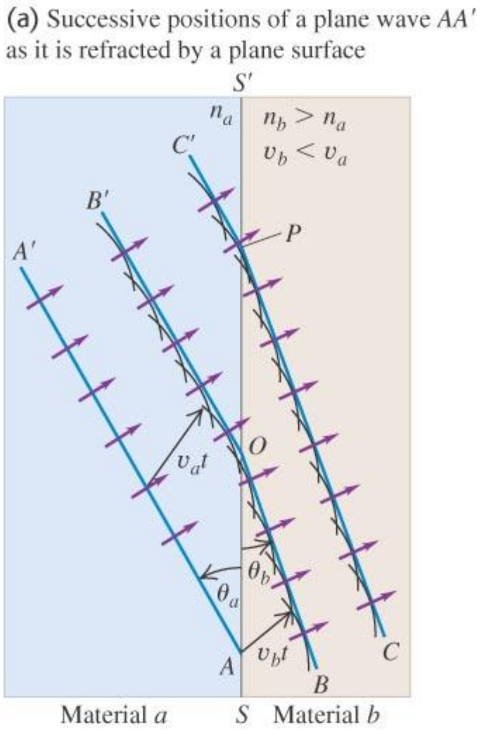


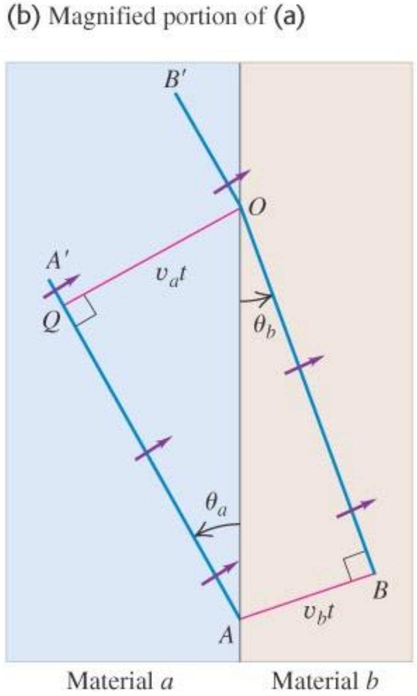
(b) Magnified portion of (a)

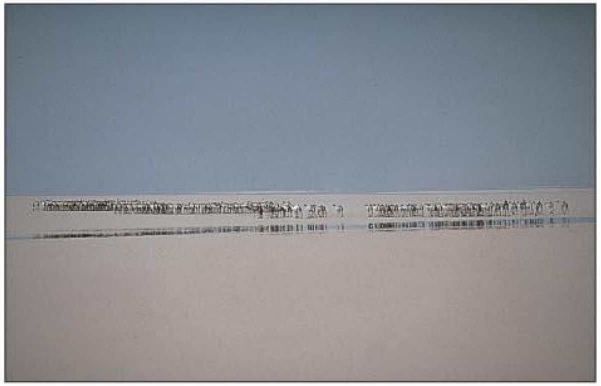


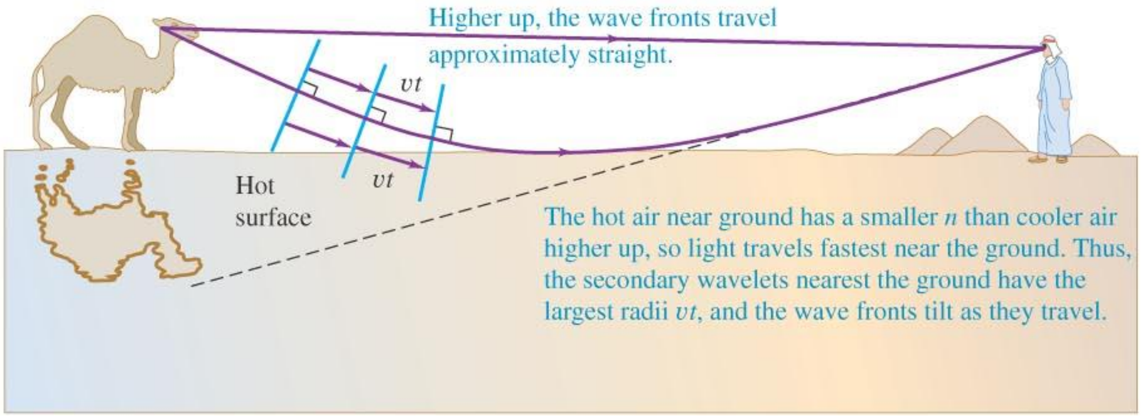
Huygens's Principle II

- Huygens's work can form an explanation of reflection and refraction.
- Refer to Figures 33.36 and 33.37.









The angles θ_a and θ_b between the surface and the incident and refracted wave fronts are the angle of incidence and the angle of refraction, respectively. To find the relationship between these angles, refer to Fig. 33.36b. We draw $OQ = v_a t$, perpendicular to AQ, and we draw $AB = v_b t$, perpendicular to BO. From the right triangle AOQ,

$$\sin\theta_a = \frac{v_a t}{AO}$$

and from the right triangle AOB,

$$\sin\theta_b = \frac{v_b t}{AO}$$

Combining these, we find

$$\frac{\sin\theta_a}{\sin\theta_b} = \frac{v_a}{v_b} \qquad (33.9)$$

We have defined the index of refraction n of a material as the ratio of the speed of light c in vacuum to its speed v in the material: $n_a = c/v_a$ and $n_b = c/v_b$. Thus

$$\frac{n_b}{n_a} = \frac{c/v_b}{c/v_a} = \frac{v_a}{v_b}$$

and we can rewrite Eq. (33.9) as

$$\frac{\sin\theta_a}{\sin\theta_b} = \frac{n_b}{n_a} \quad \text{or}$$

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

which we recognize as Snell's law, Eq. (33.4). So we have derived Snell's law from a wave theory. Alternatively, we may choose to regard Snell's law as an experimental result that defines the index of refraction of a material; in that case this analysis helps to confirm the relationship $v = c/n$ for the speed of light in a material.

It is important to keep in mind that Maxwell’s equations are the fundamental relationships for electromagnetic wave propagation. But Huygens’s principle provides a convenient way to visualize this propagation.