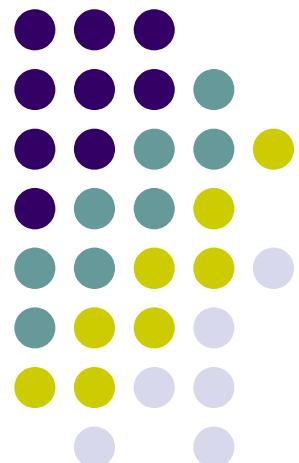


Chapter 32

The Nature of Light and the
Laws of Geometric Optics
(Reflection and Refraction)





PHYS 2321

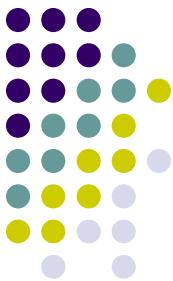
Week 14: Optics

Day 3 Outline

- 1) Hwk: Ch. 32 MiscQs 2-12 (even)
P. 3-5,11-15,19,21,34,35,39,41,55,56
Ch. 33 MiscQs 1-8
P. 1,2,5,6,10,16 (Sec 33.1-33.2) Due last Fri
- 2) P. 20. Example involve sound level, power and intensity
- 3) Ch. 32 Light: Reflection and Refraction.
 - * Particle/wave duality of light
 - * Ray model of light.
 - * Law of reflection: multiple reflections, mirror images
 - * Spherical mirror optics

Notes: Hwk Ch. 15-16 mean=9.98/10

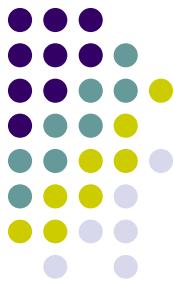
Please do course evaluations.



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

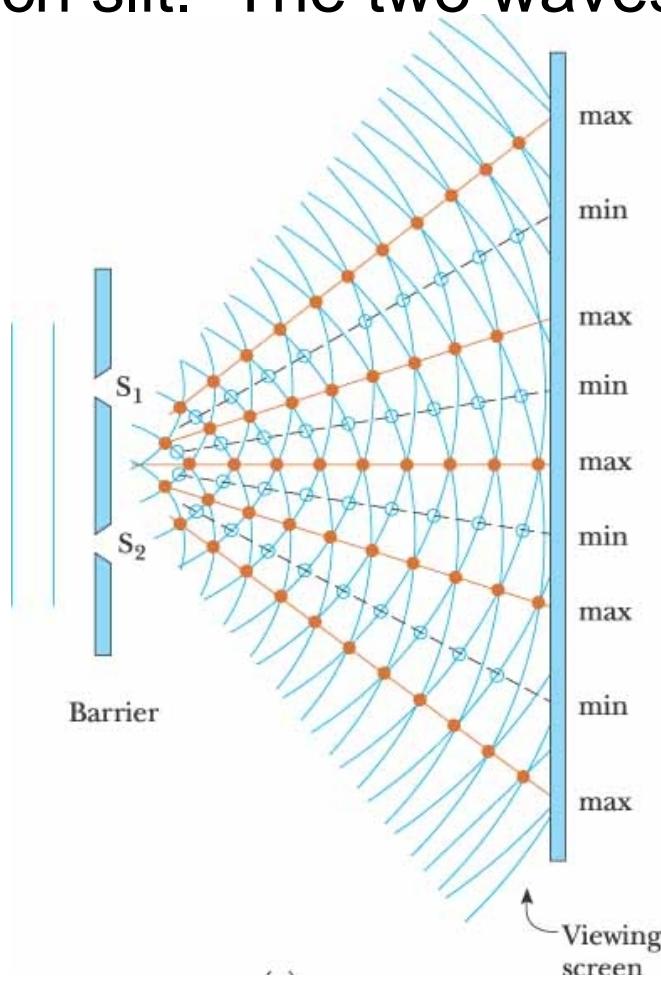
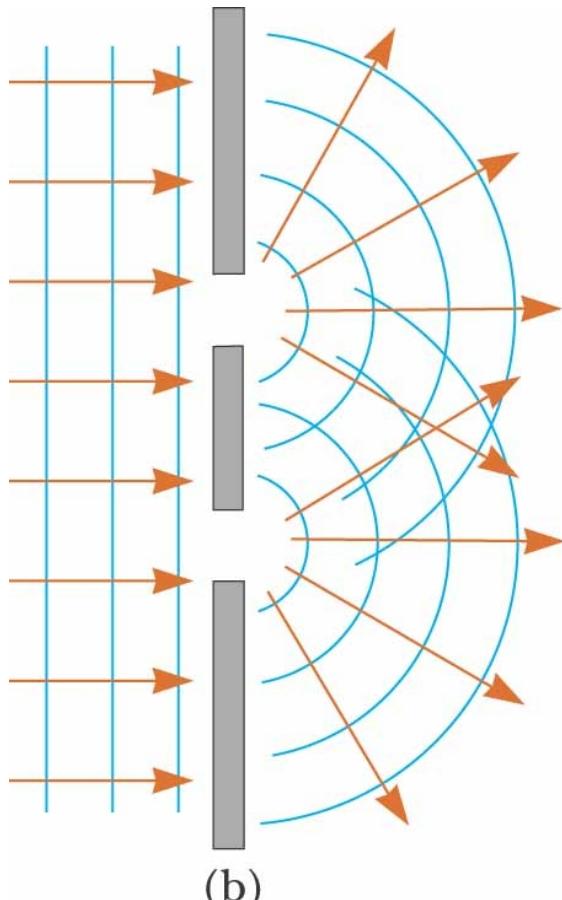


- Christian Huygens argued that light might be some sort of a wave motion
- Thomas Young (in 1801) provided the first clear demonstration of the wave nature of light
 - He showed that light rays interfere with each other
 - Such behavior could not be explained by particles

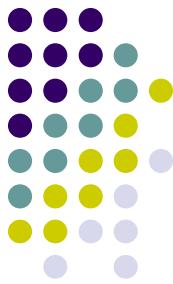


Wave nature of light: Young's double slit experiment

Diffraction occurs at each slit. The two waves interfere.



More Confirmation of Wave Nature



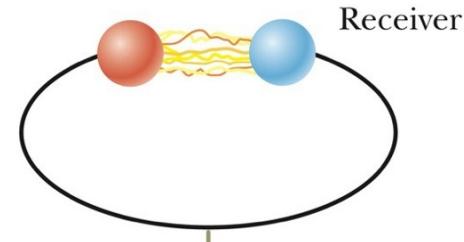
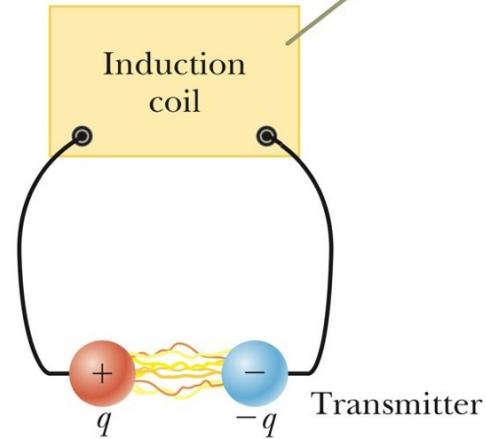
- During the nineteenth century, other developments led to the general acceptance of the wave theory of light
- Maxwell asserted that light was a form of high-frequency electromagnetic wave
- Hertz confirmed Maxwell's predictions

More Confirmation of Wave Nature

- Hertz confirmed Maxwell's predictions using radio waves.
- Maxwell showed that E-M waves moved at speed of light:

$$c = \frac{1}{\sqrt{\epsilon_0 \mu_0}} = 299792458 \text{ m/s}$$

The transmitter consists of two spherical electrodes connected to an induction coil, which provides short voltage surges to the spheres, setting up oscillations in the discharge between the electrodes.



The receiver is a nearby loop of wire containing a second spark gap.

Nature of light – electromagnetic wave

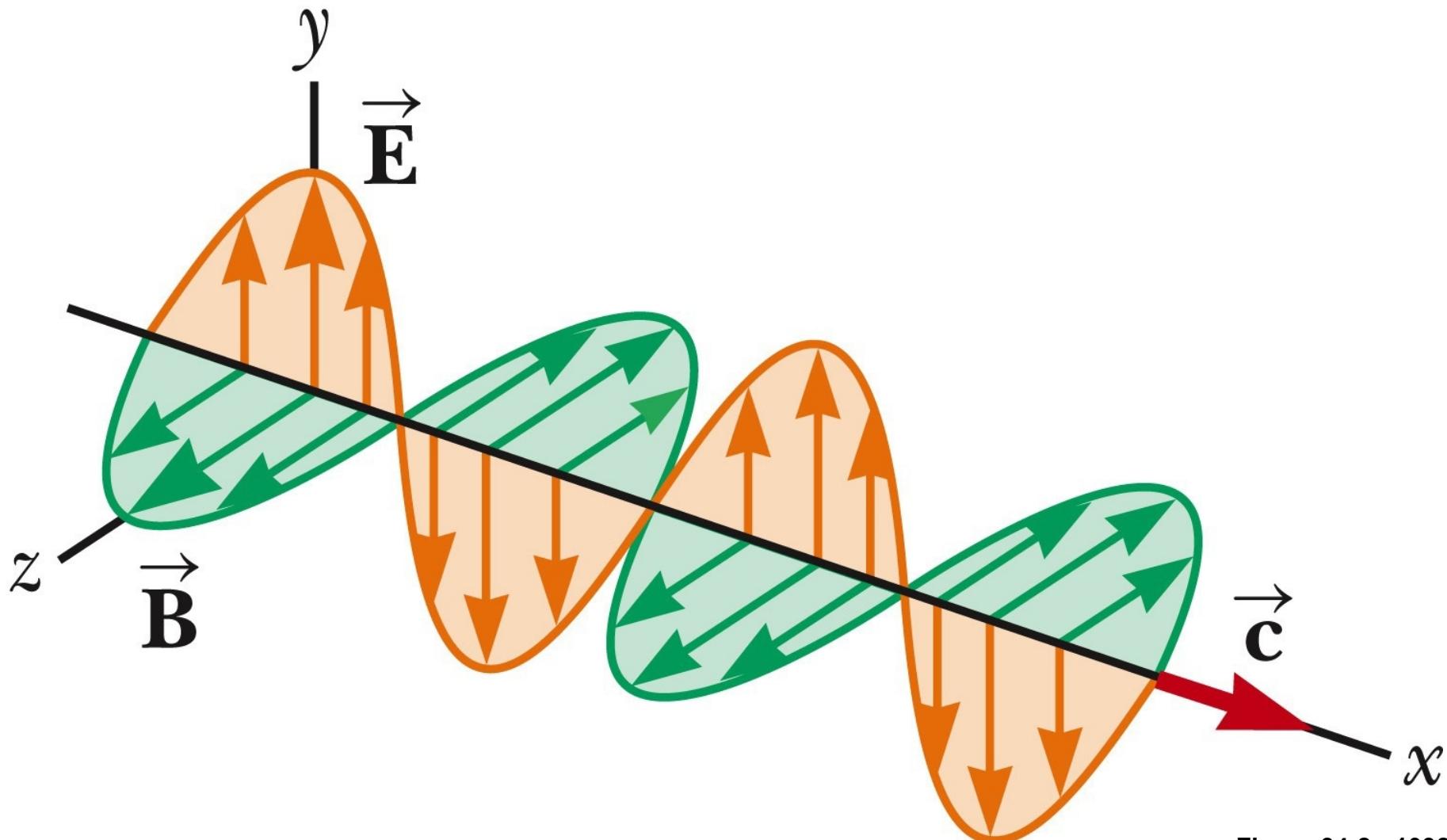
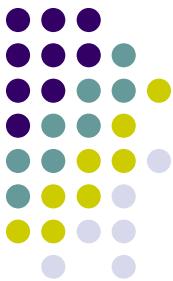


Figure 34-8 p1038



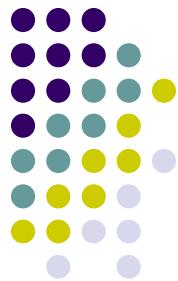
Particle Nature

- 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 intensity of the light



Particle Nature, cont.

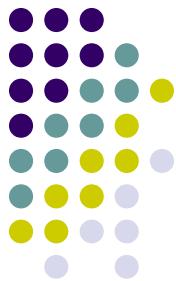
- Einstein (in 1905) proposed an explanation of the photoelectric effect that used the idea of quantization
 - The quantization model assumes that the energy of a light wave is present in particles called photons
 - $E_{\text{phot}} = hf$
 - h is Planck's Constant and = $6.63 \times 10^{-34} \text{ J}\cdot\text{s}$



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

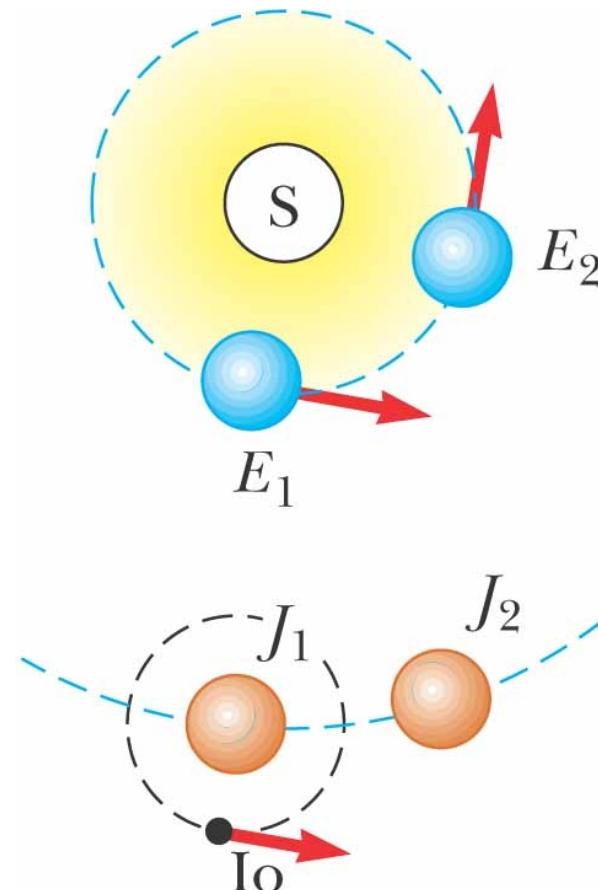


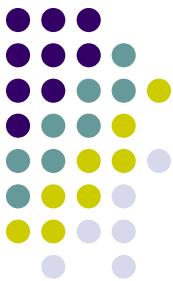
- Since light travels at a very high speed, early attempts to measure its speed were unsuccessful
 - Remember $c = 3.00 \times 10^8$ m/s
- Galileo tried by using two observers separated by about 10 km
 - The reaction time of the observers was more than the transit time of the light

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

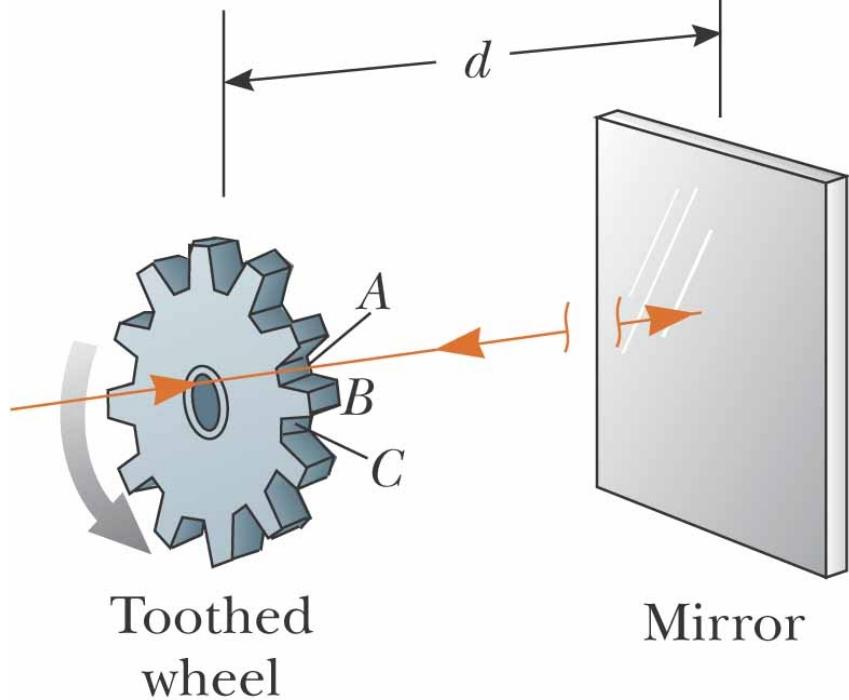


- This was the first successful method for measuring the speed of light by means of a purely terrestrial technique
- It was developed in 1849 by Armand Fizeau
- He used a rotating toothed wheel
- The distance between the wheel (considered to be the source) and a mirror was known



Fizeau's Method, cont.

- d is the distance between the wheel and the mirror
- Δt is the time for one round trip
- Then $c = 2d / \Delta t$
- Fizeau found a value of $c = 3.1 \times 10^8 \text{ m/s}$



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The Ray Approximation in Geometric Optics

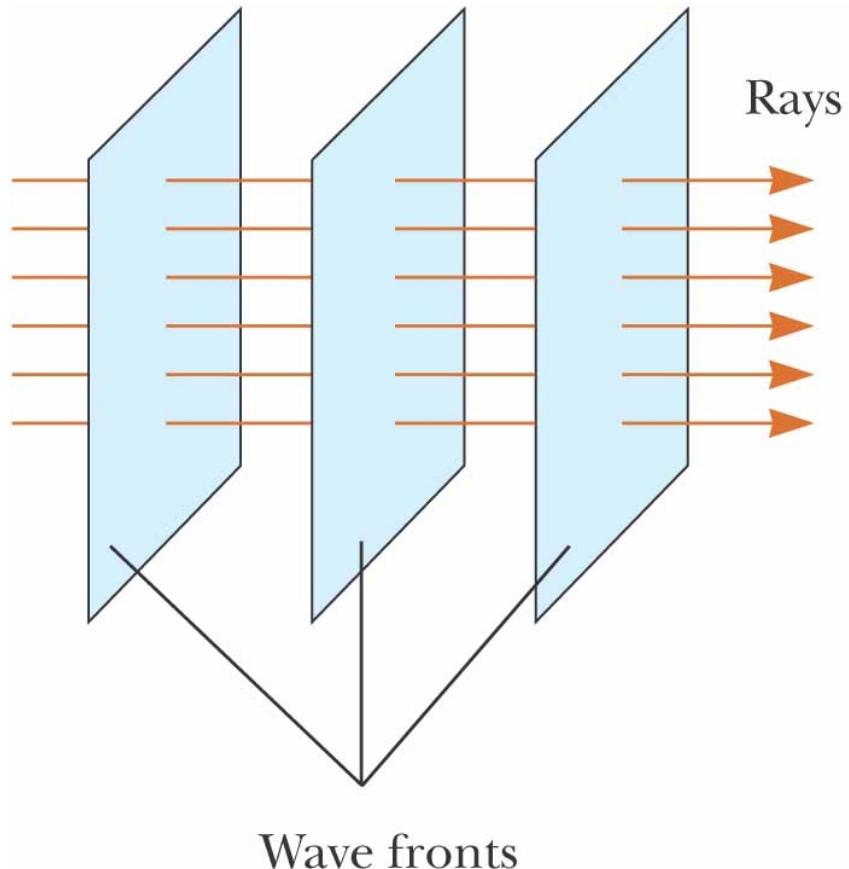


- **Geometric optics** involves the study of the propagation of light
- It uses the assumption that light travels in a straight-line path in a uniform medium and changes its direction when it meets the surface of a different medium or if the optical properties of the medium are nonuniform
- The **ray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



Ray Approximation

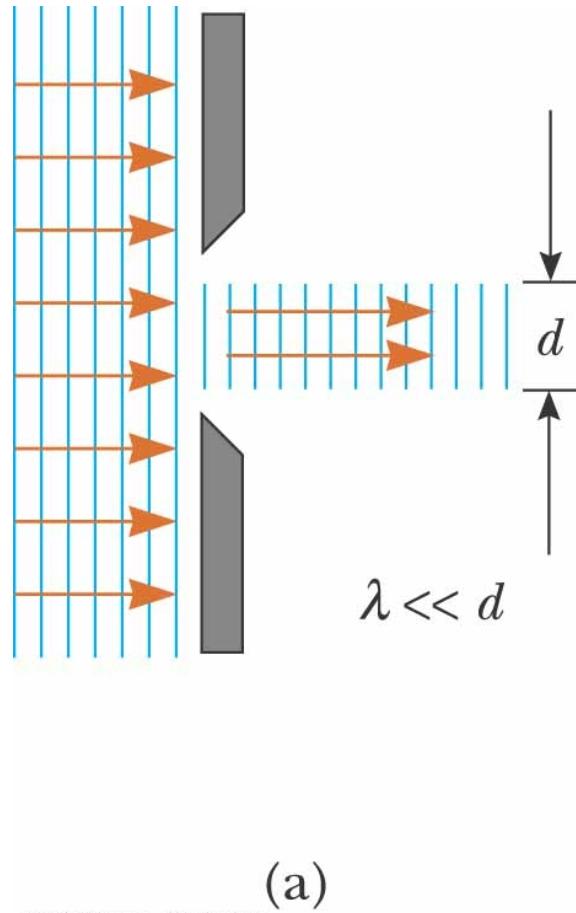
- The rays are straight lines perpendicular to the wave fronts
- With the ray approximation, we assume that a wave moving through a medium travels in a straight line in the direction of its rays

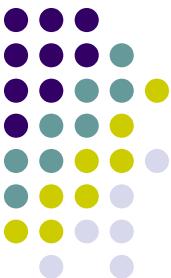




Ray Approximation, cont.

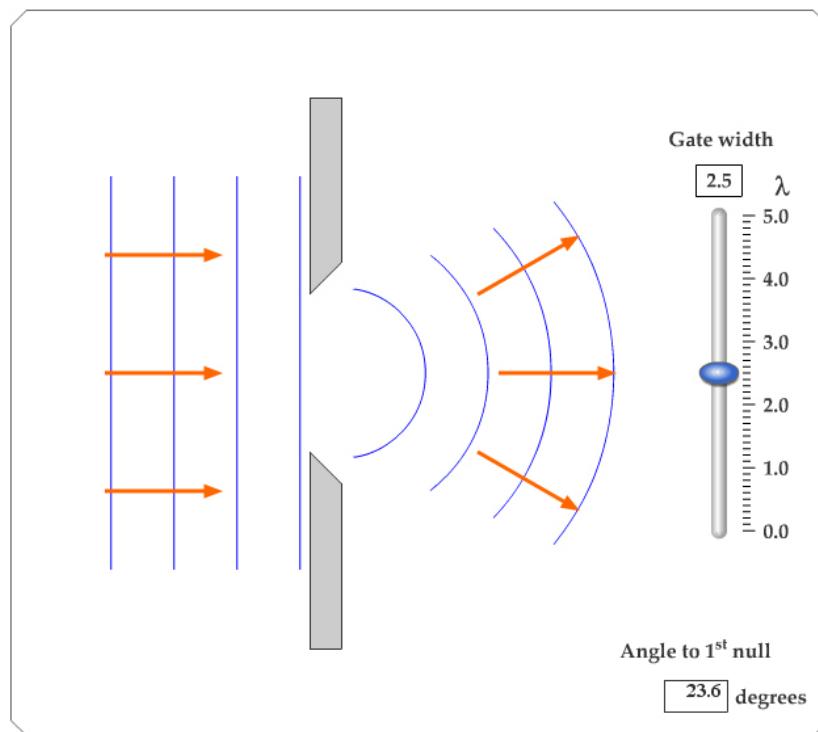
- If a wave meets a barrier, we will assume that $\lambda \ll d$
 - d is the diameter of the opening
- This approximation is good for the study of mirrors, lenses, prisms, etc.
- Diffraction effects occur for smaller openings





Active Figure 35.4

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



**PLAY
ACTIVE FIGURE**

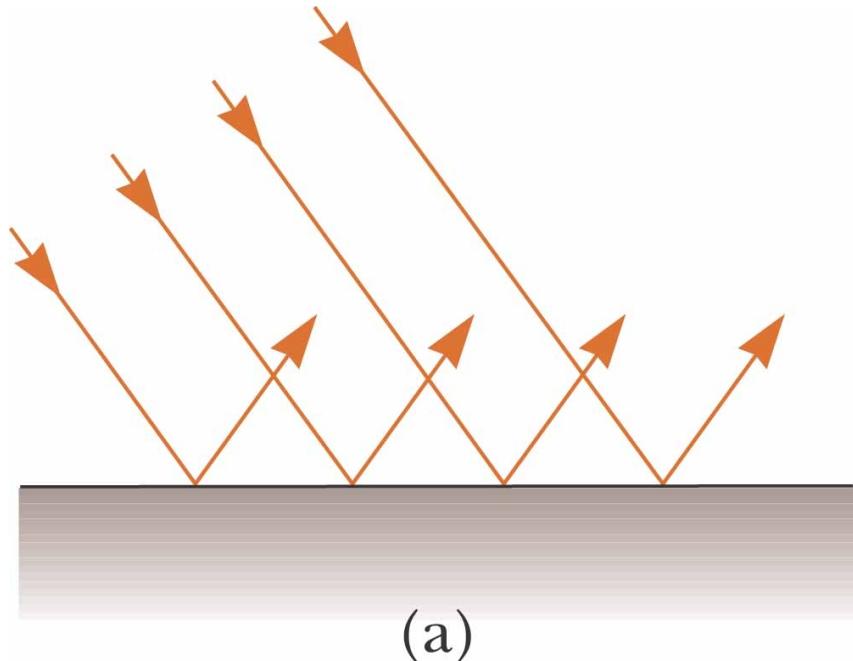


Reflection of Light

- 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

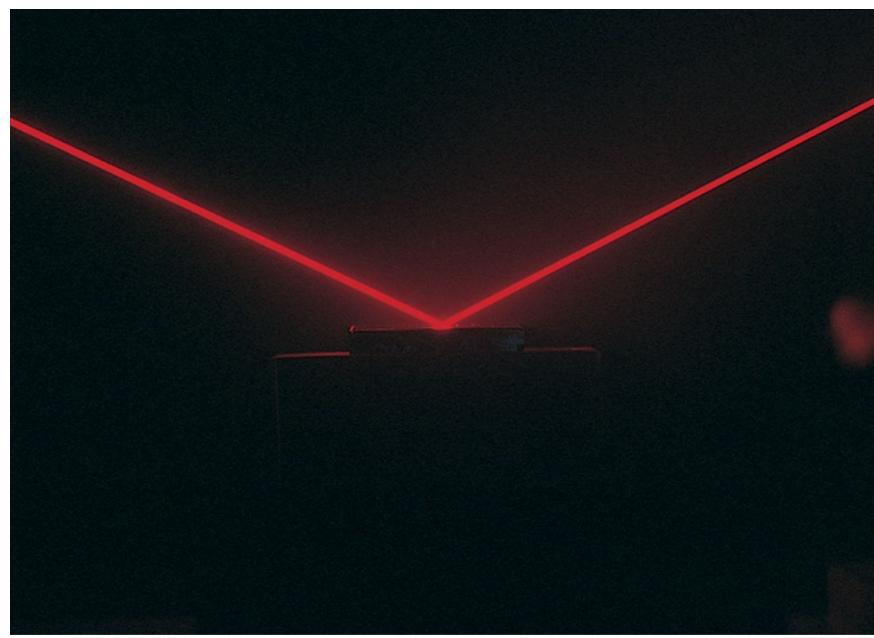
Specular Reflection

- *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



(a)

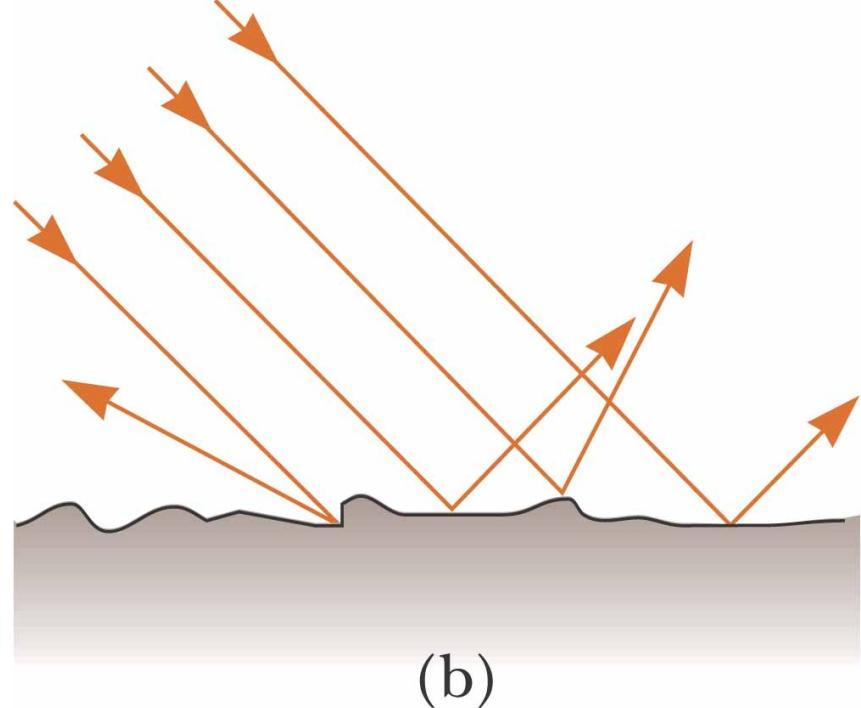
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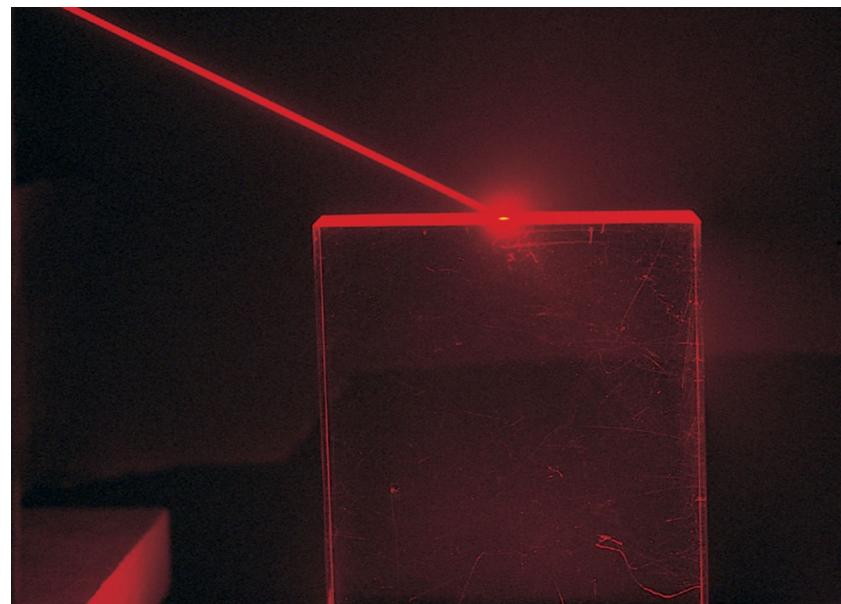
Diffuse Reflection

- *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



(b)

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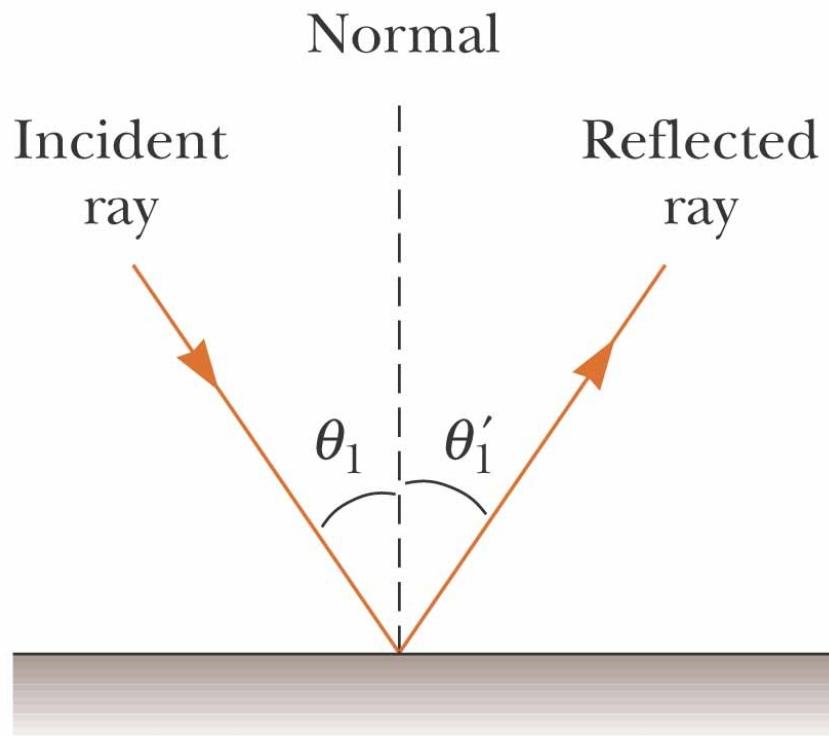


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Law of Reflection

- 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

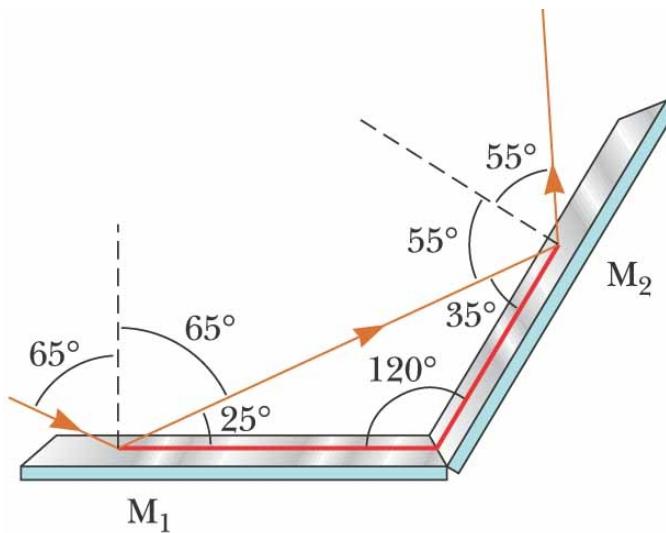


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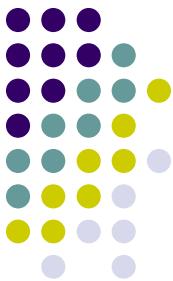


Multiple Reflections

- 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

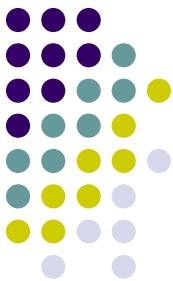


(a)



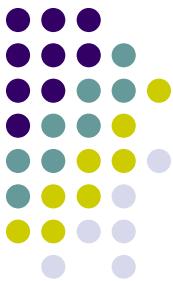
Retroreflection

- Assume the angle between two mirrors is 90°
- 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

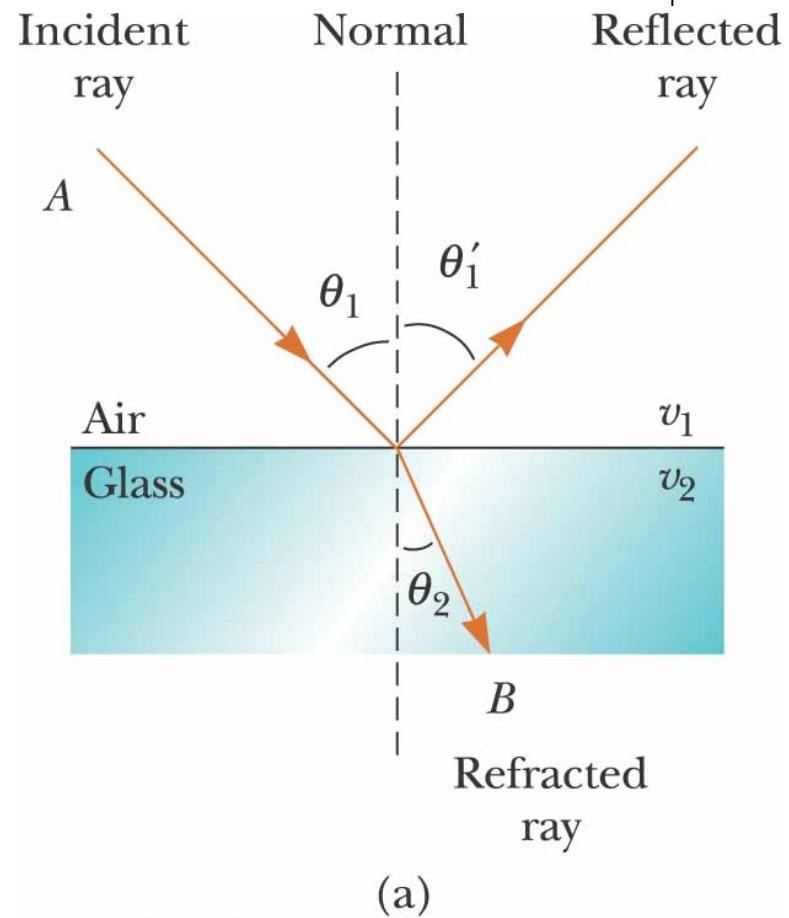
$$\frac{\sin \gamma_2}{\sin \gamma_1} = \frac{v_2}{v_1}$$

- 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

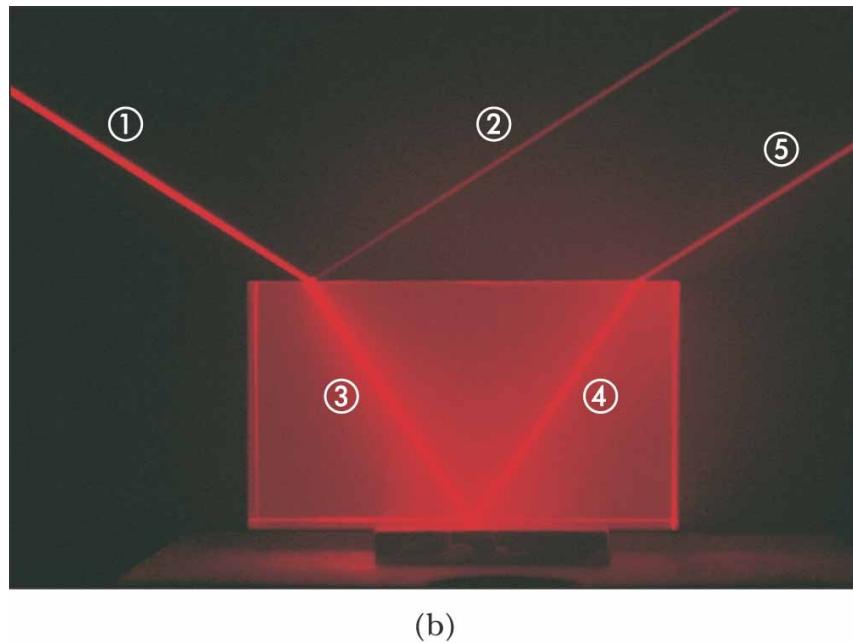
- The path of the light through the refracting surface is reversible
 - For example, a ray that travels from A to B
 - If the ray originated at B, it would follow the line AB to reach point A



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

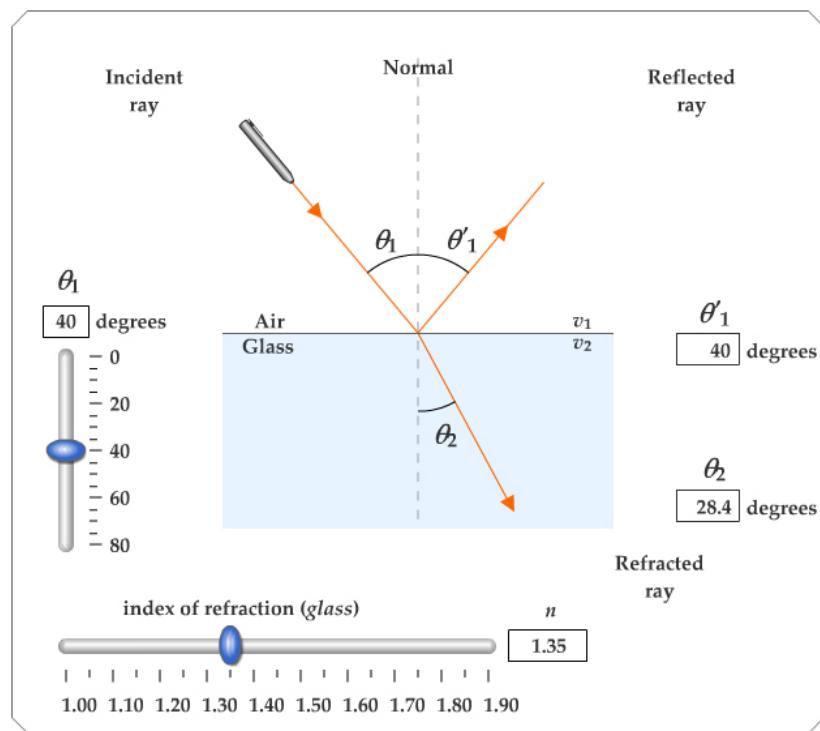


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Active Figure 35.10

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

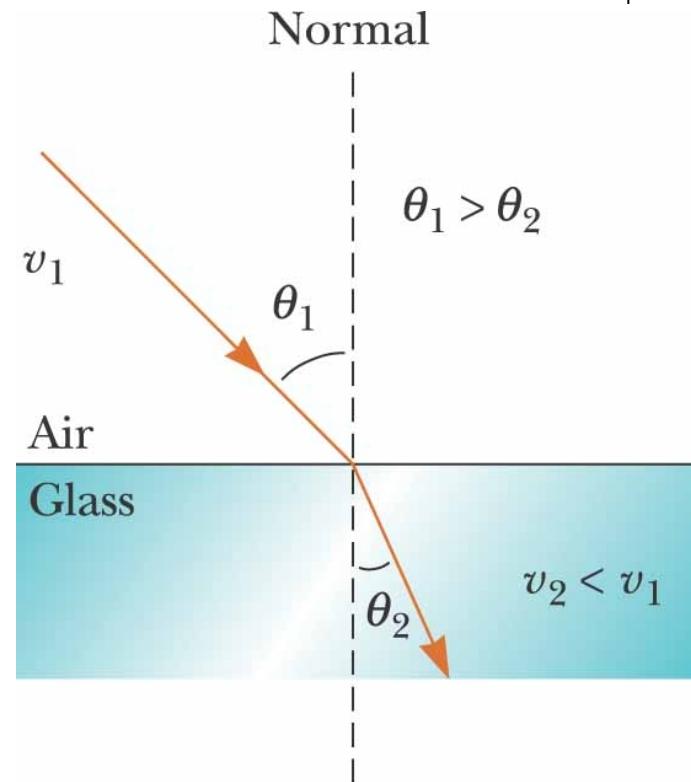


**PLAY
ACTIVE FIGURE**



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



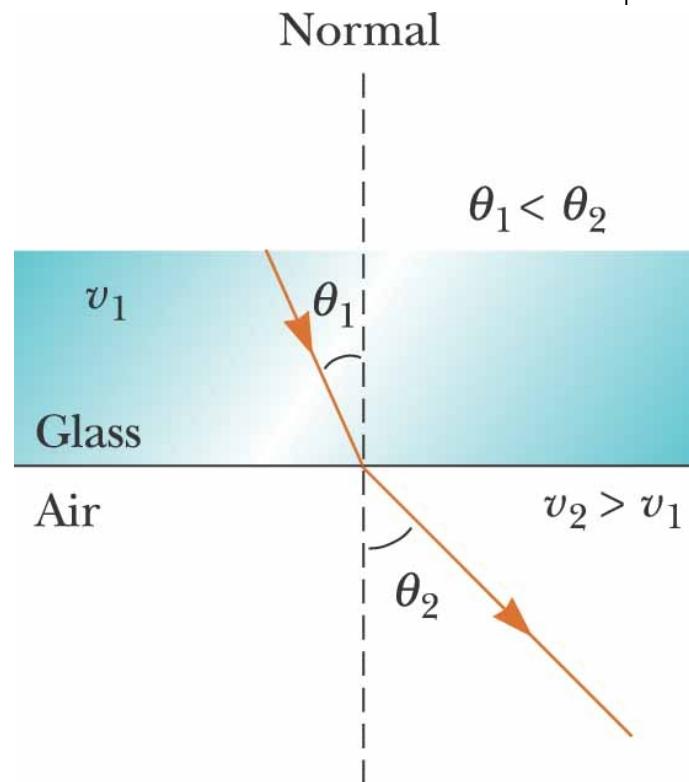
(a)

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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



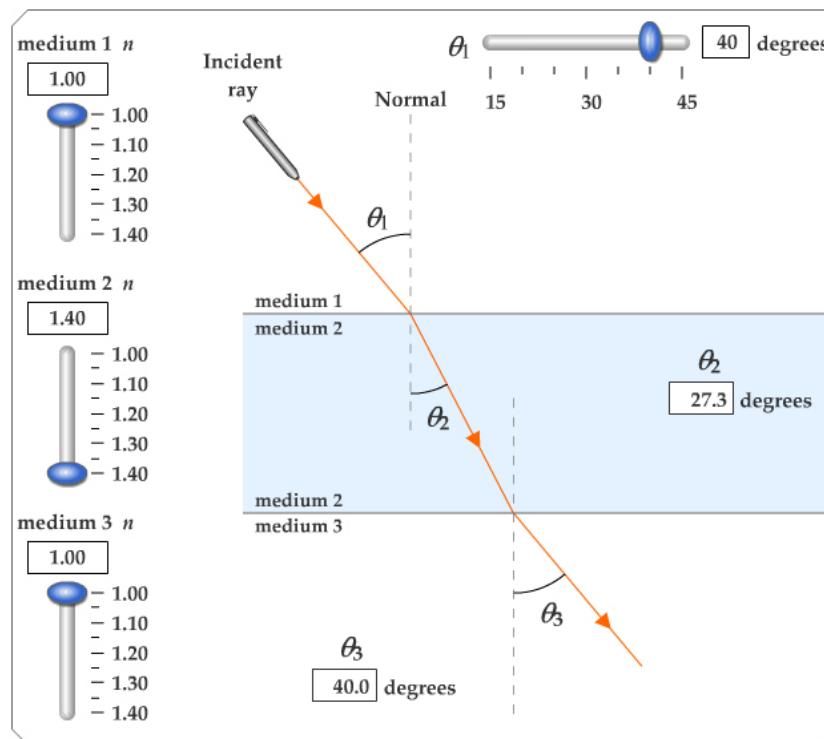
(b)

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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

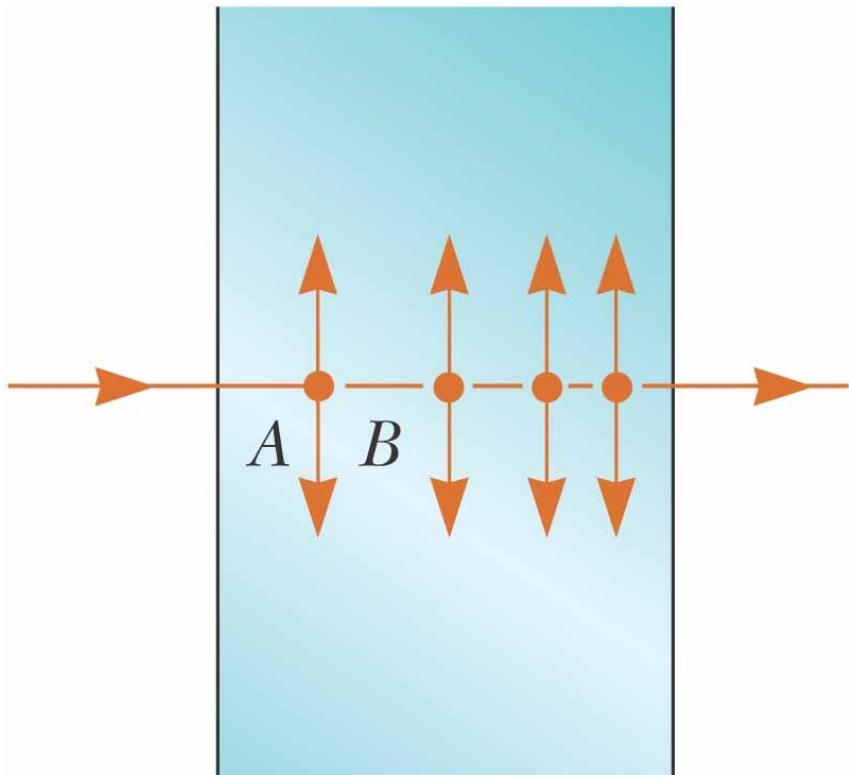


**PLAY
ACTIVE FIGURE**

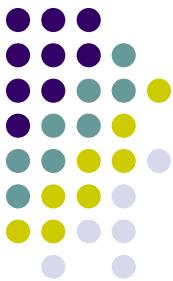


Light in a Medium

- 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



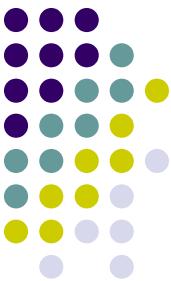
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The Index of Refraction

- 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

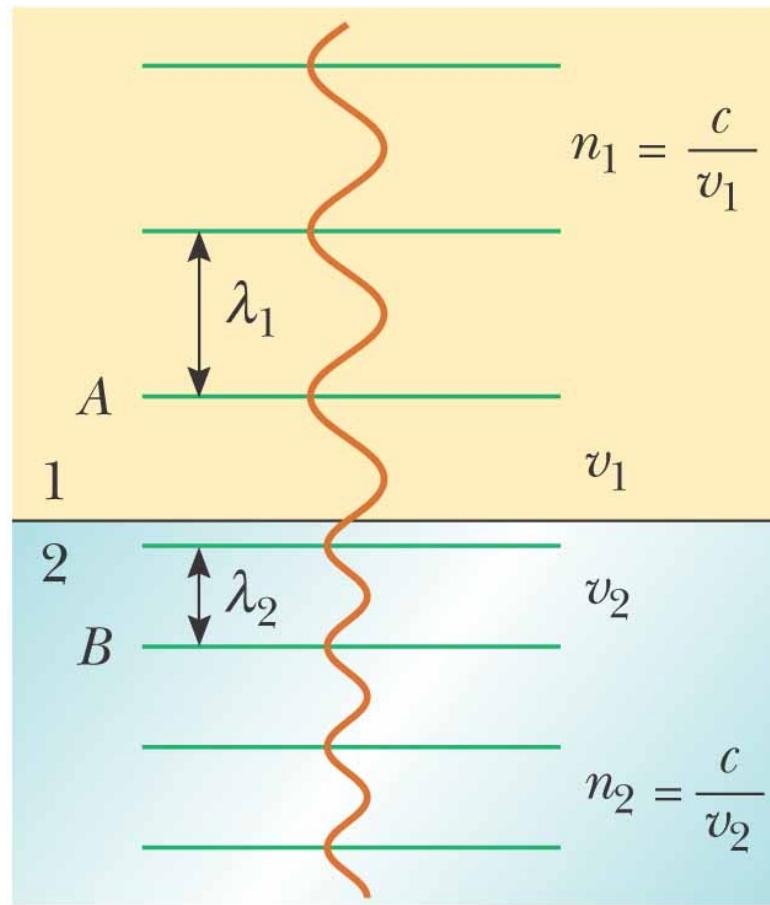
Substance	Index of Refraction	Substance	Index of Refraction	
<i>Solids at 20°C</i>			<i>Liquids at 20°C</i>	
Cubic zirconia	2.20	Benzene	1.501	
Diamond (C)	2.419	Carbon disulfide	1.628	
Fluorite (CaF_2)	1.434	Carbon tetrachloride	1.461	
Fused quartz (SiO_2)	1.458	Ethyl alcohol	1.361	
Gallium phosphide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

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

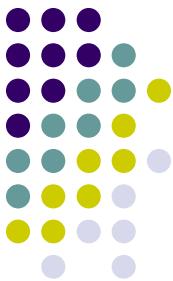


Frequency Between Media

- 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



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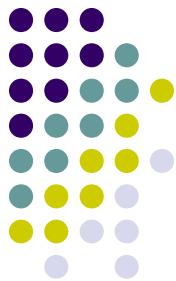


Index of Refraction Extended

- 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

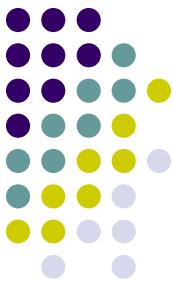
$$\frac{\lambda_1}{\lambda_2} = \frac{v_1}{v_2} = \frac{c/n_1}{c/n_2} = \frac{n_2}{n_1}$$

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

$$n = \frac{\lambda_{\text{in vacuum}}}{\lambda_{\text{in a medium}}}$$



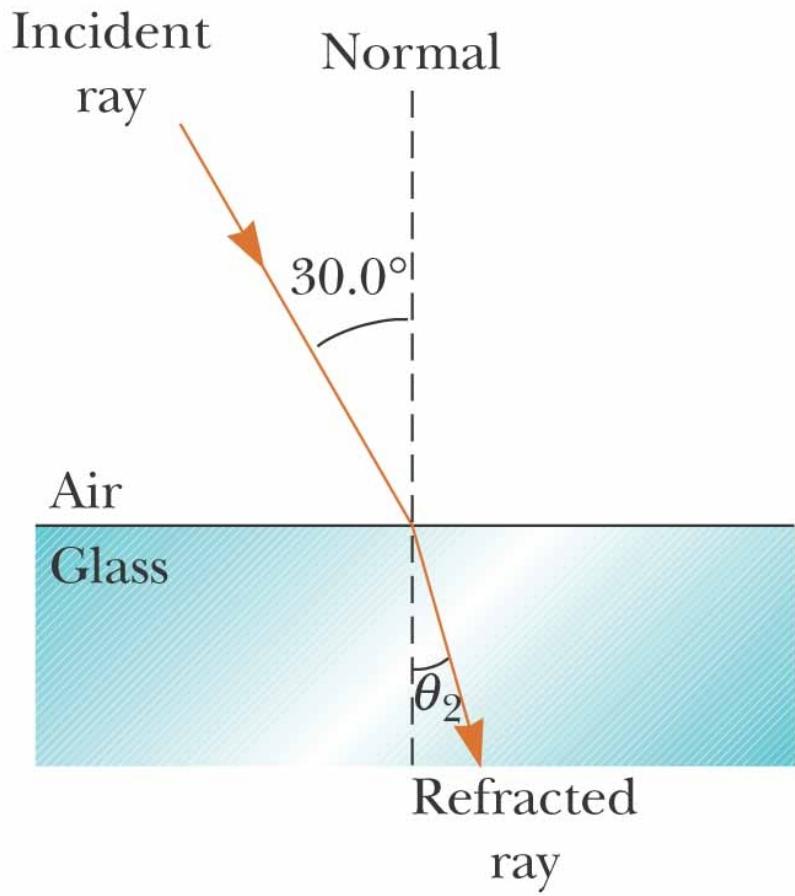
Snell's Law of Refraction

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

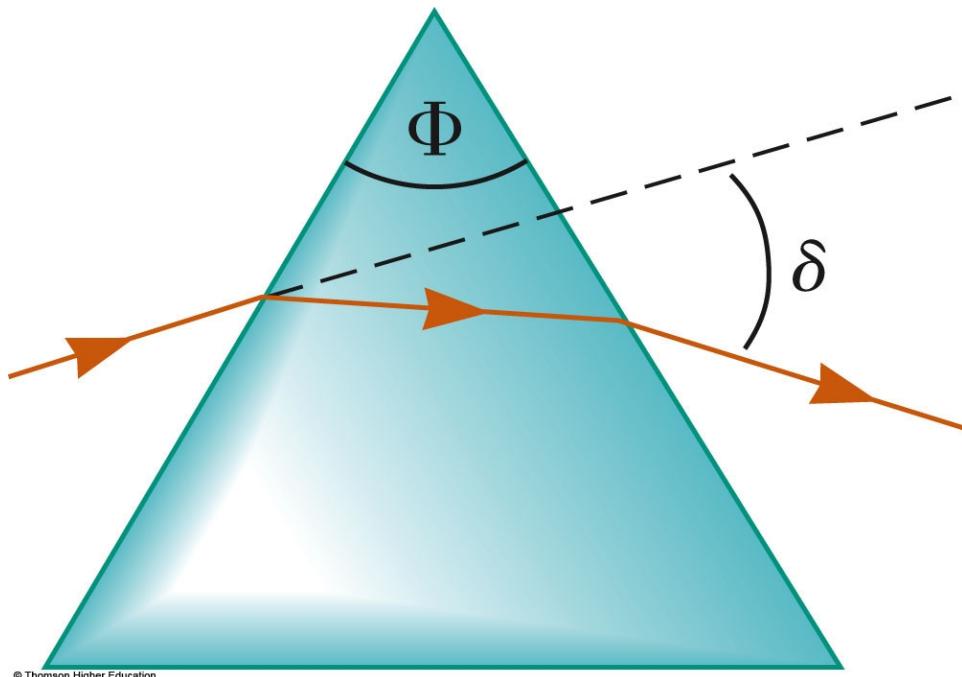
- Light is refracted into a crown glass slab
- $\theta_1 = 30.0^\circ$, $\theta_2 = ?$
- $n_1 = 1.00$ and $n_2 = 1.52$
 - From Table 35.1
- $\theta_2 = \sin^{-1}(n_1 / n_2) \sin \theta_1 = 19.2^\circ$
- The ray bends toward the normal, as expected

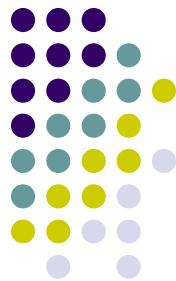




Prism

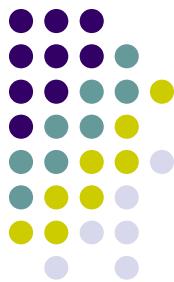
- A ray of single-wavelength light incident on the prism will emerge at angle δ from its original direction of travel
 - δ is called the **angle of deviation**
 - Φ is the apex angle





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



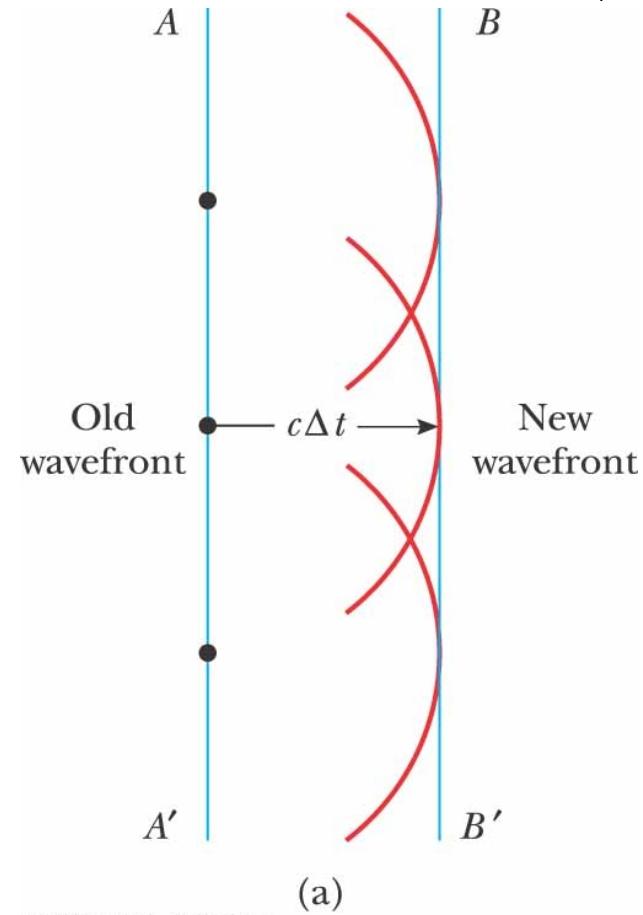
Huygens's Principle, cont.

- 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



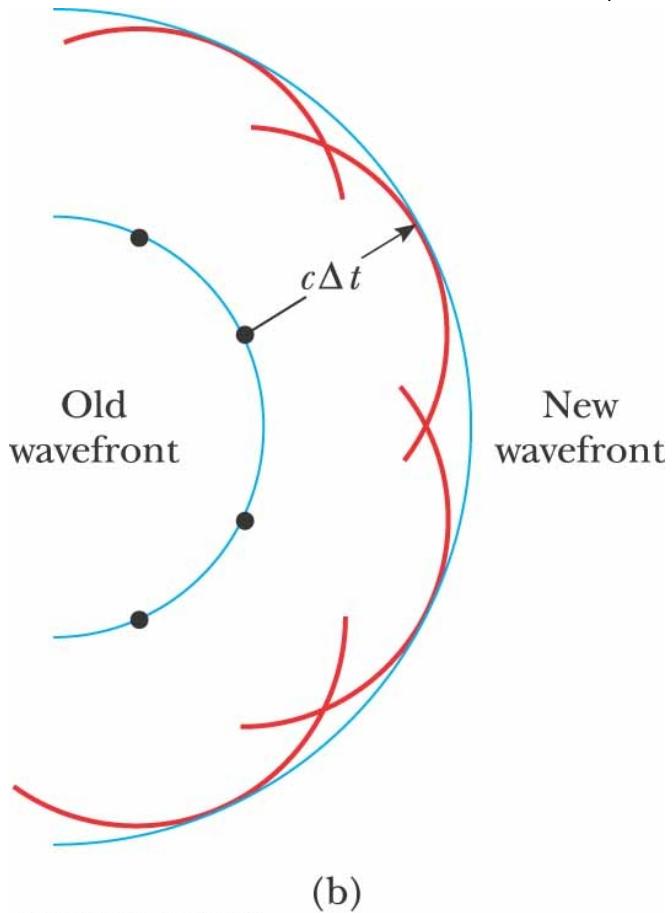
- At $t = 0$, the wave front is indicated by the plane AA'
- The points are representative sources for the wavelets
- After the wavelets have moved a distance $c\Delta t$, a new plane BB' can be drawn tangent to the wavefronts



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

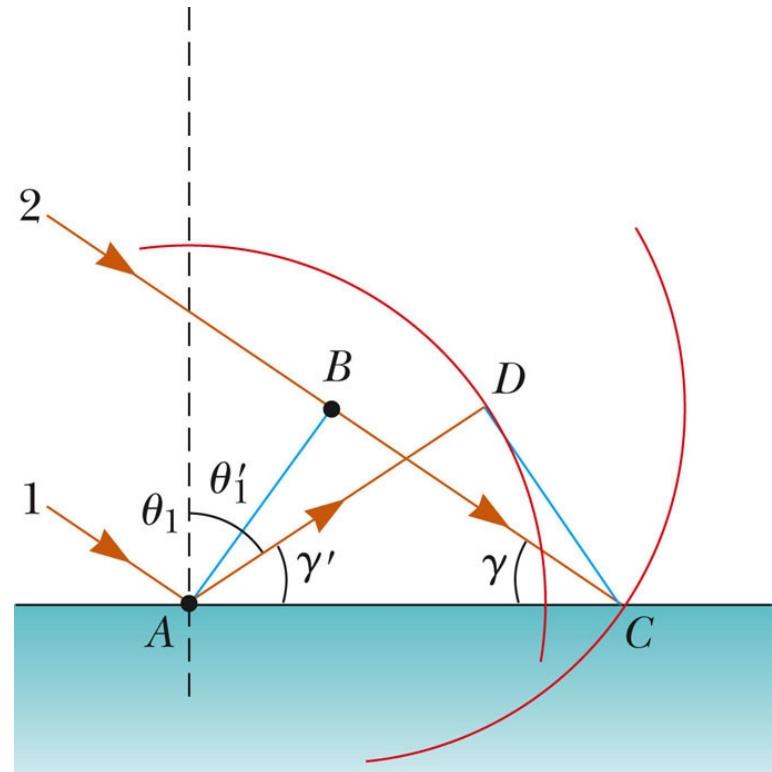


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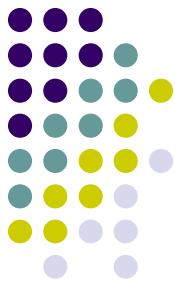
Huygens's Principle and the Law of Reflection



- 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.

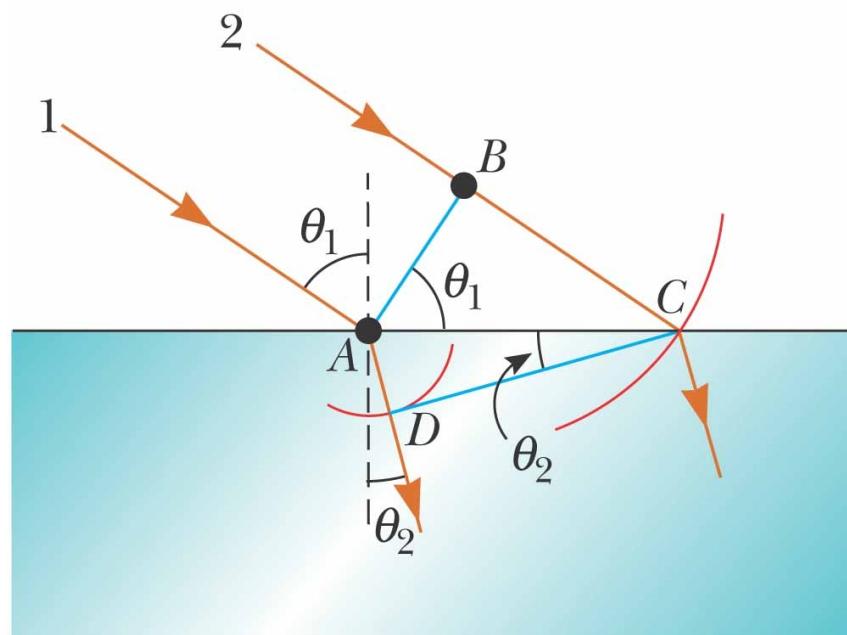


- Triangle ABC is congruent to triangle ADC
- $\cos \gamma = BC / AC$
- $\cos \gamma' = AD / AC$
- Therefore, $\cos \gamma = \cos \gamma'$ and $\gamma = \gamma'$
- This gives $\theta_1 = \theta_1'$
- This is the law of reflection

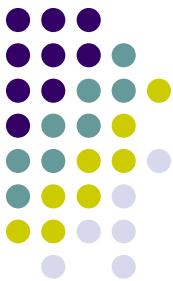
Huygens's Principle and the Law of Refraction



- 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



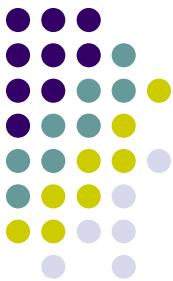
Huygens's Principle and the Law of Refraction, cont.



- 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

$$\sin \gamma_1 = \frac{BC}{AC} = \frac{v_1 \Delta t}{AC} \quad \text{and} \quad \sin \gamma_2 = \frac{AD}{AC} = \frac{v_2 \Delta t}{AC}$$

Huygens's Principle and the Law of Refraction, final



- The preceding equation can be simplified to

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

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

$$\text{and so } n_1 \sin \theta_1 = n_2 \sin \theta_2$$

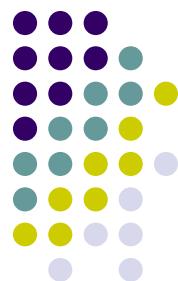
- This is Snell's law of refraction



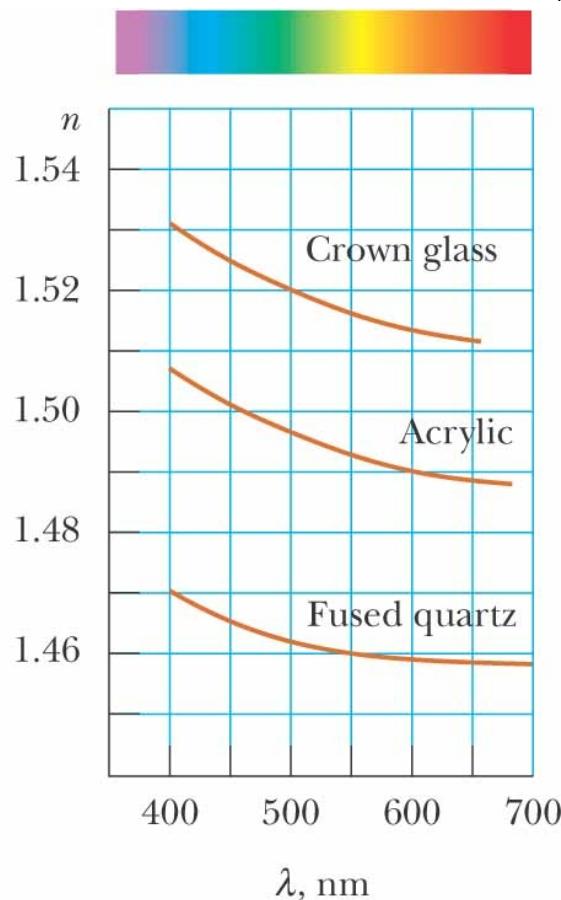
Dispersion

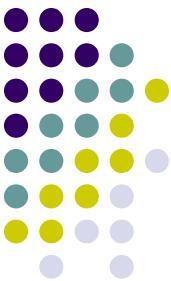
- For a given material, the index of refraction varies with the wavelength of the light passing through the material
- This dependence of n on λ is called dispersion
- Snell's law indicates light of different wavelengths is bent at different angles when incident on a refracting material

Variation of Index of Refraction with Wavelength



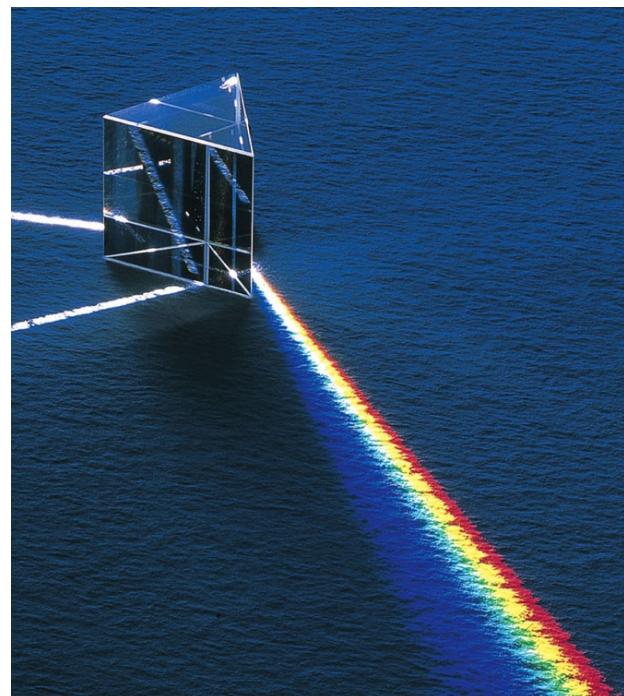
- The index of refraction for a material generally decreases with increasing wavelength
- Violet light bends more than red light when passing into a refracting material



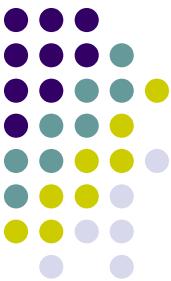


Refraction in a Prism

- 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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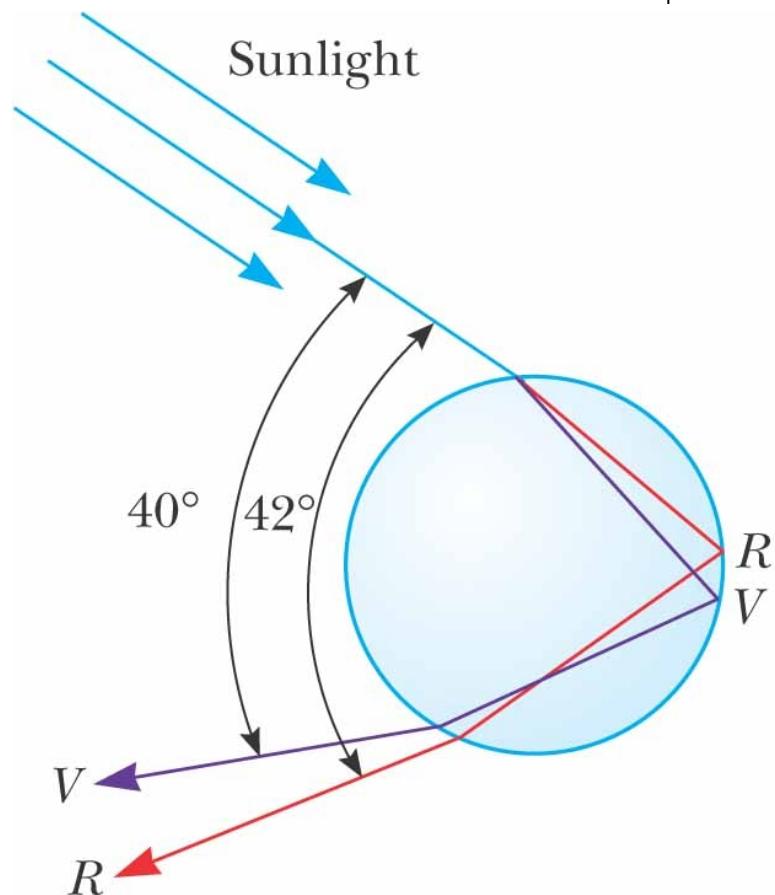
The Rainbow

- 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

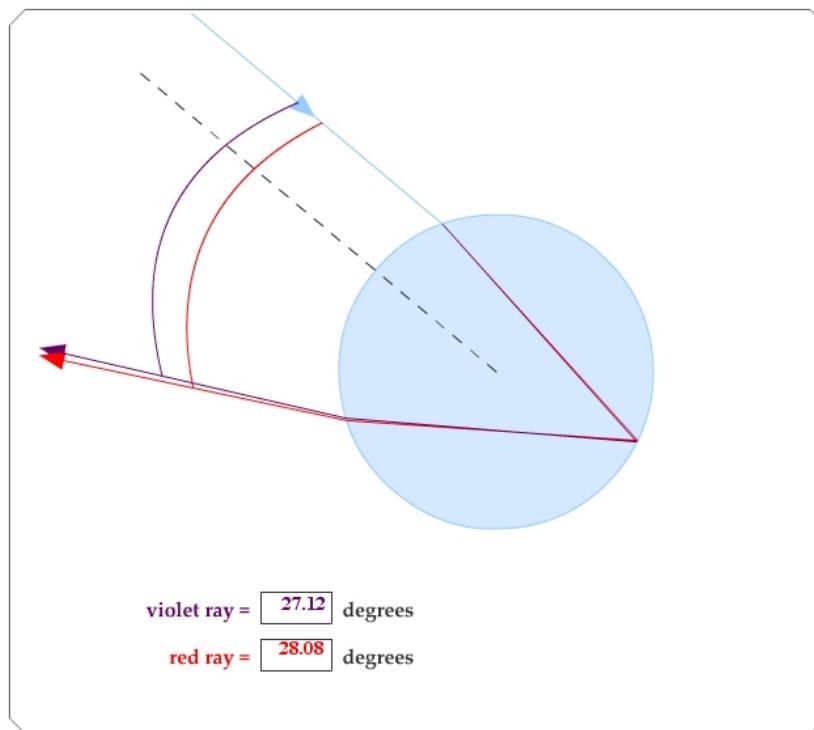
- At the back surface the light is reflected
- It is refracted again as it returns to the front surface and moves into the air
- The rays leave the drop at various angles
 - The angle between the white light and the most intense violet ray is 40°
 - The angle between the white light and the most intense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



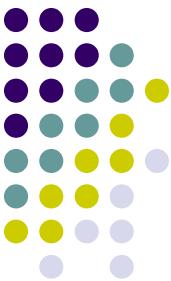


Active Figure 35.23

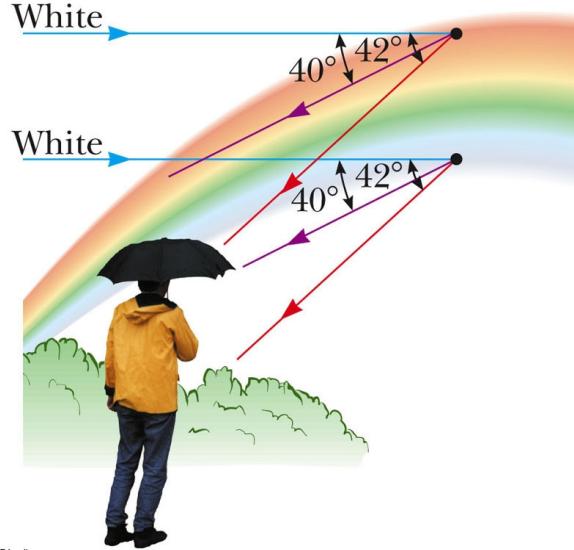
- Use the active figure to vary the point at which the sunlight enters the raindrop
- Observe the angles and verify the maximum angles



**PLAY
ACTIVE FIGURE**



Observing the Rainbow



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- 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



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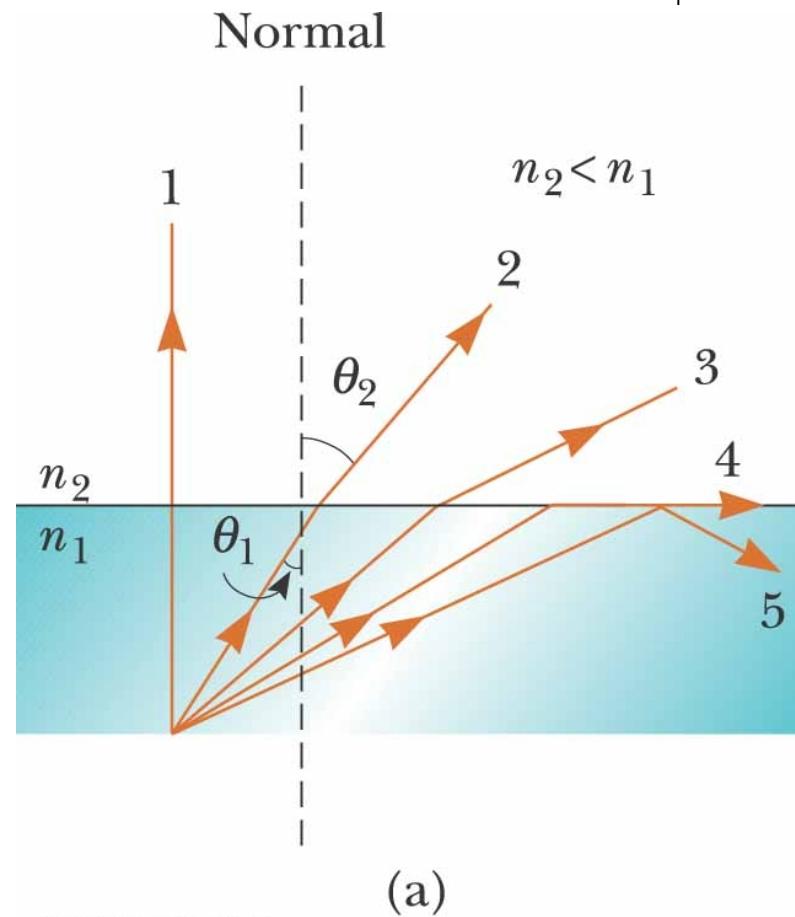
Total Internal Reflection

- 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 $n_1 > n_2$

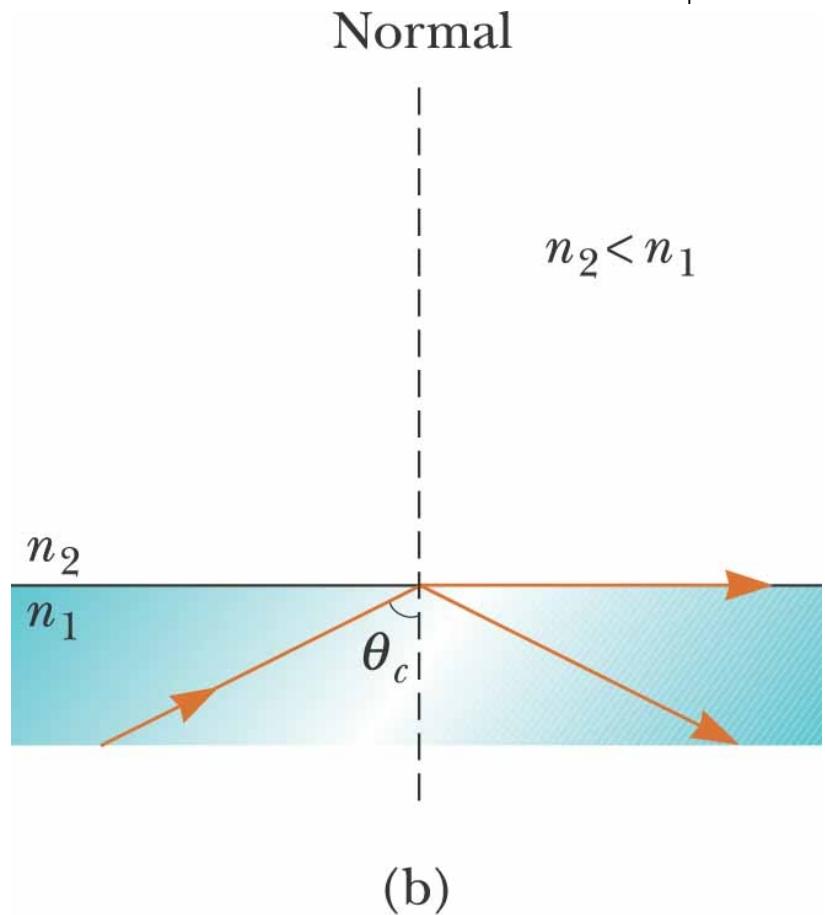




Critical Angle

- 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

$$\sin \theta_c = \frac{n_2}{n_1}$$

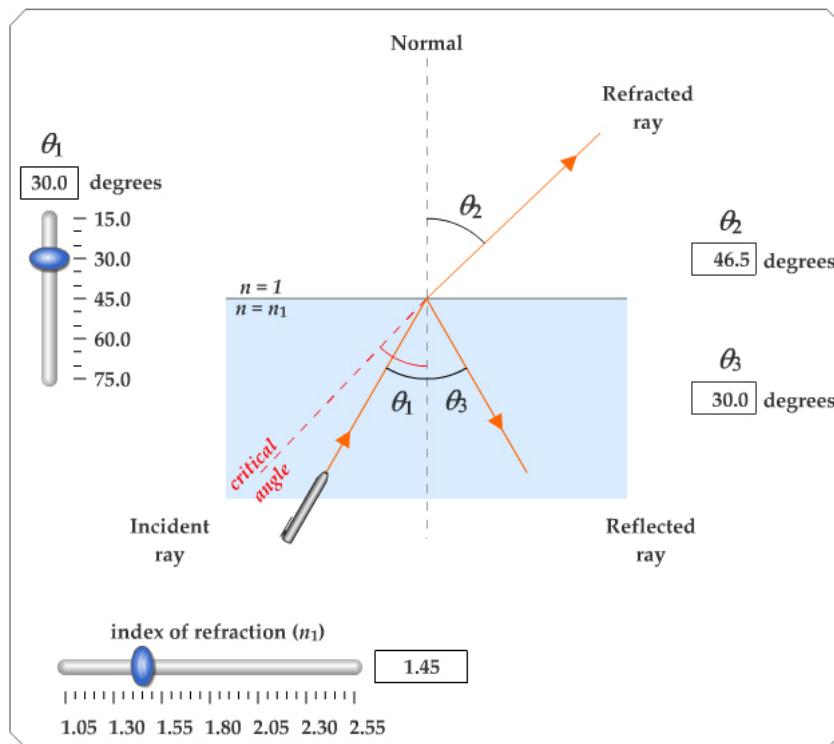


(b)

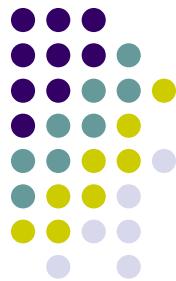


Active Figure 35.25

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

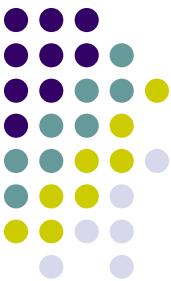


**PLAY
ACTIVE FIGURE**



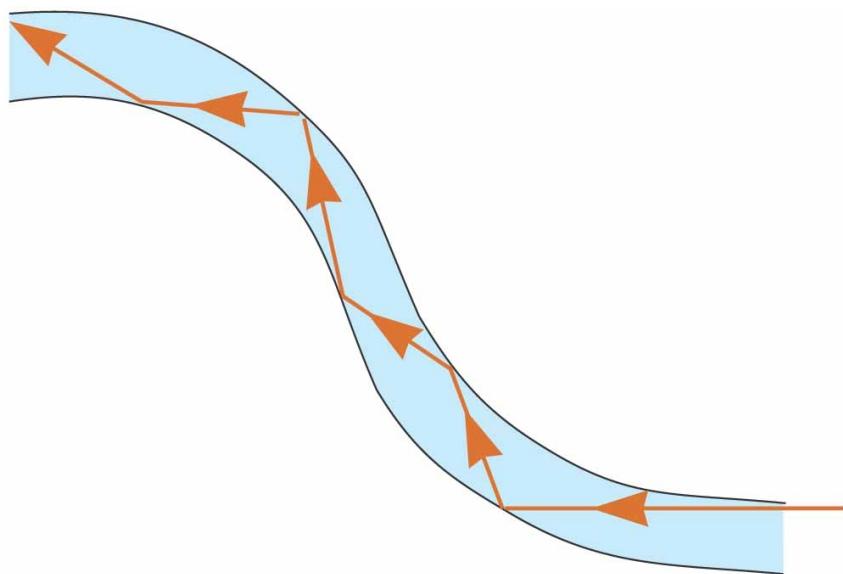
Critical Angle, cont.

- 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

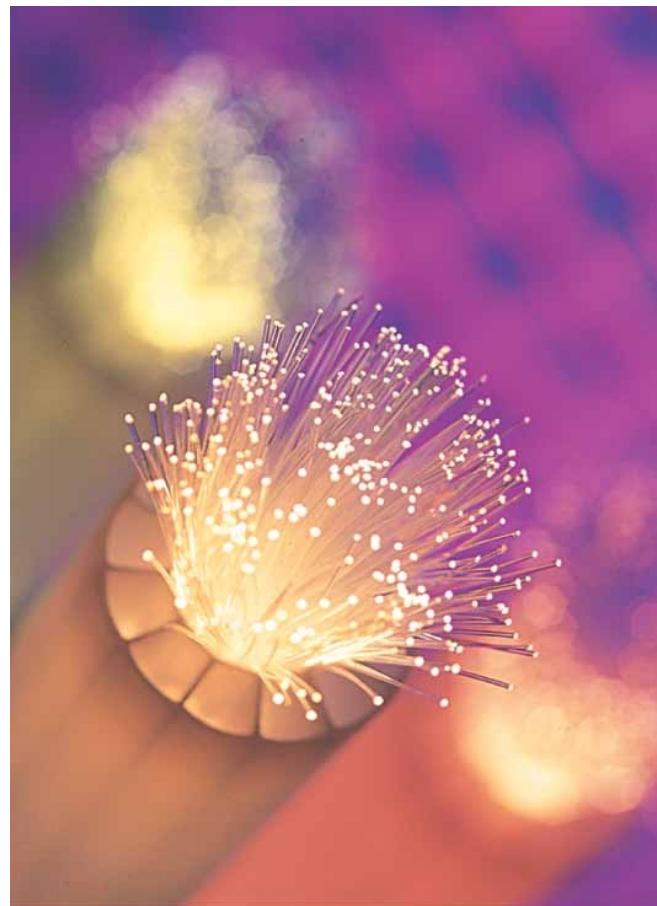


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Fiber Optics, cont.

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

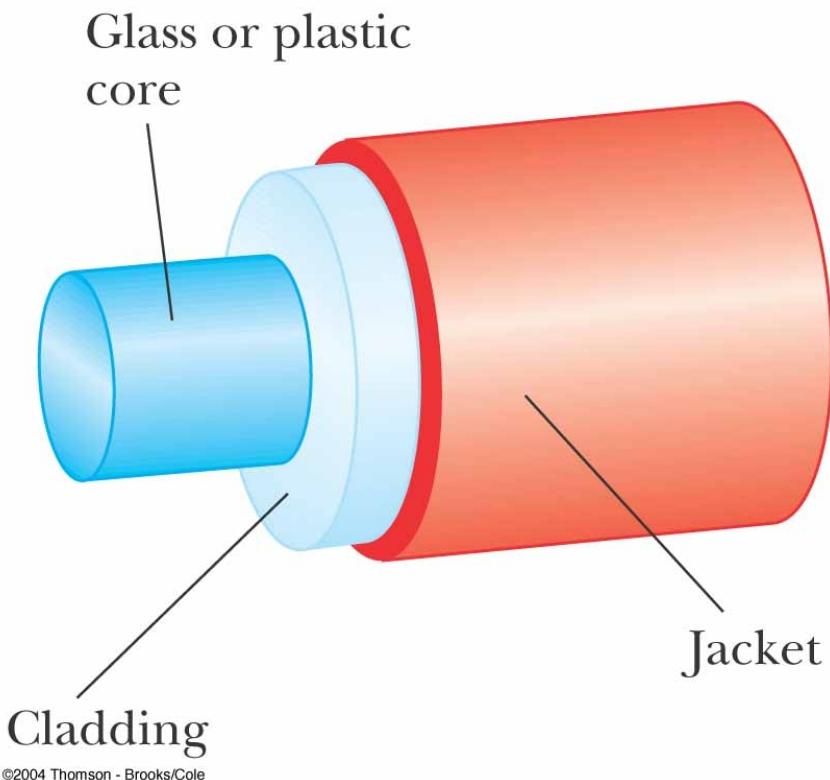


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Construction of an Optical Fiber



- 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



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