Chapter 35

The Nature of Light and the Laws of Geometric Optics

The Nature of Light

- Before the beginning of the nineteenth century, light was considered to be a stream of particles
- The particles were either emitted by the object being viewed or emanated from the eyes of the viewer
- Newton was the chief architect of the particle theory of light
  - He believed the particles left the object and stimulated the sense of sight upon entering the eyes

Nature of Light – Alternative View

- Christian Huygens argued that light might be some sort of a wave motion
- Thomas Young (in 1801) provided the first clear demonstration of the wave nature of light
  - He showed that light rays interfere with each other
  - Such behavior could not be explained by particles

More Confirmation of Wave Nature

- During the nineteenth century, other developments led to the general acceptance of the wave theory of light
- Maxwell asserted that light was a form of high-frequency electromagnetic wave
- Hertz confirmed Maxwell's predictions

Particle Nature

- Some experiments could not be explained by the wave nature of light
- The photoelectric effect was a major phenomenon not explained by waves
  - When light strikes a metal surface, electrons are sometimes ejected from the surface
  - The kinetic energy of the ejected electron is independent of the frequency of the light

Particle Nature, cont.

- Einstein (in 1905) proposed an explanation of the photoelectric effect that used the idea of quantization
  - The quantization model assumes that the energy of a light wave is present in particles called photons
  - $E = hf$
    - h is Planck's Constant and = 6.63×10^{-34} J·s

Dual Nature of Light

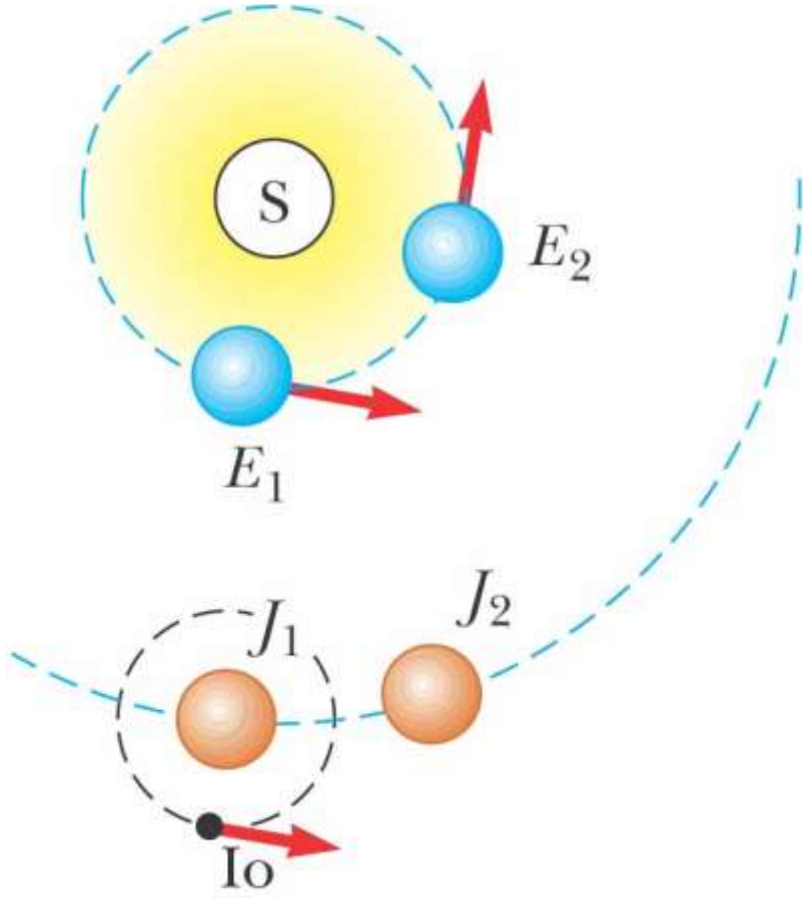
- In view of these developments, light must be regarded as having a dual nature
- Light exhibits the characteristics of a wave in some situations and the characteristics of a particle in other situations

Measurements of the Speed of Light

- Since light travels at a very high speed, early attempts to measure its speed were unsuccessful
  - Remember $c = 3.00 \times 10^8$ m/s
- Galileo tried by using two observers separated by about 10 km
  - The reaction time of the observers was more than the transit time of the light

Measurement of the Speed of Light – Roemer's Method

- Ole Roemer (1675) used astronomical observations to estimate the speed of light
- He used the period of revolution of Io, a moon of Jupiter, as Jupiter revolved around the sun



Roemer's Method, cont.

- The periods of revolution were longer when the Earth was receding from Jupiter
  - Shorter when the Earth was approaching
- Using Roemer's data, Huygens estimated the lower limit of the speed of light to be 2.3×10^8 m/s
  - This was important because it demonstrated that light has a finite speed as well as giving an estimate of that speed

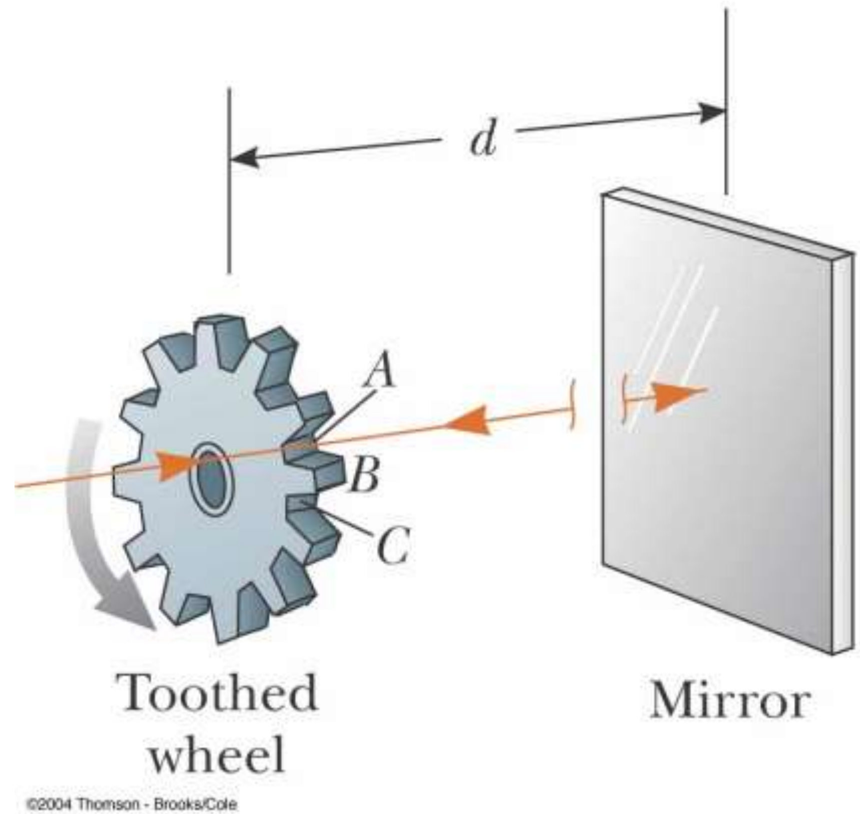
Measurements of the Speed of Light – Fizeau's Method

- This was the first successful method for measuring the speed of light by means of a purely terrestrial technique
- It was developed in 1849 by Armand Fizeau
- He used a rotating toothed wheel
- The distance between the wheel (considered to be the source) and a mirror was known

Fizeau's Method, cont.

- *d* is the distance between the wheel and the mirror
- ⊗*t* is the time for one round trip
- Then $c = 2d / \otimes t$
- Fizeau found a value of

  $c = 3.1 \times 10^8$ m/s

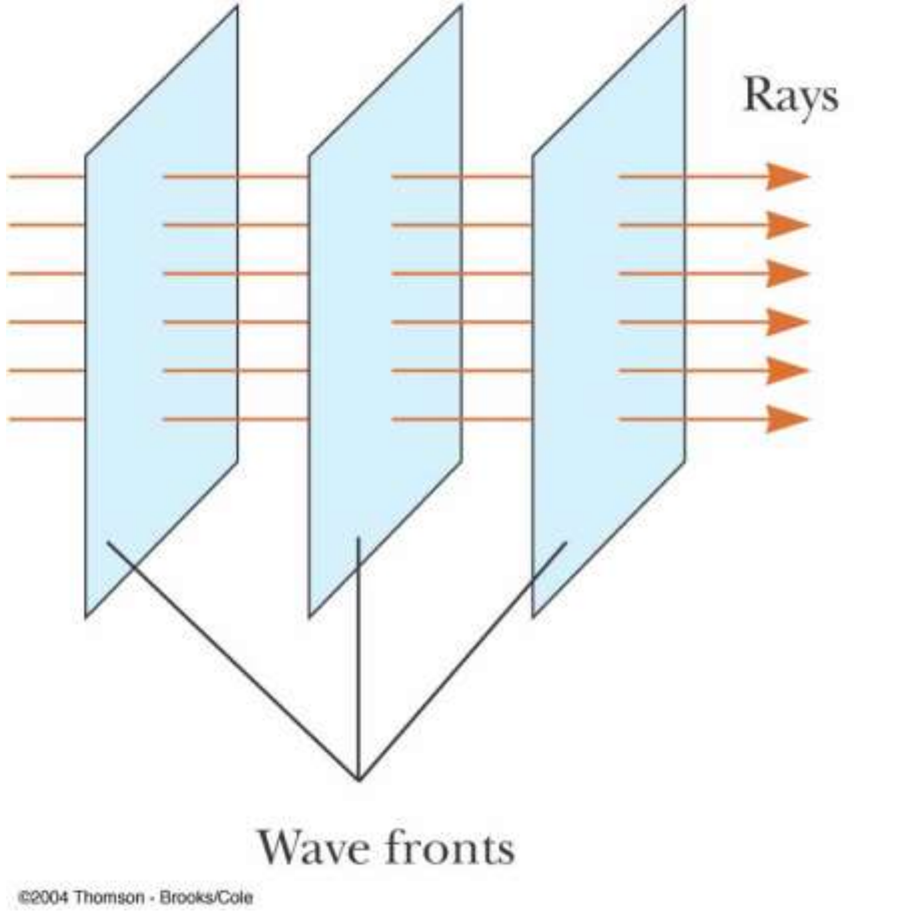


The Ray Approximation in Geometric Optics

- **Geometric optics** involves the study of the propagation of light
- It uses the assumption that light travels in a straight-line path in a uniform medium and changes its direction when it meets the surface of a different medium or if the optical properties of the medium are nonuniform
- The ray approximation is used to represent beams of light

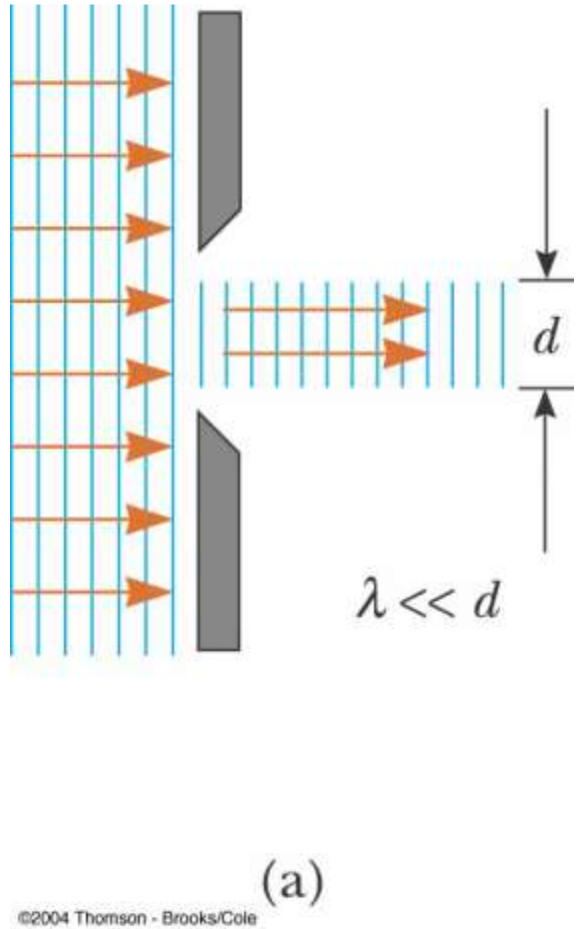
Ray Approximation

- The rays are straight lines perpendicular to the wave fronts
- With the ray approximation, we assume that a wave moving through a medium travels in a straight line in the direction of its rays



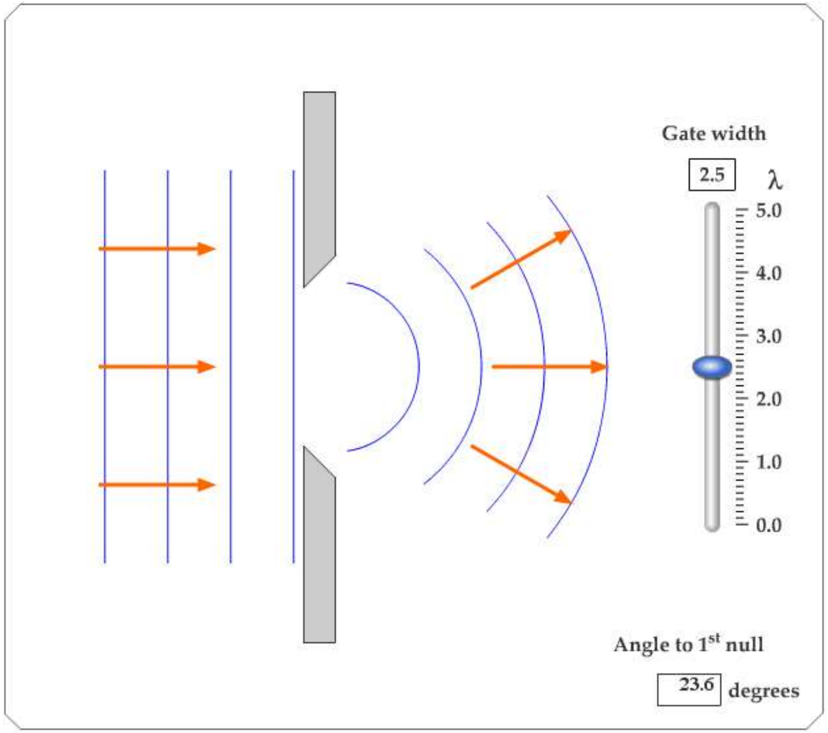
Ray Approximation, cont.

- If a wave meets a barrier, we will assume that $\lambda << d$
  - d is the diameter of the opening
- This approximation is good for the study of mirrors, lenses, prisms, etc.
- Other effects occur for openings of other sizes



Active Figure 35.4

- Adjust the size of the opening
- Observe the effects on the waves passing through



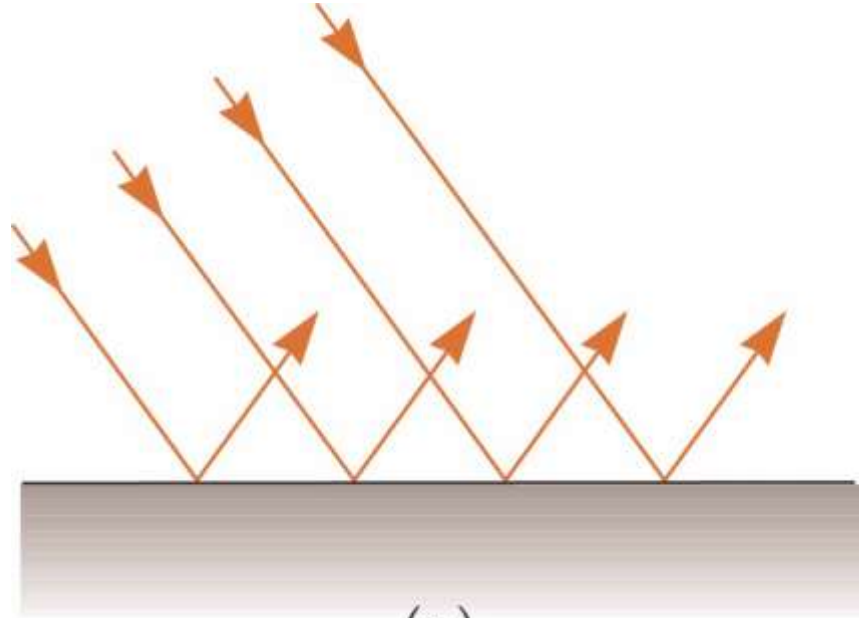
PLAY ACTIVE FIGURE

Reflection of Light

- A ray of light, the *incident ray*, travels in a medium
- When it encounters a boundary with a second medium, part of the incident ray is reflected back into the first medium
  - This means it is directed backward into the first medium

Specular Reflection

- *Specular reflection* is reflection from a smooth surface
- The reflected rays are parallel to each other
- All reflection in this text is assumed to be specular



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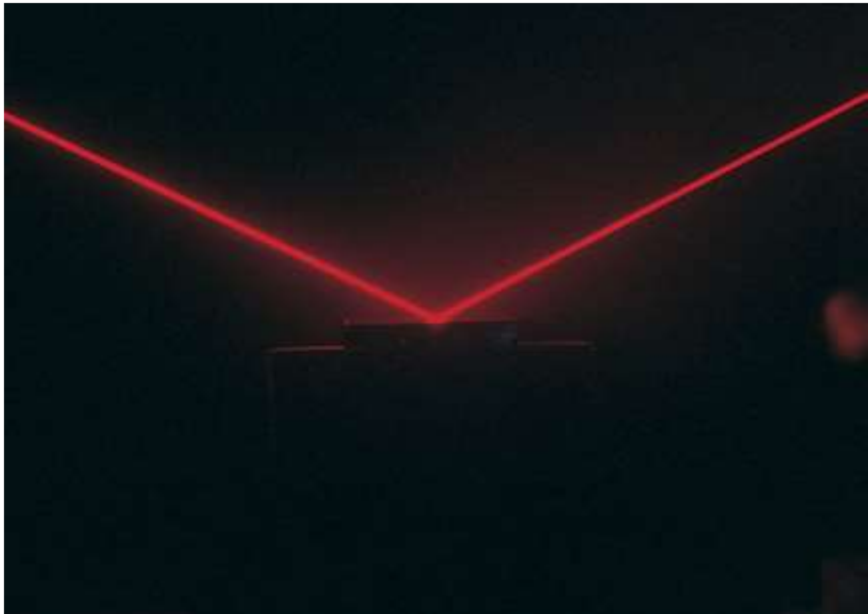
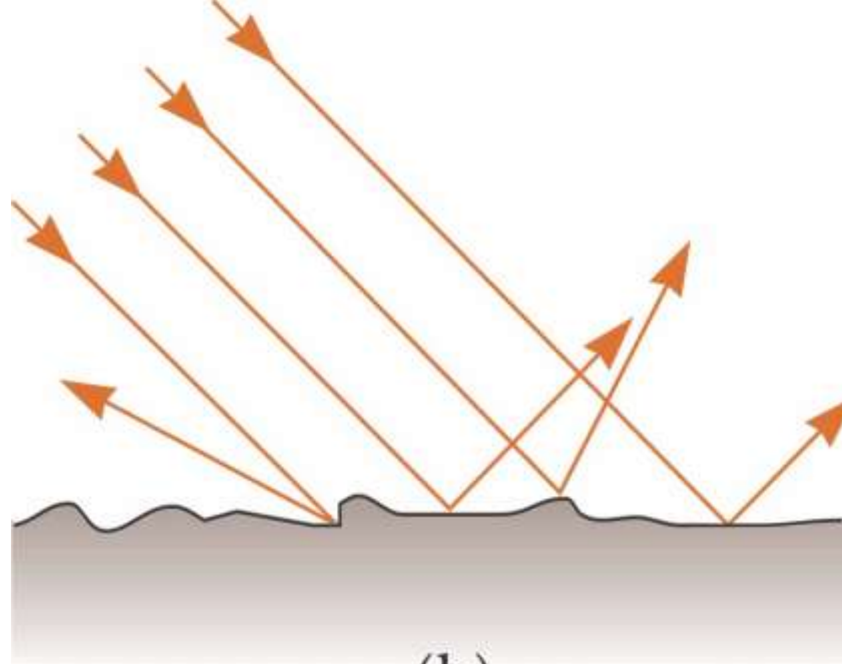


Diffuse Reflection

- *Diffuse reflection* is reflection from a rough surface
- The reflected rays travel in a variety of directions
- A surface behaves as a smooth surface as long as the surface variations are much smaller than the wavelength of the light



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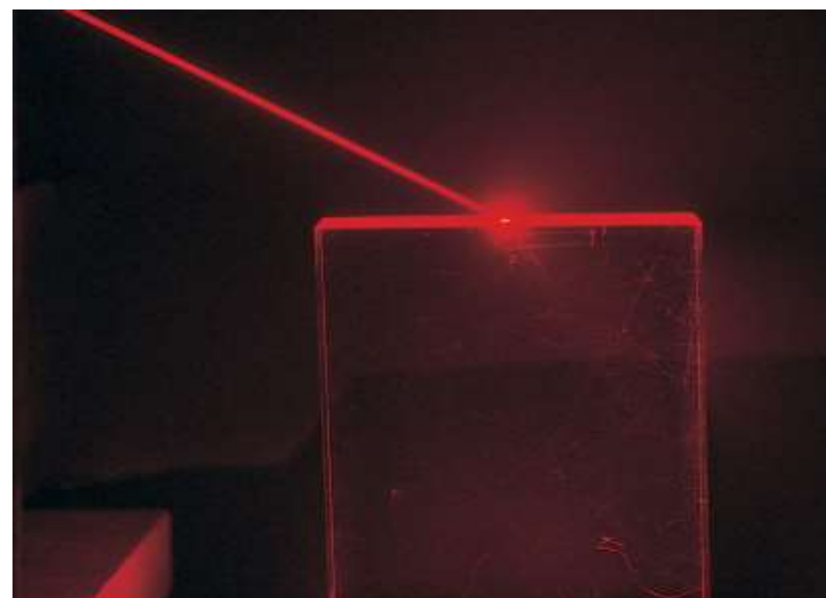
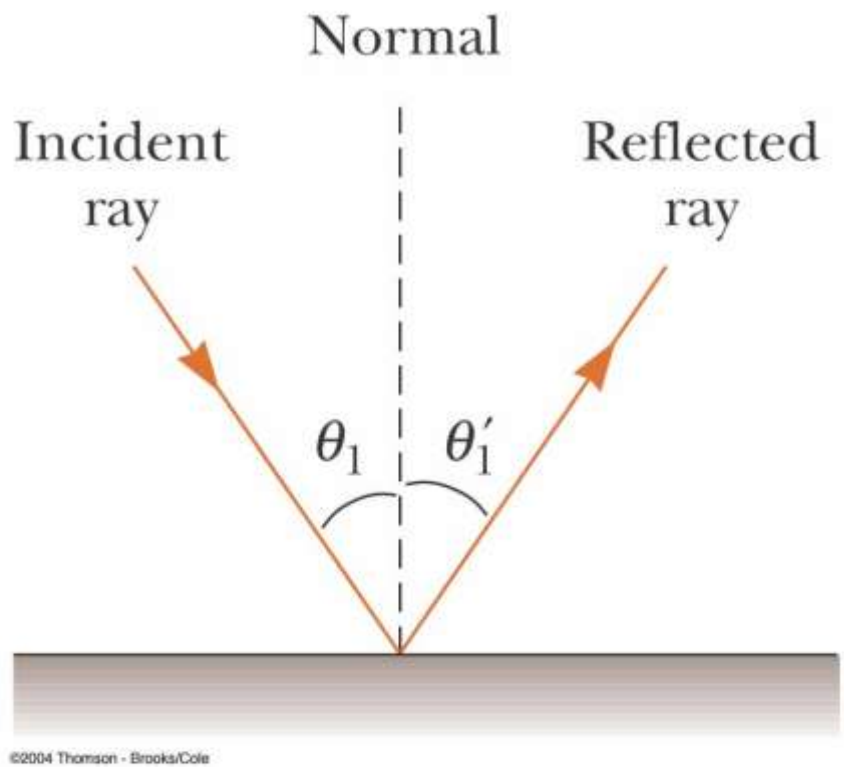


Law of Reflection

- The *normal* is a line perpendicular to the surface
  - It is at the point where the incident ray strikes the surface
- The incident ray makes an angle of θ_1 with the normal
- The reflected ray makes an angle of θ_1' with the normal

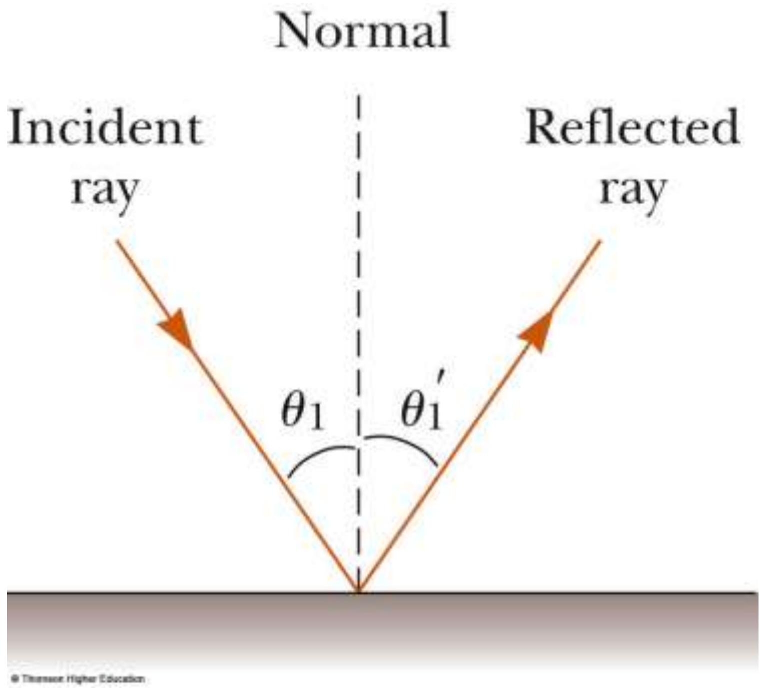


Law of Reflection, cont.

- The angle of reflection is equal to the angle of incidence
- $\theta_1' = \theta_1$
  - This relationship is called the Law of Reflection
- The incident ray, the reflected ray and the normal are all in the same plane
- Because this situation happens often, an analysis model, *wave under reflection*, is identified

Active Figure 35.6

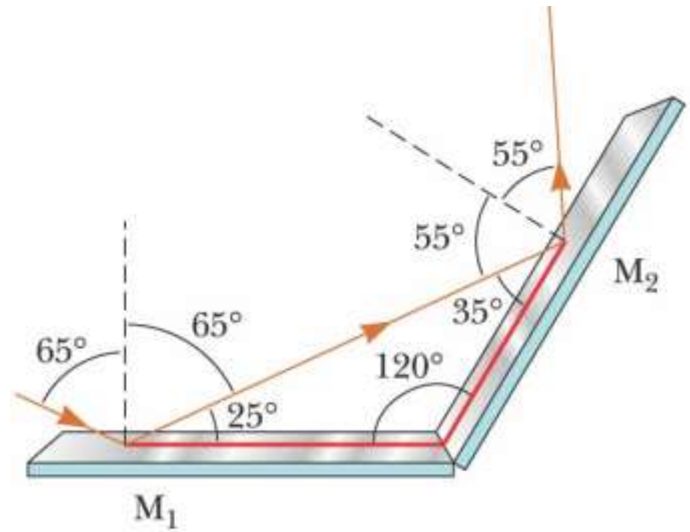
- Use the active figure to vary the angle of incidence
- Observe the effect on the angle of reflection



PLAY ACTIVE FIGURE

Multiple Reflections

- The incident ray strikes the first mirror
- The reflected ray is directed toward the second mirror
- There is a second reflection from the second mirror
- Apply the Law of Reflection and some geometry to determine information about the rays



(a)

Retroreflection

- Assume the angle between two mirrors is 90^o
- The reflected beam returns to the source parallel to its original path
- This phenomenon is called *retroreflection*
- Applications include
  - Measuring the distance to the Moon
  - Automobile taillights
  - Traffic signs

Refraction of Light

- When a ray of light traveling through a transparent medium encounters a boundary leading into another transparent medium, part of the energy is reflected and part enters the second medium
- The ray that enters the second medium is bent at the boundary
  - This bending of the ray is called *refraction*

Refraction, 2

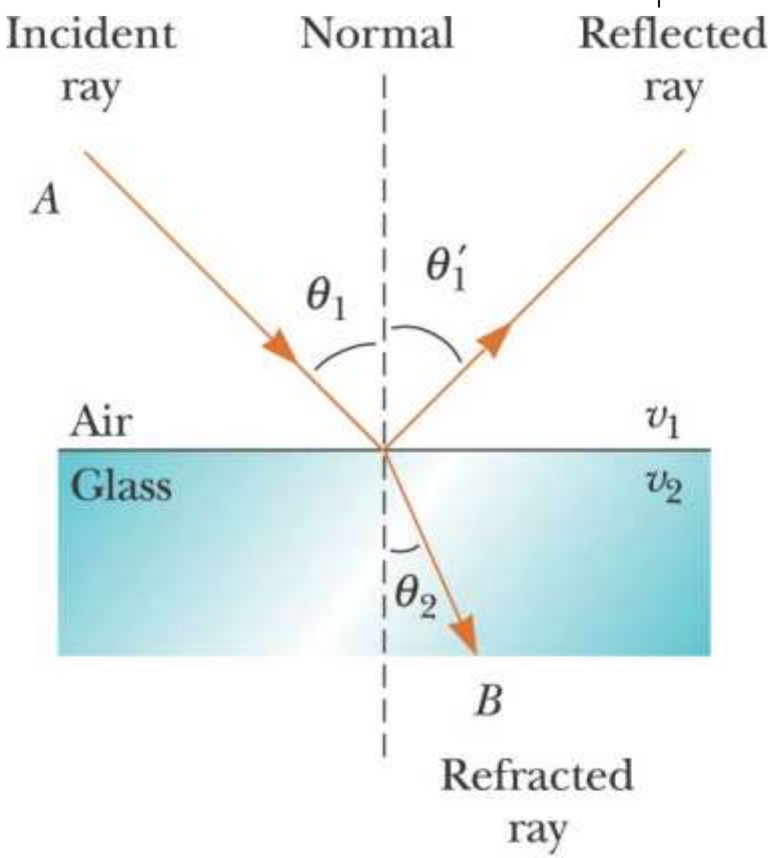
- The incident ray, the reflected ray, the refracted ray, and the normal all lie on the same plane
- The angle of refraction depends upon the material and the angle of incidence

$$\frac{\sin\theta_2}{\sin\theta_1} = \frac{v_2}{v_1}$$

  - v_1 is the speed of the light in the first medium and v_2 is its speed in the second

Refraction of Light, 3

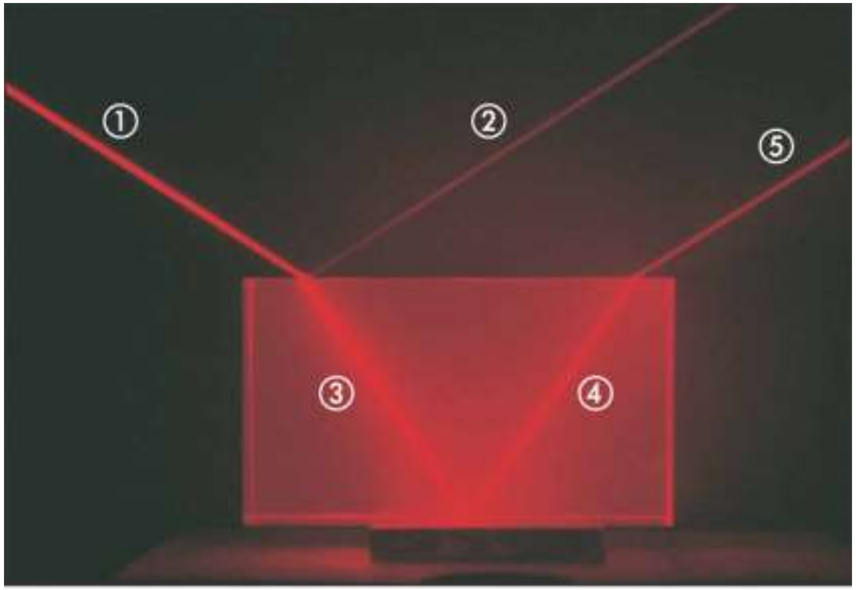
- The path of the light through the refracting surface is reversible
  - For example, a ray that travels from A to B
  - If the ray originated at B, it would follow the line AB to reach point A



(a)

Following the Reflected and Refracted Rays

- Ray ① is the incident ray
- Ray ② is the reflected ray
- Ray ③ is refracted into the lucite
- Ray ④ is internally reflected in the lucite
- Ray ⑤ is refracted as it enters the air from the lucite



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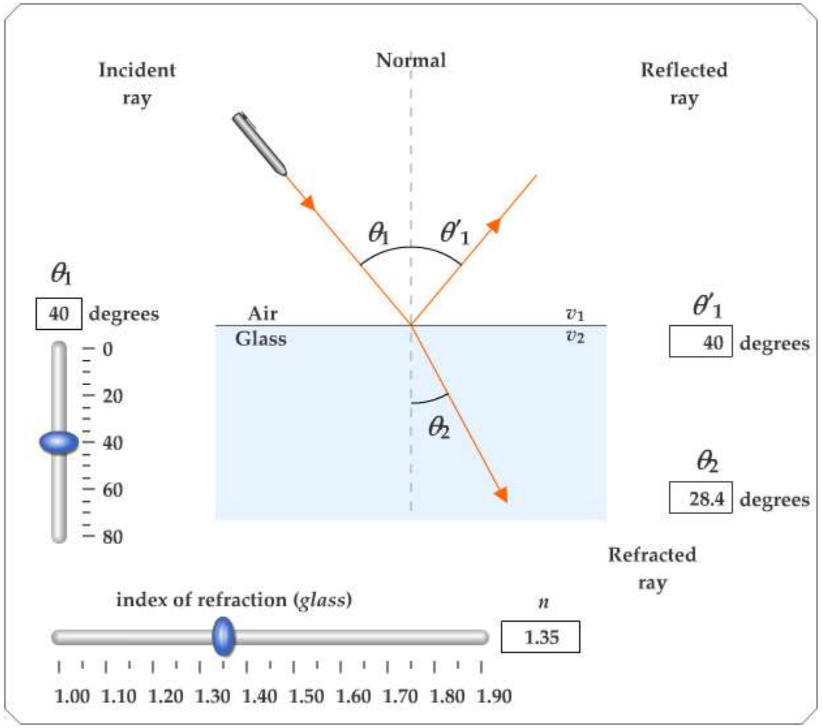
Active Figure 35.10

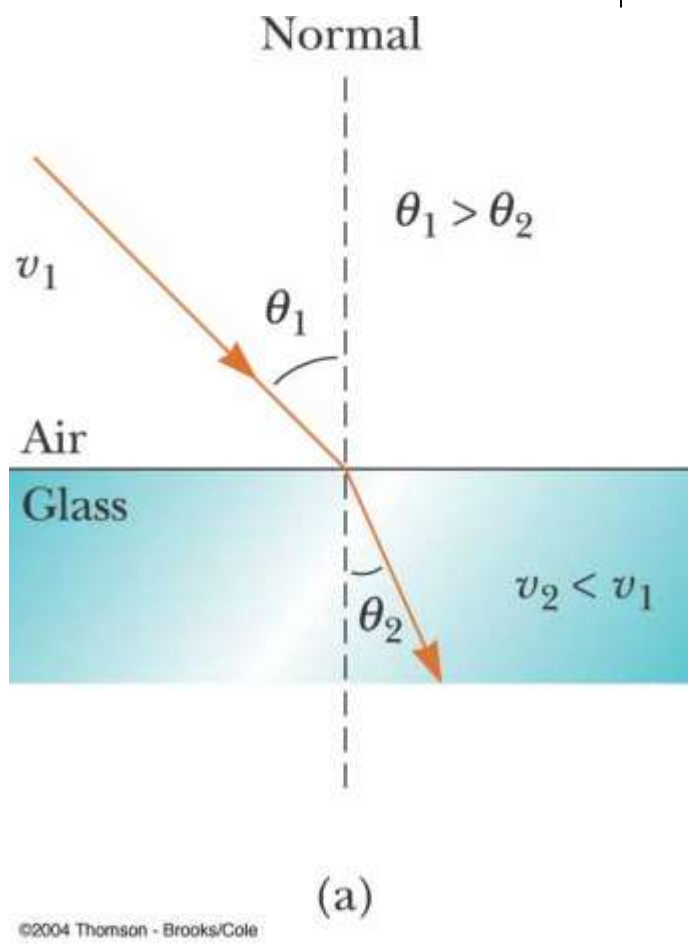
- Use the active figure to vary the incident angle
- Observe the effect on the reflected and refracted rays



PLAY ACTIVE FIGURE

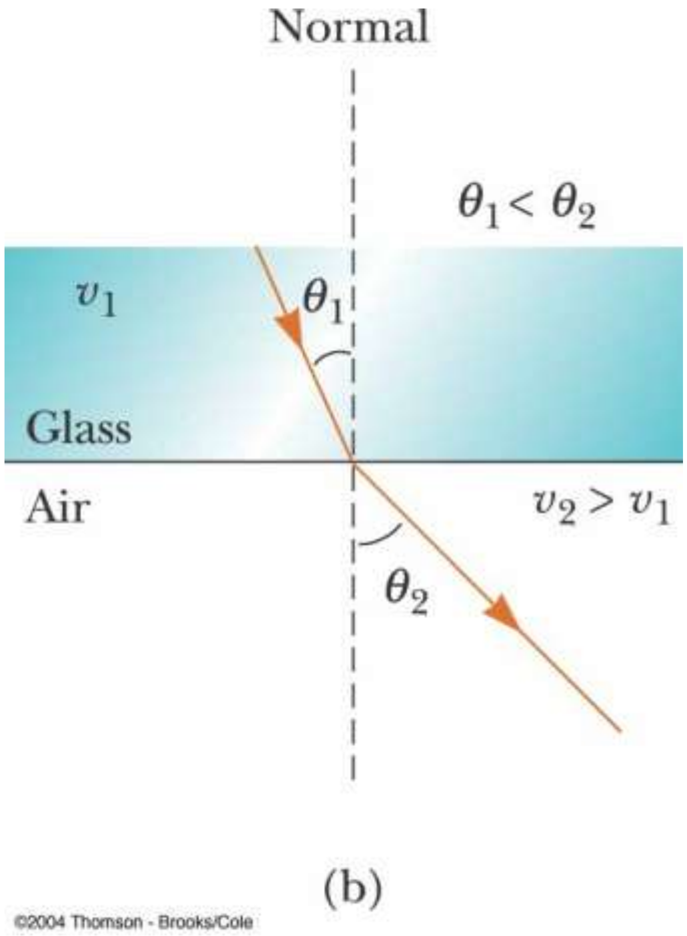
Refraction Details, 1

- Light may refract into a material where its speed is lower
- The angle of refraction is less than the angle of incidence
  - The ray bends *toward* the normal



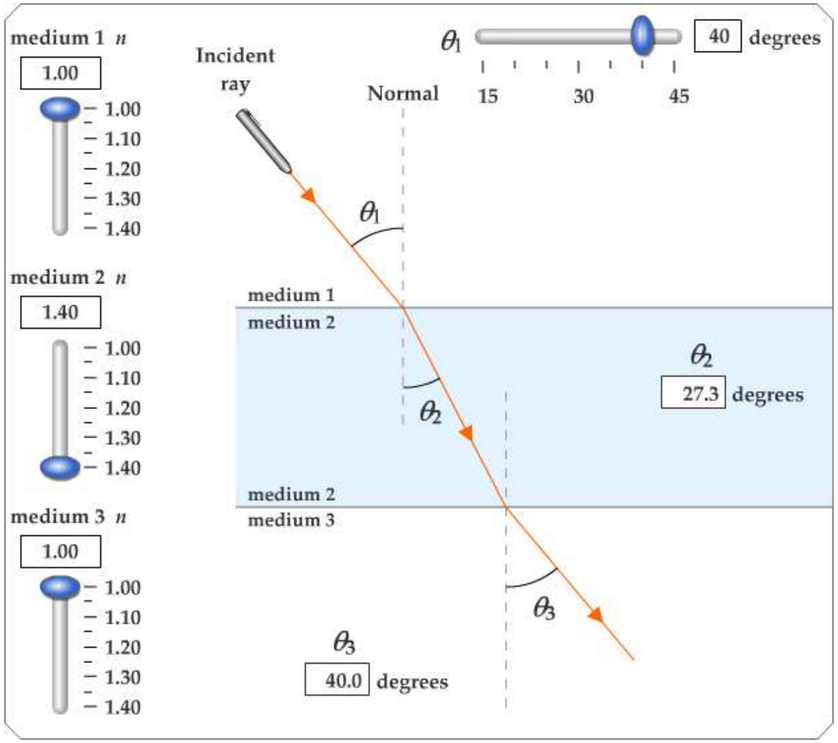
Refraction Details, 2

- Light may refract into a material where its speed is higher
- The angle of refraction is greater than the angle of incidence
  - The ray bends *away from* the normal



Active Figure 35.11

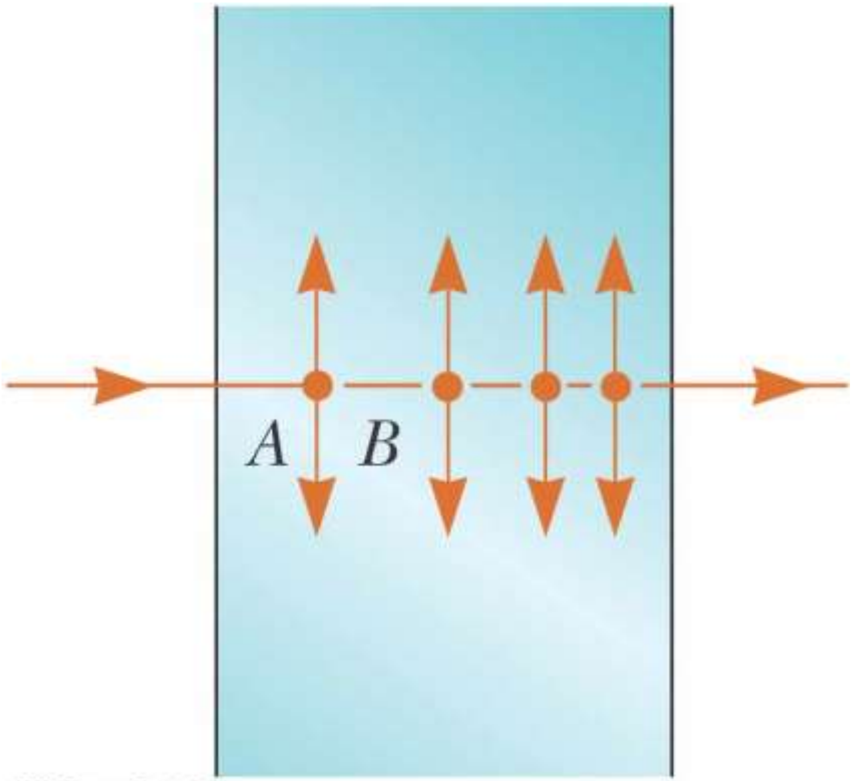
- Use the active figure to observe the light passing through three layers of material
- Vary the incident angle and the materials
- Observe the effect on the refracted ray



PLAY
ACTIVE FIGURE

Light in a Medium

- The light enters from the left
- The light may encounter an electron
- The electron may absorb the light, oscillate, and reradiate the light
- The absorption and radiation cause the average speed of the light moving through the material to decrease



The Index of Refraction

- The speed of light in any material is less than its speed in vacuum
- The **index of refraction**, n, of a medium can be defined as

$$n \equiv \frac{\text{speed of light in a vacuum}}{\text{speed of light in a medium}} = \frac{c}{v}$$

Index of Refraction, cont.

- For a vacuum, n = 1
  - We assume n = 1 for air also
- For other media, n > 1
- n is a dimensionless number greater than unity
  - n is not necessarily an integer

Some Indices of Refraction

TABLE 35.1

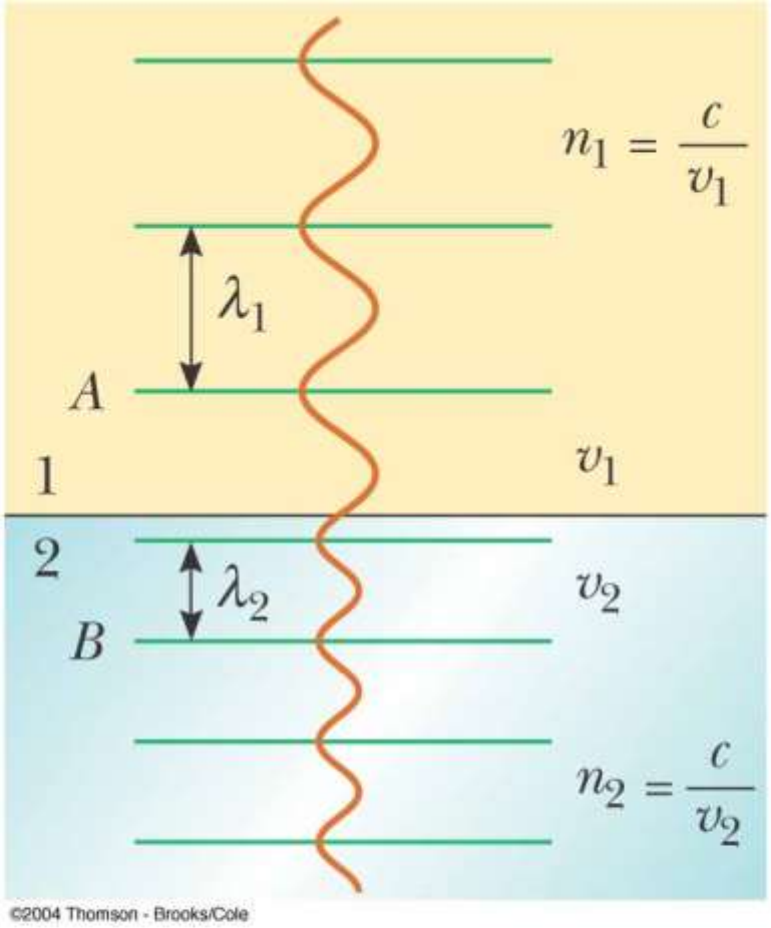
Indices of Refraction

Substance	Index of Refraction	Substance	Index of Refraction
Solids at 20°C		*Liquids at 20°C*	
Cubic zirconia	2.20	Benzene	1.501
Diamond (C)	2.419	Carbon disulfide	1.628
Fluorite (CaF_2)	1.434	Carbon tetrachloride	1.461
Fused quartz (SiO_2)	1.458	Ethyl alcohol	1.361
Gallium phosphide	3.50	Glycerin	1.473
Glass, crown	1.52	Water	1.333
Glass, flint	1.66		
Ice (H_2O)	1.309	*Gases at 0°C, 1 atm*	
Polystyrene	1.49	Air	1.000 293
Sodium chloride (NaCl)	1.544	Carbon dioxide	1.000 45

Note: All values are for light having a wavelength of 589 nm in vacuum.

Frequency Between Media

- As light travels from one medium to another, *its frequency does not change*
  - Both the wave speed and the wavelength do change
  - The wavefronts do not pile up, nor are created or destroyed at the boundary, so f must stay the same



Index of Refraction Extended

- The frequency stays the same as the wave travels from one medium to the other
- $v = f\lambda$
  - $f_1 = f_2$ but $v_1 \neq v_2$ so $\lambda_1 \neq \lambda_2$
- The ratio of the indices of refraction of the two media can be expressed as various ratios

$$\frac{\lambda_1}{\lambda_2} = \frac{v_1}{v_2} = \frac{c/n_1}{c/n_2} = \frac{n_2}{n_1}$$

More About Index of Refraction

- The previous relationship can be simplified to compare wavelengths and indices: $\lambda_1 n_1 = \lambda_2 n_2$
- In air, $n_1 = 1$ and the index of refraction of the material can be defined in terms of the wavelengths

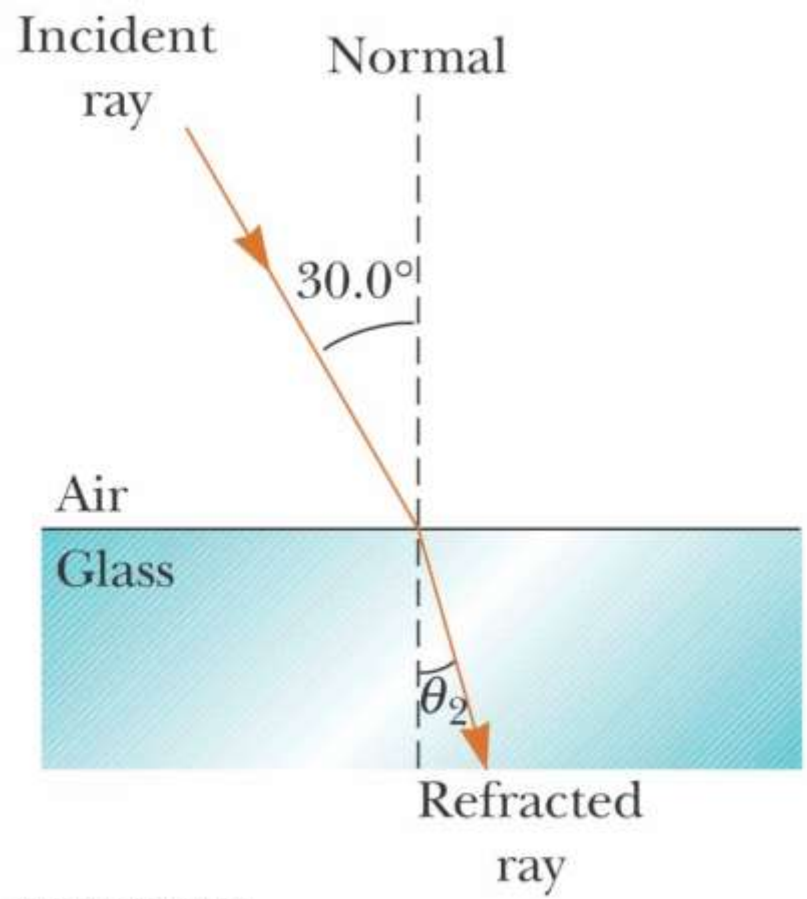
$$n = \frac{\lambda}{\lambda_n} \quad \left(\frac{\lambda \text{ in vacuum}}{\lambda \text{ in a medium}} \right)$$

Snell's Law of Refraction

- $n_1 \sin \theta_1 = n_2 \sin \theta_2$
  - θ_1 is the angle of incidence
  - θ_2 is the angle of refraction
- The experimental discovery of this relationship is usually credited to Willebrord Snell and is therefore known as **Snell's law of refraction**
- Refraction is a commonplace occurrence, so identify an analysis model as a **wave under refraction**

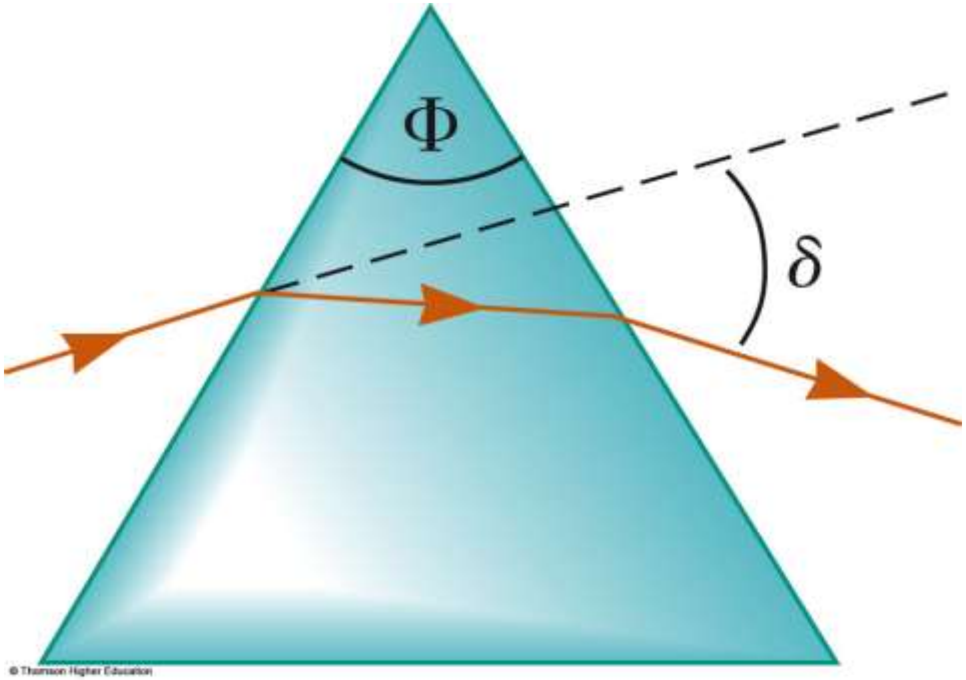
Snell's Law – Example

- Light is refracted into a crown glass slab
- θ_1 = 30.0°, θ_2 = ?
- n_1 = 1.00 and n_2 = 1.52
  - From Table 35.1
- $\theta_2 = \sin^{-1}(n_1 / n_2) \sin \theta_1$ = 19.2°
- The ray bends toward the normal, as expected



Prism

- A ray of single-wavelength light incident on the prism will emerge at angle δ from its original direction of travel
  - δ is called the **angle of deviation**
  - Φ is the apex angle



Huygens's Principle

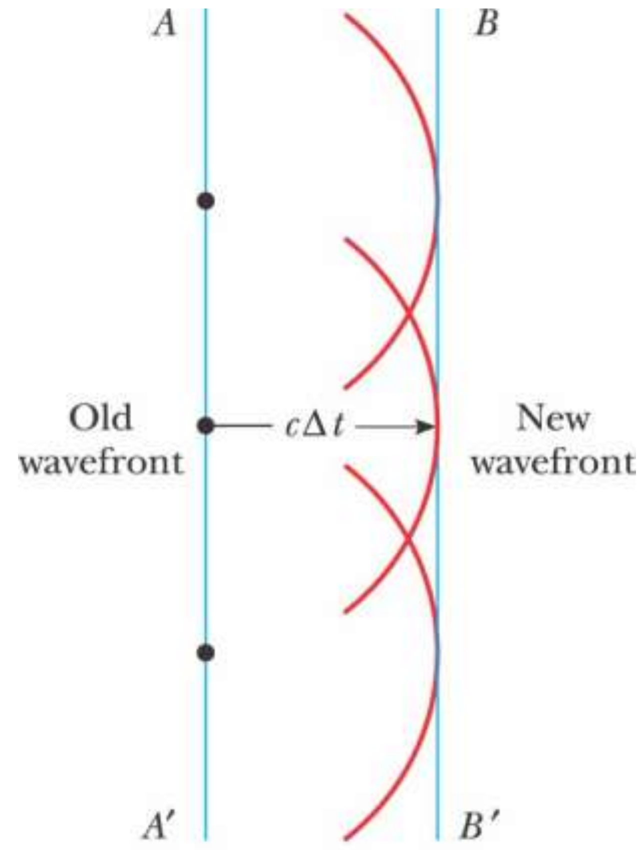
- Huygens assumed that light is a form of wave motion rather than a stream of particles
- Huygens's Principle is a geometric construction for determining the position of a new wave at some point based on the knowledge of the wave front that preceded it

Huygens's Principle, cont.

- All points on a given wave front are taken as point sources for the production of spherical secondary waves, called wavelets, which propagate outward through a medium with speeds characteristic of waves in that medium
- After some time has passed, the new position of the wave front is the surface tangent to the wavelets

Huygens's Construction for a Plane Wave

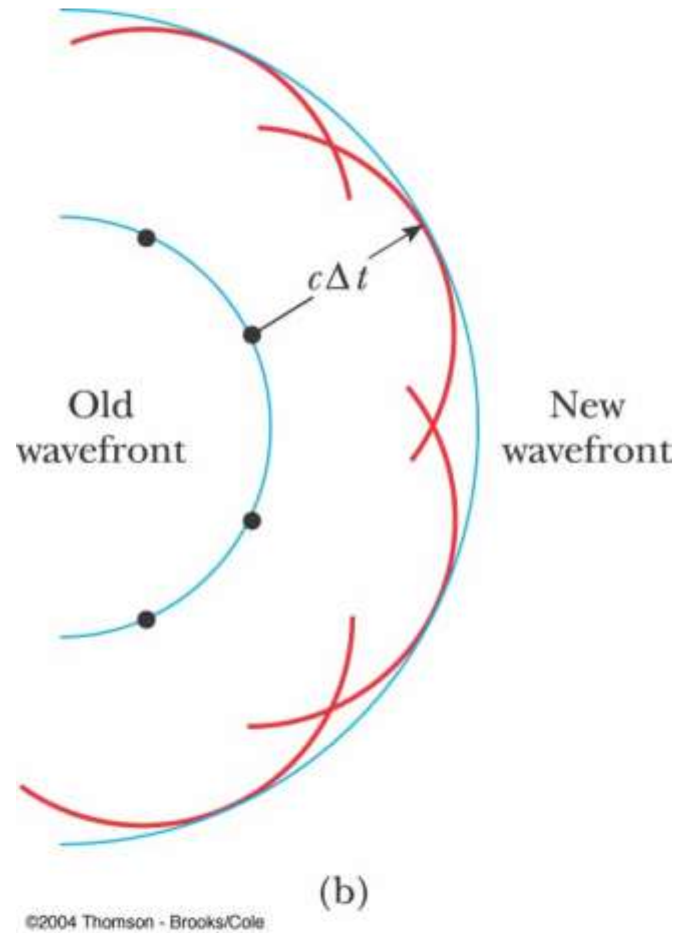
- At $t = 0$, the wave front is indicated by the plane *AA*'
- The points are representative sources for the wavelets
- After the wavelets have moved a distance $c\Delta t$, a new plane *BB*' can be drawn tangent to the wavefronts



(a)

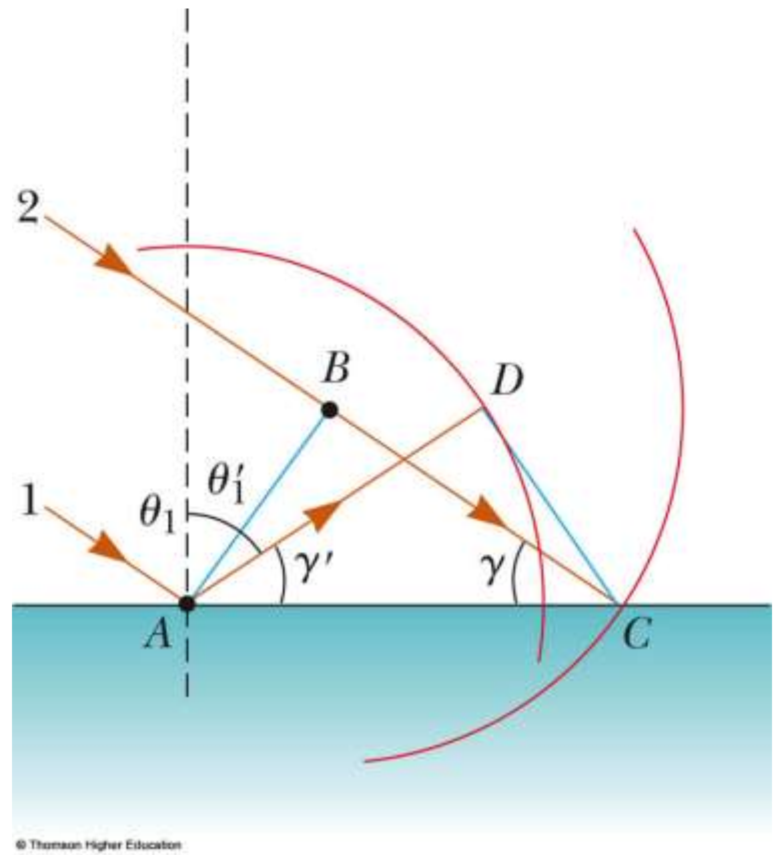
Huygens's Construction for a Spherical Wave

- The inner arc represents part of the spherical wave
- The points are representative points where wavelets are propagated
- The new wavefront is tangent at each point to the wavelet



Huygens's Principle and the Law of Reflection

- The law of reflection can be derived from Huygens's principle
- *AB* is a plane wave front of incident light
  - The wave at *A* sends out a wavelet centered on *A* toward *D*
  - The wave at *B* sends out a wavelet centered on *B* toward *C*
- $AD = BC = c\Delta t$

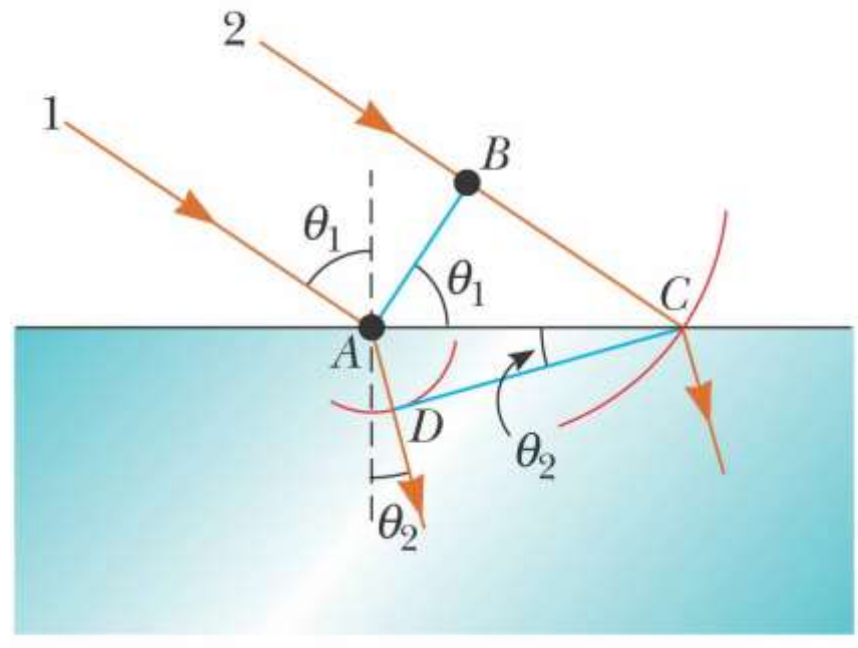


Huygens's Principle and the Law of Reflection, cont.

- Triangle *ABC* is congruent to triangle *ADC*
- $\cos \gamma = BC / AC$
- $\cos \gamma' = AD / AC$
- Therefore, $\cos \gamma = \cos \gamma'$ and $\gamma = \gamma'$
- This gives $\theta_1 = \theta_1'$
- This is the law of reflection

Huygens's Principle and the Law of Refraction

- Ray 1 strikes the surface and at a time interval Δt later, ray 2 strikes the surface
- During this time interval, the wave at *A* sends out a wavelet, centered at *A*, toward *D*



Huygens's Principle and the Law of Refraction, cont.

- The wave at *B* sends out a wavelet, centered at *B*, toward *C*
- The two wavelets travel in different media, therefore their radii are different
- From triangles ABC and ADC, we find

$$\sin\theta_1 = \frac{BC}{AC} = \frac{v_1\Delta t}{AC} \quad \text{and} \quad \sin\theta_2 = \frac{AD}{AC} = \frac{v_2\Delta t}{AC}$$

Huygens's Principle and the Law of Refraction, final

- The preceding equation can be simplified to

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{v_1}{v_2}$$

But $\dfrac{\sin\theta_1}{\sin\theta_2} = \dfrac{c/n_1}{c/n_2} = \dfrac{n_2}{n_1}$

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

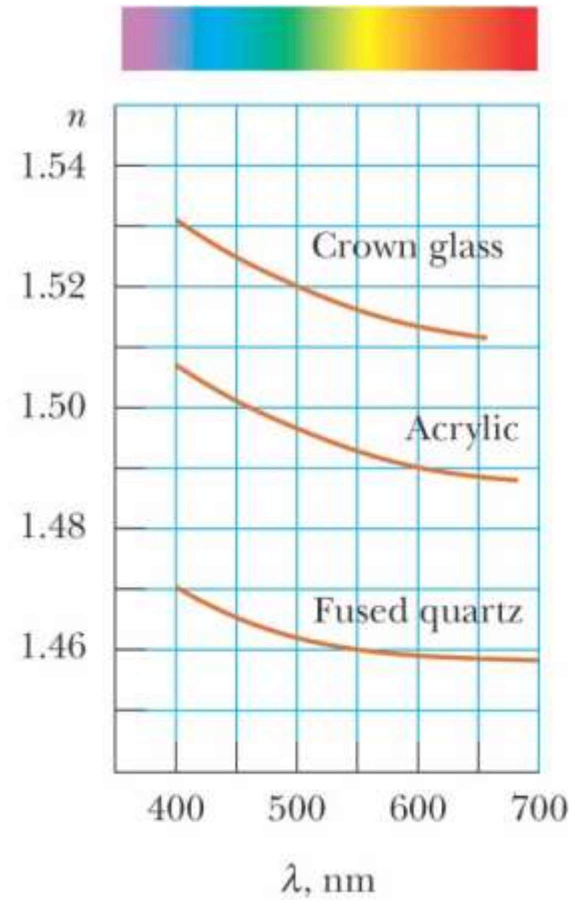
- This is Snell's law of refraction

Dispersion

- For a given material, the index of refraction varies with the wavelength of the light passing through the material
- This dependence of n on λ is called dispersion
- Snell's law indicates light of different wavelengths is bent at different angles when incident on a refracting material

Variation of Index of Refraction with Wavelength

- The index of refraction for a material generally decreases with increasing wavelength
- Violet light bends more than red light when passing into a refracting material



Refraction in a Prism

- Since all the colors have different angles of deviation, white light will spread out into a *spectrum*
  - Violet deviates the most
  - Red deviates the least
  - The remaining colors are in between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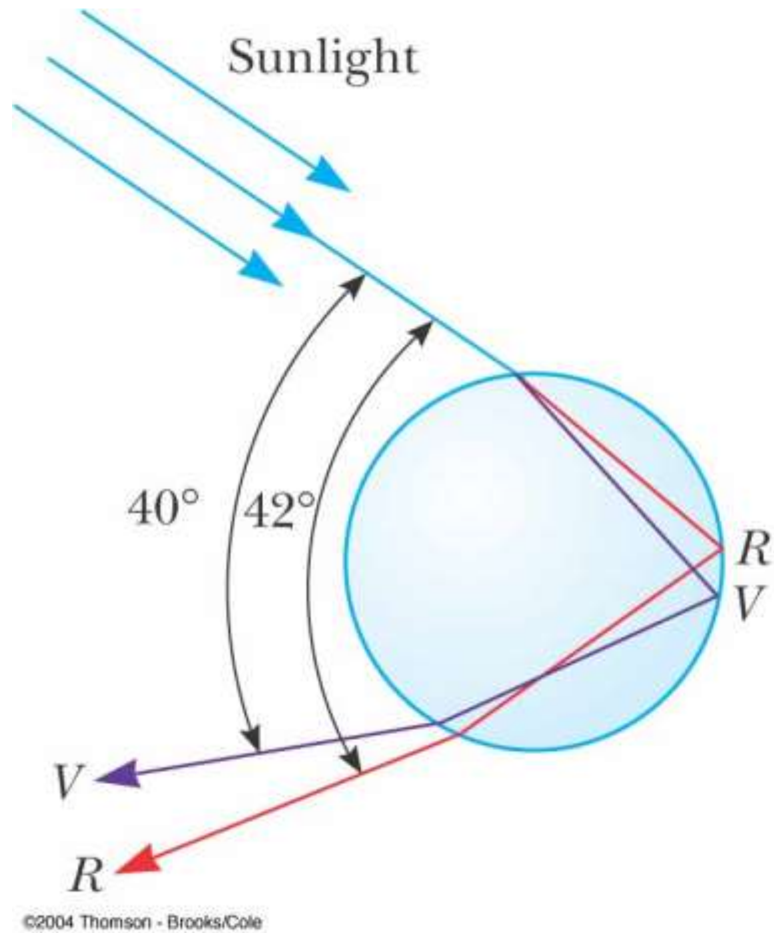
The Rainbow

- A ray of light strikes a drop of water in the atmosphere
- It undergoes both reflection and refraction
  - First refraction at the front of the drop
    - Violet light will deviate the most
    - Red light will deviate the least

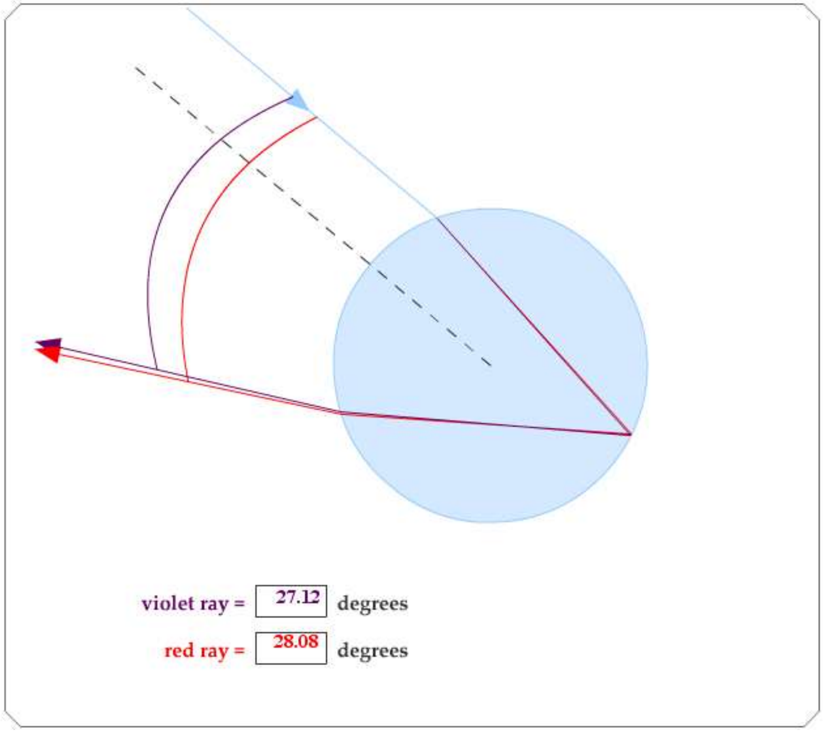
The Rainbow, 2

- At the back surface the light is reflected
- It is refracted again as it returns to the front surface and moves into the air
- The rays leave the drop at various angles
  - The angle between the white light and the most intense violet ray is 40°
  - The angle between the white light and the most intense red ray is 42°



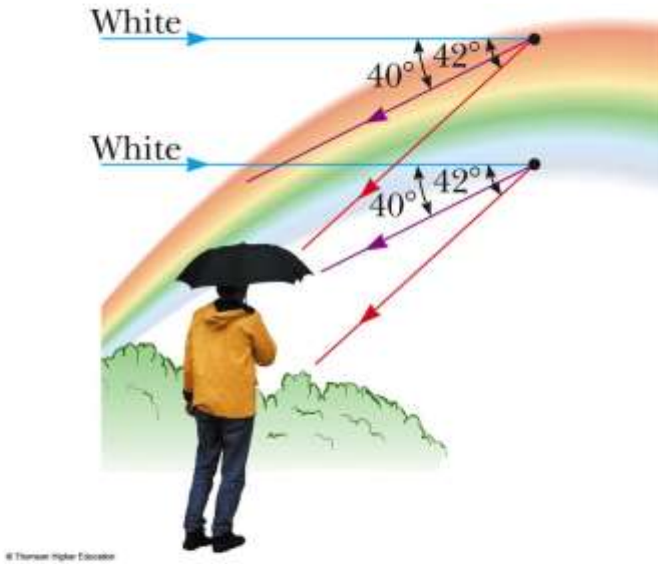
Active Figure 35.23

- Use the active figure to vary the point at which the sunlight enters the raindrop
- Observe the angles and verify the maximum angles



PLAY
ACTIVE FIGURE

Observing the Rainbow



- If a raindrop high in the sky is observed, the red ray is seen
- A drop lower in the sky would direct violet light to the observer
- The other colors of the spectra lie in between the red and the violet

Double Rainbow

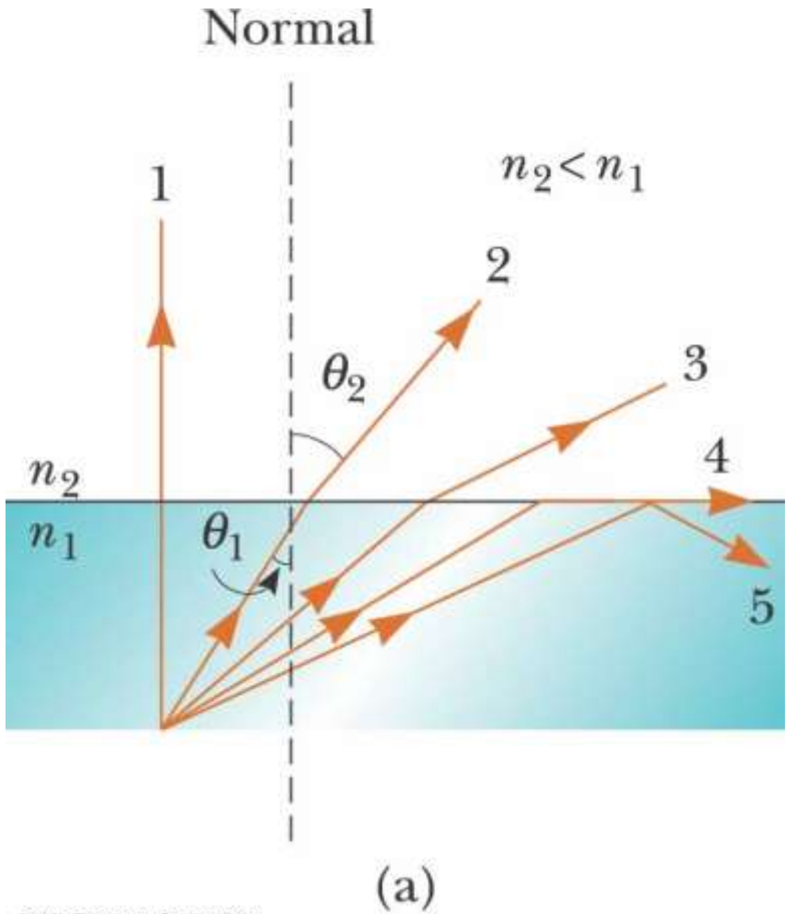
- The secondary rainbow is fainter than the primary
- The colors are reversed
- The secondary rainbow arises from light that makes two reflections from the interior surface before exiting the raindrop
- Higher-order rainbows are possible, but their intensity is low

Total Internal Reflection

- A phenomenon called **total internal reflection** can occur when light is directed from a medium having a given index of refraction toward one having a lower index of refraction

Possible Beam Directions

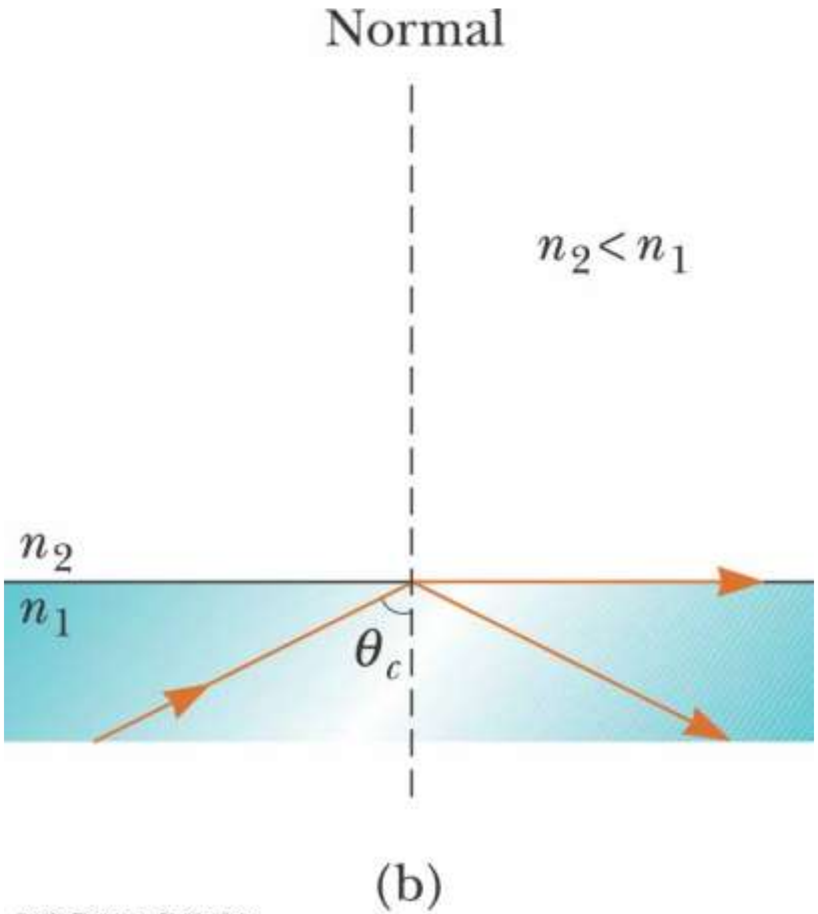
- Possible directions of the beam are indicated by rays numbered 1 through 5
- The refracted rays are bent away from the normal since $n_1 > n_2$



Critical Angle

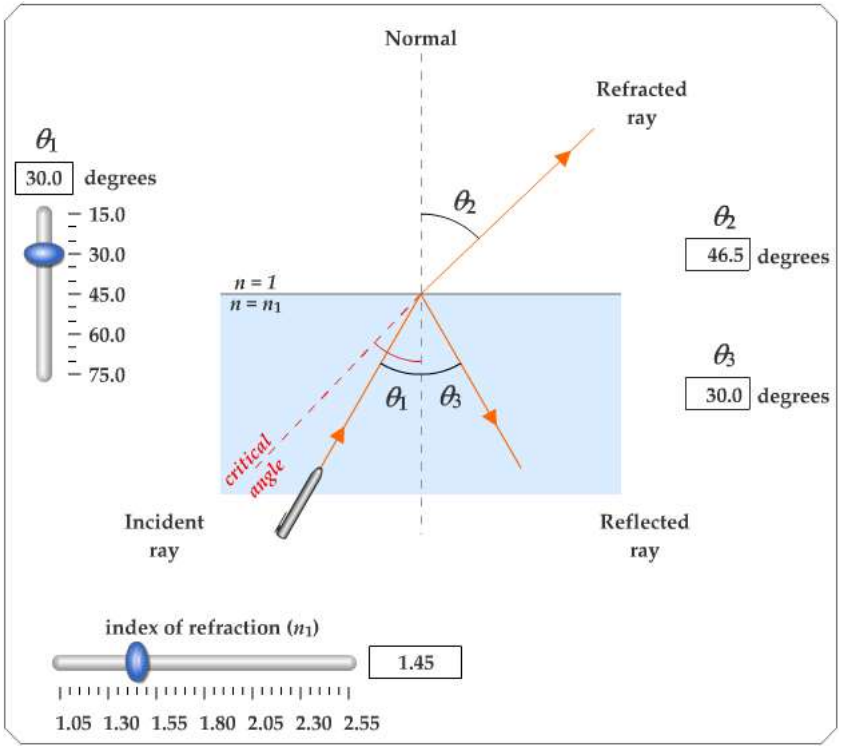
- There is a particular angle of incidence that will result in an angle of refraction of 90°
  - This angle of incidence is called the *critical angle*, θ_C

$$\sin\theta_C = \frac{n_2}{n_1} \quad (\text{for } n_1 > n_2)$$



Active Figure 35.25

- Use the active figure to vary the incident angle
- Observe the effect on the refracted ray



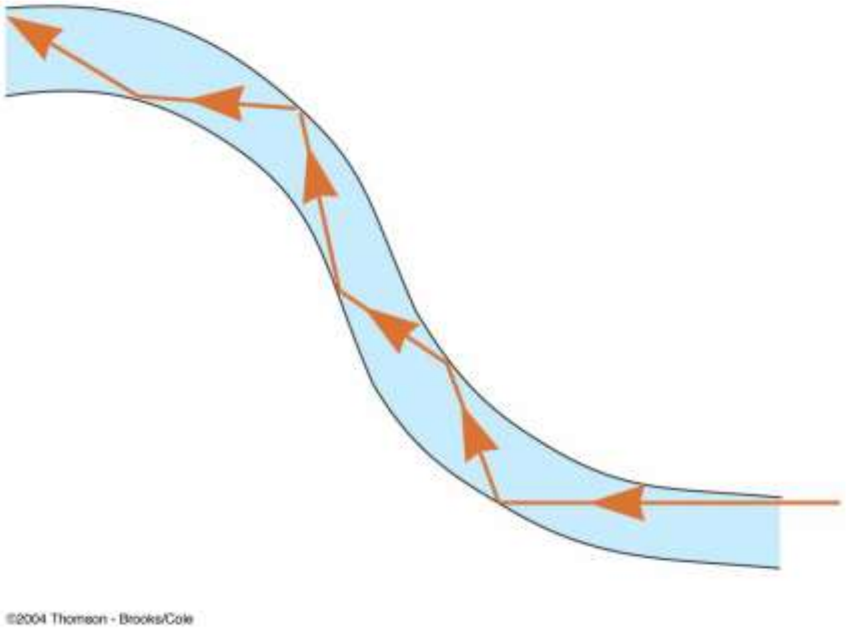
PLAY ACTIVE FIGURE

Critical Angle, cont.

- For angles of incidence *greater* than the critical angle, the beam is entirely reflected at the boundary
  - This ray obeys the law of reflection at the boundary
- Total internal reflection occurs only when light is directed from a medium of a given index of refraction toward a medium of lower index of refraction

Fiber Optics

- An application of internal reflection
- Plastic or glass rods are used to "pipe" light from one place to another
- Applications include
  - Medical examination of internal organs
  - Telecommunications



Fiber Optics, cont.

- A flexible light pipe is called an **optical fiber**
- A bundle of parallel fibers (shown) can be used to construct an optical transmission line

Construction of an Optical Fiber

- The transparent core is surrounded by *cladding*
  - The cladding has a lower *n* than the core
  - This allows the light in the core to experience total internal reflection
- The combination is surrounded by the jacket