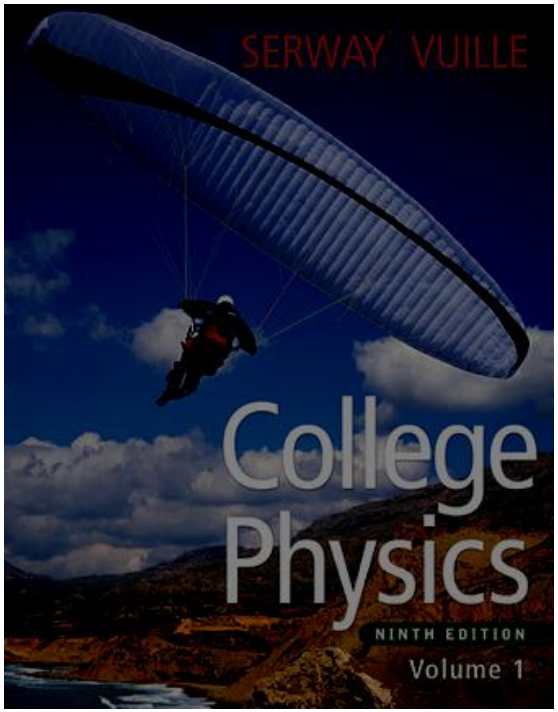
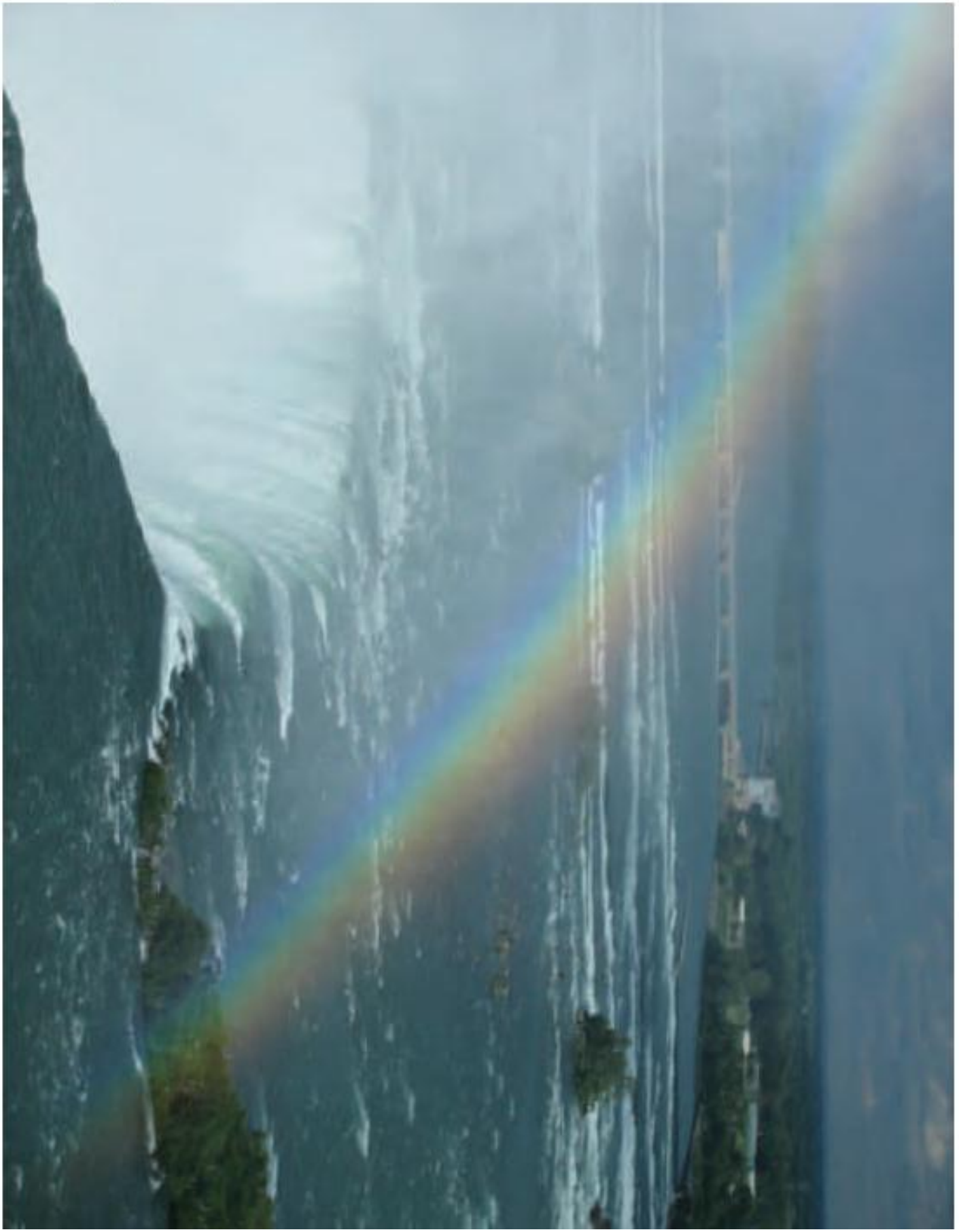


BROOKS/COLE
CENGAGE Learning

Chapter 22

Reflection and Refraction of Light

Dianne Kowing



Nature of Light

- Light has a dual nature.
  - Particle
  - Wave
- Wave characteristics will be discussed in this chapter.
  - Reflection
  - Refraction
  - These characteristics can be used to understand mirrors and lenses.

A Brief History of Light

- Early models of light
  - It was proposed that light consisted of tiny particles.
- Newton
  - Used this particle model to explain reflection and refraction
- Huygens
  - 1678
  - Explained many properties of light by proposing light was wave-like

A Brief History of Light, Cont.

- Young
  - 1801
  - Strong support for wave theory by showing interference
- Maxwell
  - 1865
  - Electromagnetic waves travel at the speed of light.

A Brief History of Light, Final

- Einstein
  - Particle nature of light
  - Explained the photoelectric effect
  - Used Planck's ideas

The Particle Nature of Light

- "Particles" of light are called *photons.*
- Each photon has a particular energy.
  - $E = h f$
  - h is *Planck's constant*
    - $h = 6.63 \times 10^{-34}$ J s
  - Encompasses both natures of light
    - Interacts like a particle
    - Has a given frequency like a wave

Dual Nature of Light

- In some experiments light acts as a wave and in others it acts as a particle.
  - Classical electromagnetic wave theory provides explanations of light propagation and interference.
  - Experiments involving the interaction of light with matter are best explained by assuming light is a particle.
- Light has a number of physical properties, some associated with waves and others with particles.

Reflection and Refraction

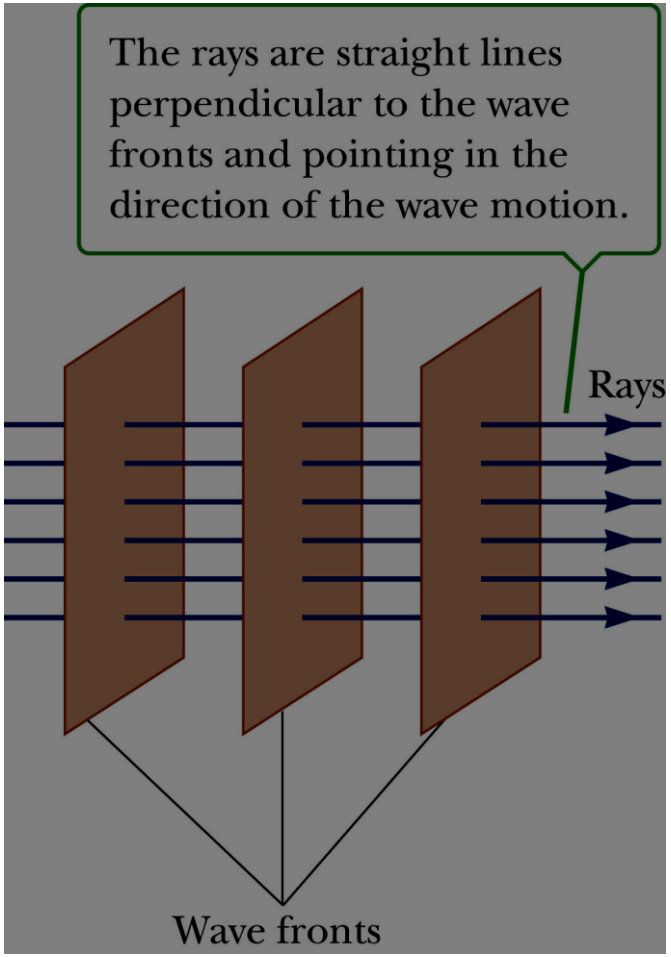
- The processes of reflection and refraction can occur when light traveling in one medium encounters a boundary leading to a second medium.
- In ***reflection***, part of the light bounces off the second medium.
- In ***refraction***, the light passing into the second medium bends.
- Often, both processes occur at the same time.

Geometric Optics – Using a Ray Approximation

- Light travels in a straight-line path in a homogeneous medium until it encounters a boundary between two different media.
- The *ray approximation* is used to represent beams of light.
- A *ray* of light is an imaginary line drawn along the direction of travel of the light beams.

Ray Approximation

- A *wave front* is a surface passing through points of a wave that have the same phase and amplitude.
- The rays, corresponding to the direction of the wave motion, are perpendicular to the wave fronts.

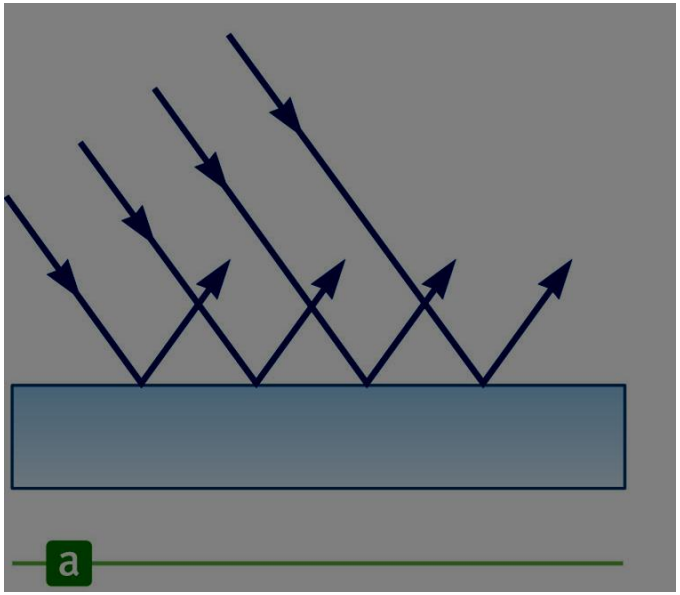


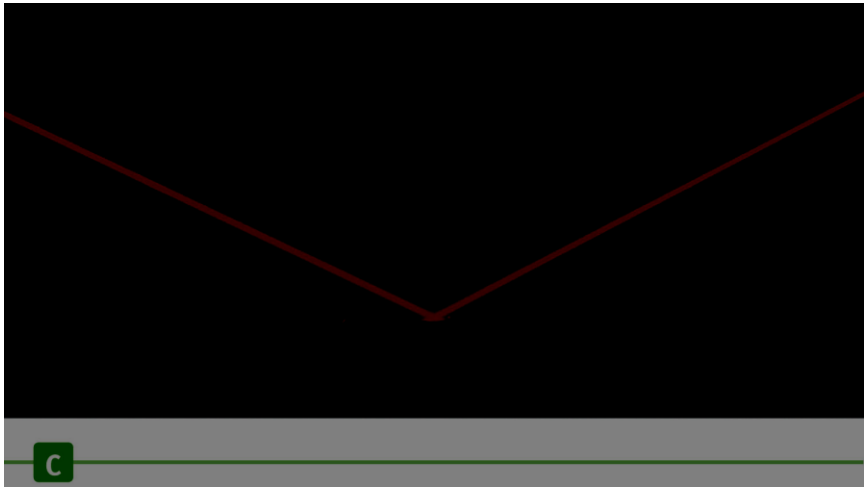
Reflection of Light

- 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

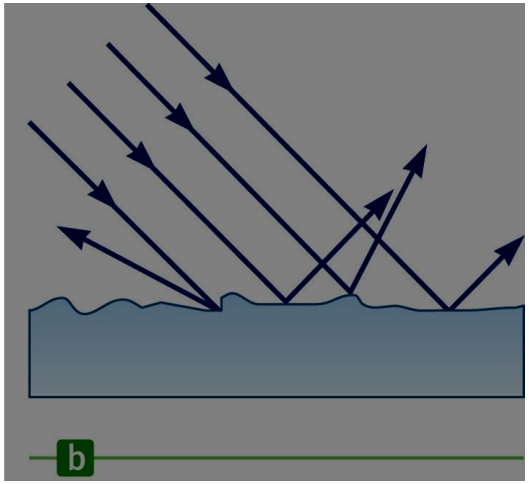
- *Specular reflection* is reflection from a smooth surface.
- The reflected rays are parallel to each other.
- All reflection in this text is assumed to be specular.

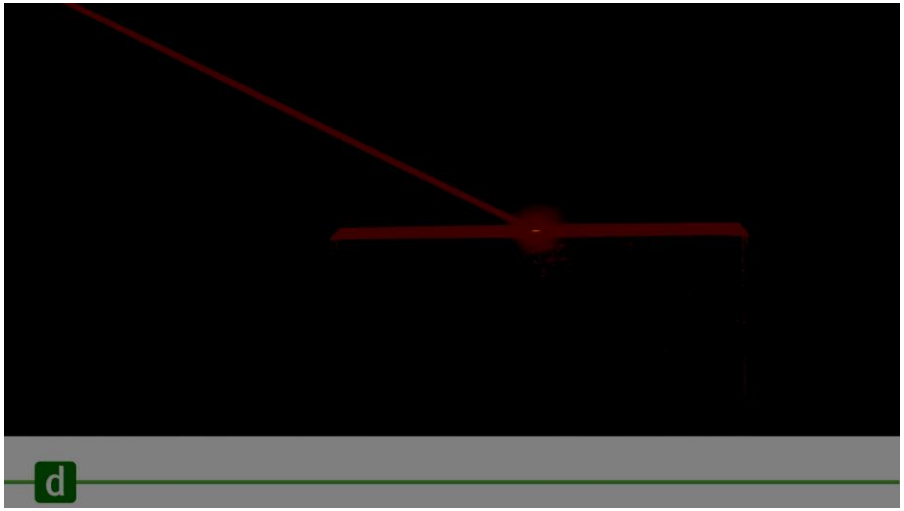




Diffuse Reflection

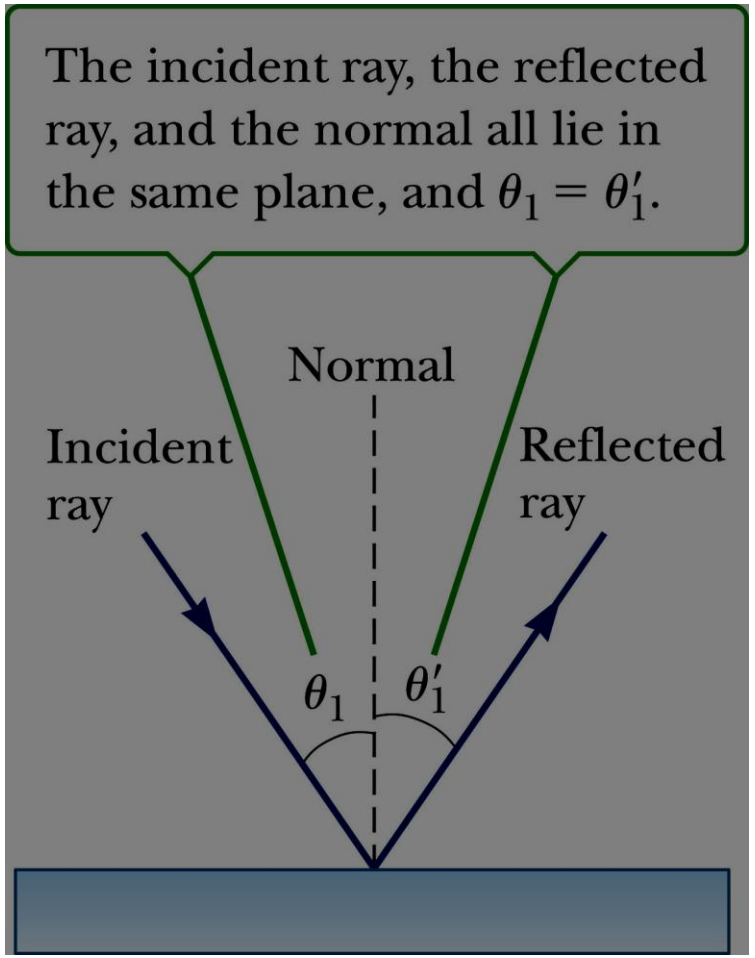
- *Diffuse reflection* is reflection from a rough surface.
- The reflected rays travel in a variety of directions.
- Diffuse reflection makes the dry road easy to see at night.





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.

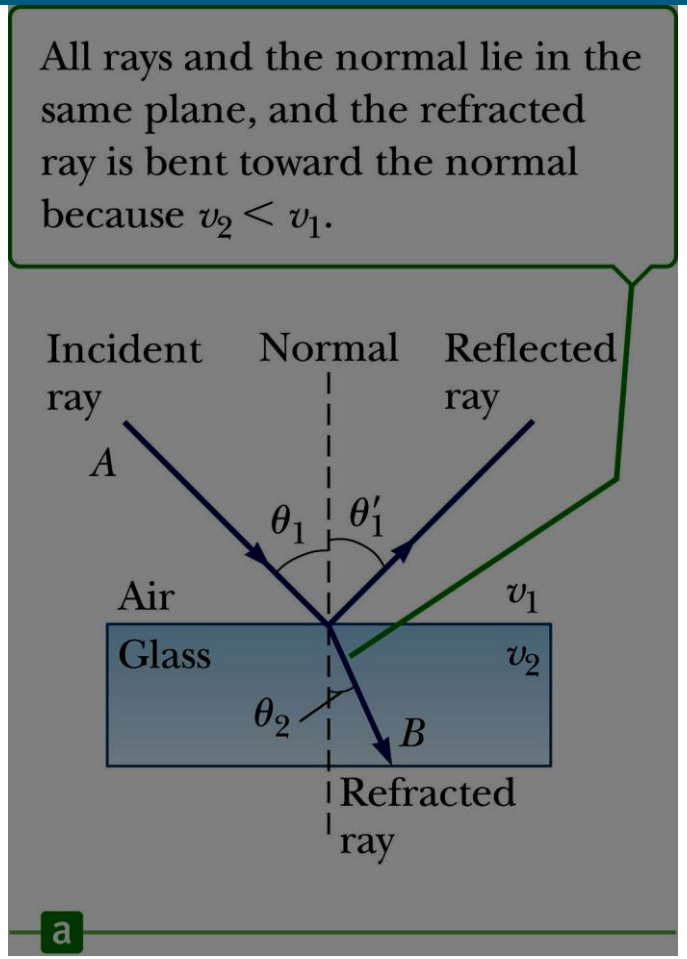
- The angle of reflection is equal to the angle of incidence.
- $\theta_1 = \theta_1'$

Refraction of Light

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

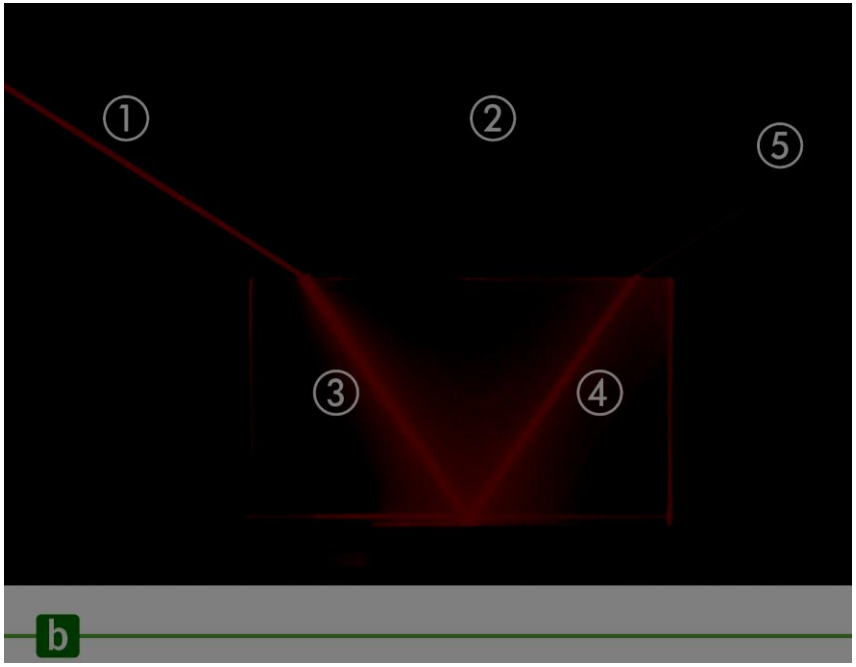
Refraction of Light, Cont.

- The incident ray, the reflected ray, the refracted ray, and the normal all lie on the same plane.
- The angle of refraction, θ_2, depends on the properties of the medium.



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.



More About Refraction

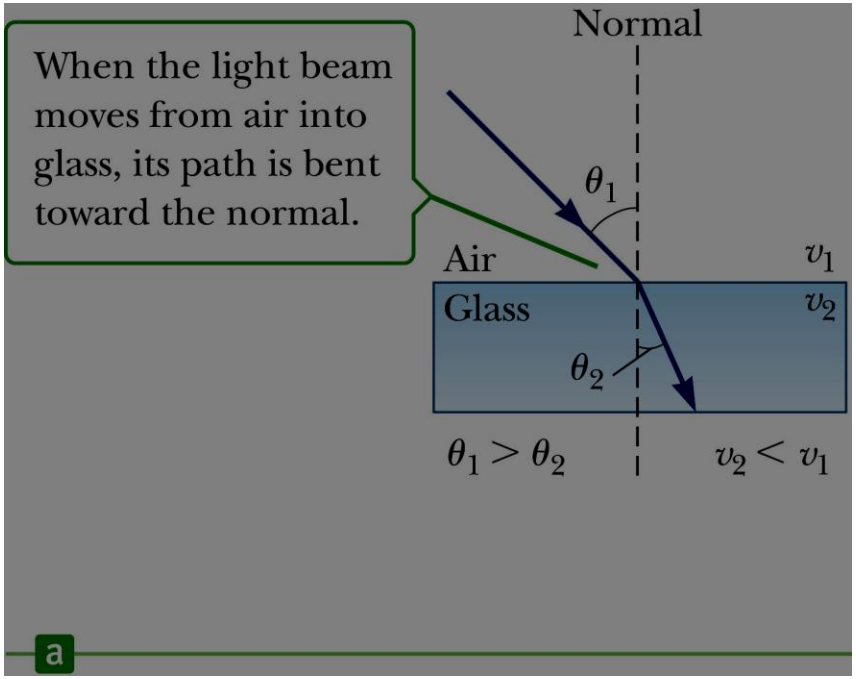
- The angle of refraction depends upon the material and the angle of incidence.

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

- The path of the light through the refracting surface is reversible.

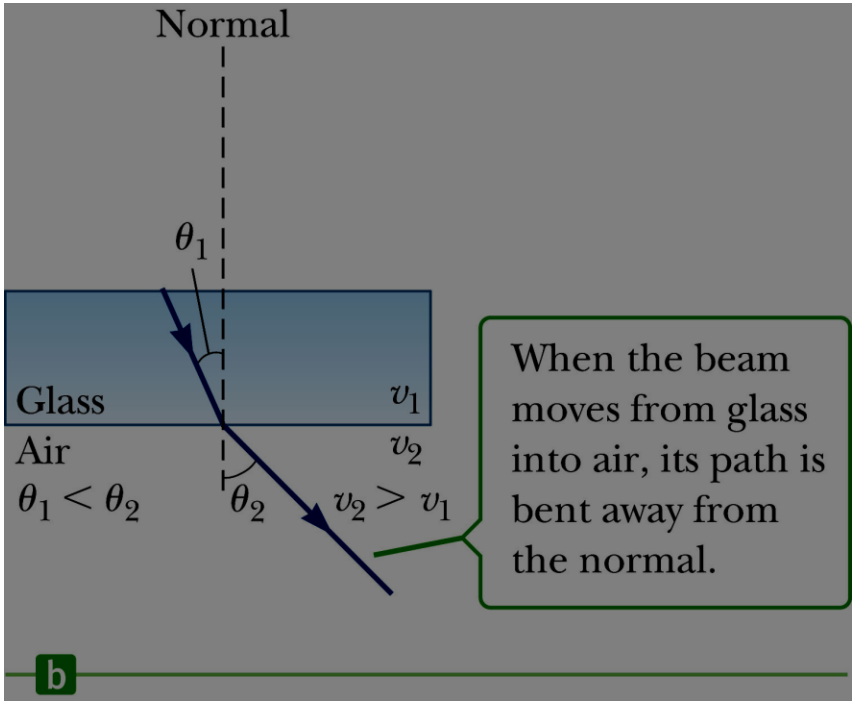
Refraction Details, 1

- Light may move from a material where its speed is high to a material where is 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 move from a material where its speed is low to a material where is speed is higher.
- The angle of refraction is greater than the angle of incidence.
  - –The ray bends *away from* the normal.



The Index of Refraction

- When light passes from one medium to another, it is refracted because the speed of light is different in the two media.
- The *index of refraction, n,* of a medium can be defined

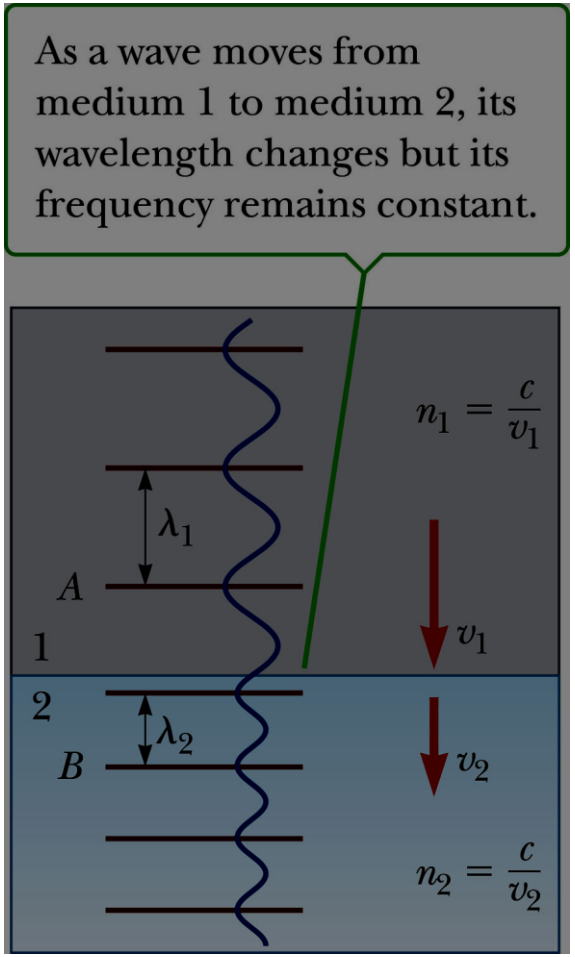
$$n \equiv \frac{\text{speed of light in a vacuum}}{\text{speed of light in a medium}} = \frac{c}{v}$$

Index of Refraction, Cont.

- Some values of n
  - For a vacuum, n = 1
  - For other media, n > 1
- n is a unitless ratio
- As the value of n increases, the speed of the wave decreases.

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 ƒ must stay the same.



Index of Refraction Extended

- The frequency stays the same as the wave travels from one medium to the other.
- $v = f \lambda$
- The ratio of the indices of refraction of the two media can be expressed as various ratios.

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

Some Indices of Refraction

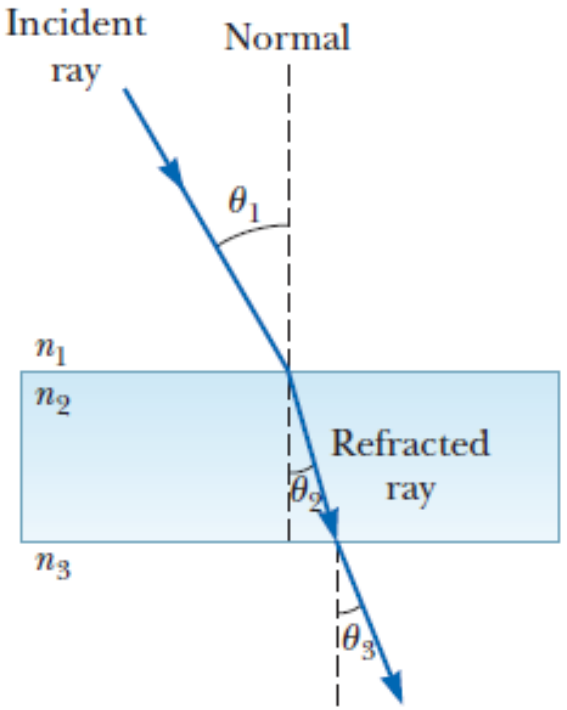
Table 22.1 Indices of Refraction for Various Substances, Measured with Light of Vacuum Wavelength $\lambda_0 = 589$ mn

Substance	Index of Refraction	Substance	Index of Refraction
Solids at 20°C		**Liquids at 20°C**	
Diamond (C)	2.419	Benzene	1.501
Fluorite (CaF_2)	1.434	Carbon disulfide	1.628
Fused quartz (SiO_2)	1.458	Carbon tetrachloride	1.461
Glass, crown	1.52	Ethyl alcohol	1.361
Glass, flint	1.66	Glycerine	1.473
Ice (H_2O) (at 0°C)	1.309	Water	1.333
Polystyrene	1.49		
Sodium chloride (NaCl)	1.544	**Gases at 0°C, 1 atm**	
Zircon	1.923	Air	1.000 293
		Carbon dioxide	1.000 45

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 Willebrørd Snell (1591 – 1626).

PROBLEM A light ray of wavelength 589 nm (produced by a sodium lamp) traveling through air is incident on a smooth, flat slab of crown glass at an angle θ_1 of 30.0° to the normal, as sketched in Figure 22.11. (a) Find the angle of refraction, θ_2. (b) At what angle θ_3 does the ray leave the glass as it re-enters the air? (c) How does the answer for θ_3 change if the ray enters water below the slab instead of the air?



$n_1 = 1.00$

$n_2 = 1.52$ $\quad n_1 \sin\theta_1 = n_2 \sin\theta_2$

$\therefore 1 \cdot \sin 30^\circ = 1.52 \sin\theta_2$

$\sin\theta_2 = \frac{0.5}{1.52}$, $\quad \theta_2 = \sin^{-1} 0.329 = 19.2^\circ$

$n_2 \sin\theta_2 = n_3 \sin\theta_3$ $\quad \theta_3$ is in air $n_3 = 1$

$\therefore 1.52 \sin 19.2 = 1.00 \sin\theta_3$

$\sin\theta_3 = \frac{1.52 \times \sin 19.2}{1.0} = 0.5$; $\therefore \theta_3 = 30.0^\circ$

If n_3 is water, $n_3 = 1.33$

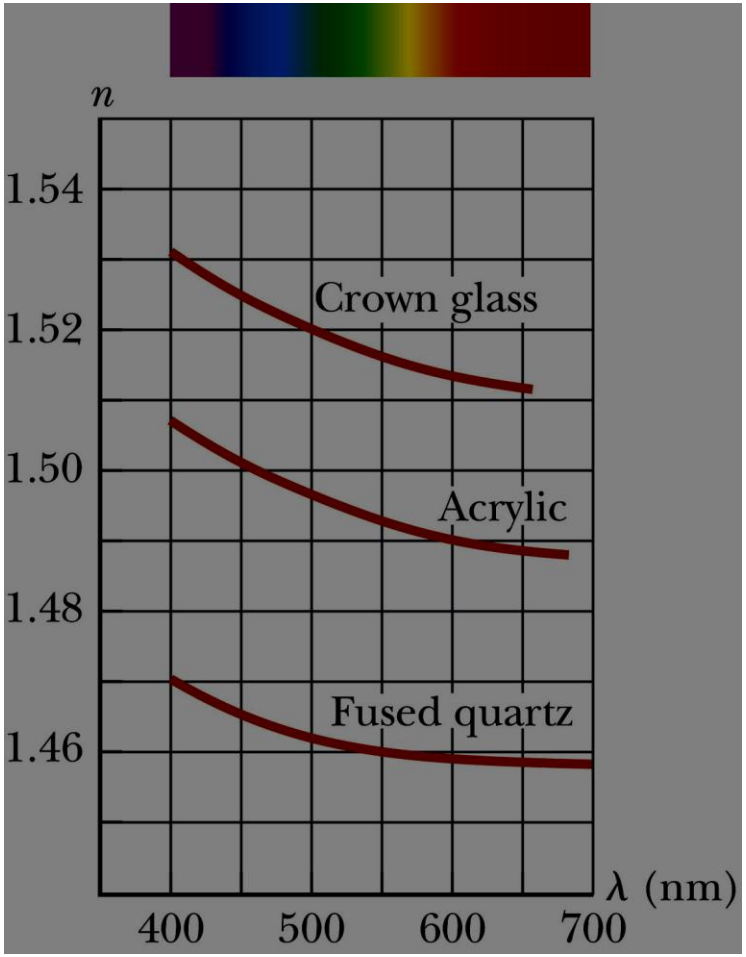
$\therefore \sin\theta_3 = n_2 \sin\theta_2 / 1.33 = 0.375$; $\theta_3 = 22.1^\circ$

Dispersion

- The index of refraction in anything except a vacuum depends on the wavelength of the light.
- This dependence of n on λ is called *dispersion.*
- Snell's Law indicates that the angle of refraction made when light enters a material depends on the wavelength of the light.

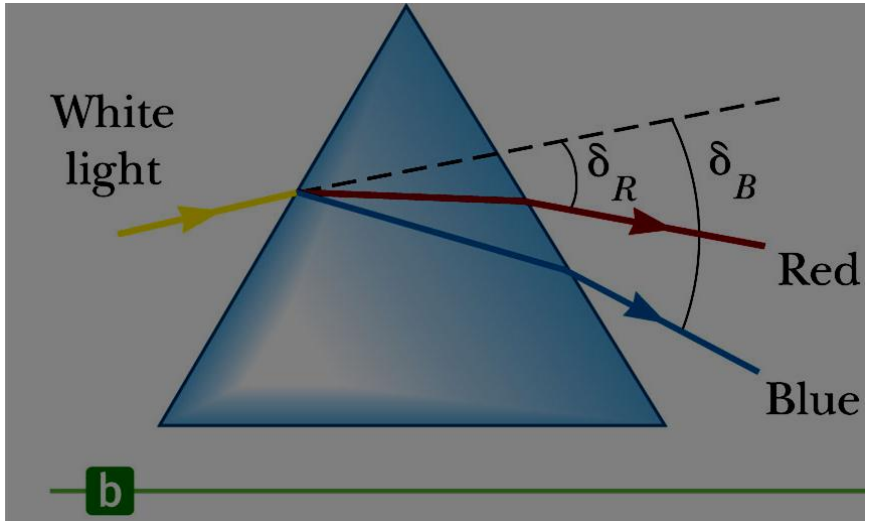
Variation of Index of Refraction with Wavelength

- The index of refraction for a material usually decreases with increasing wavelength.
- Violet light refracts more than red light when passing from air into a material.

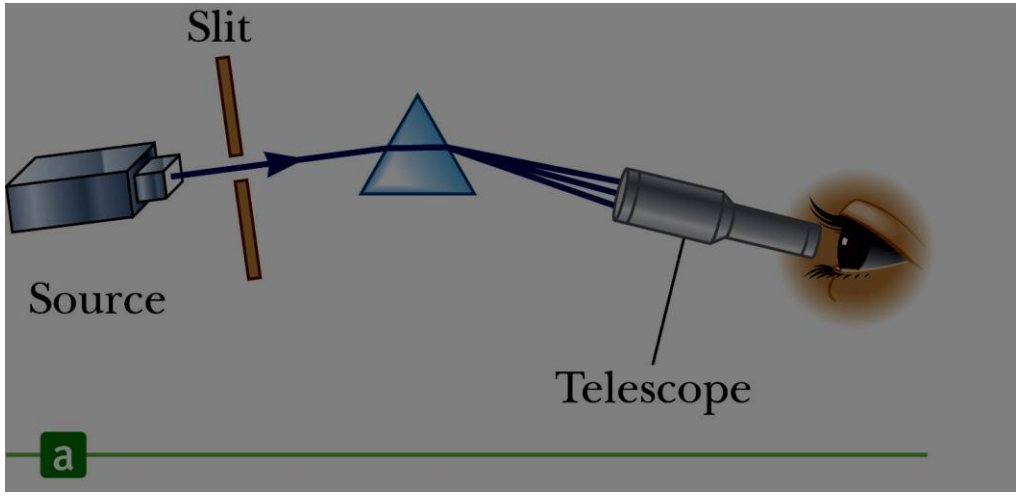


Refraction in a Prism

- The amount the ray is bent away from its original direction is called the *angle of deviation*, δ
- Since all the colors have different angles of deviation, they will spread out into a *spectrum.*
  - –Violet deviates the most.
  - –Red deviates the least.



Prism Spectrometer



- A prism spectrometer uses a prism to cause the wavelengths to separate.
- The instrument is commonly used to study wavelengths emitted by a light source.

Using Spectra to Identify Gases

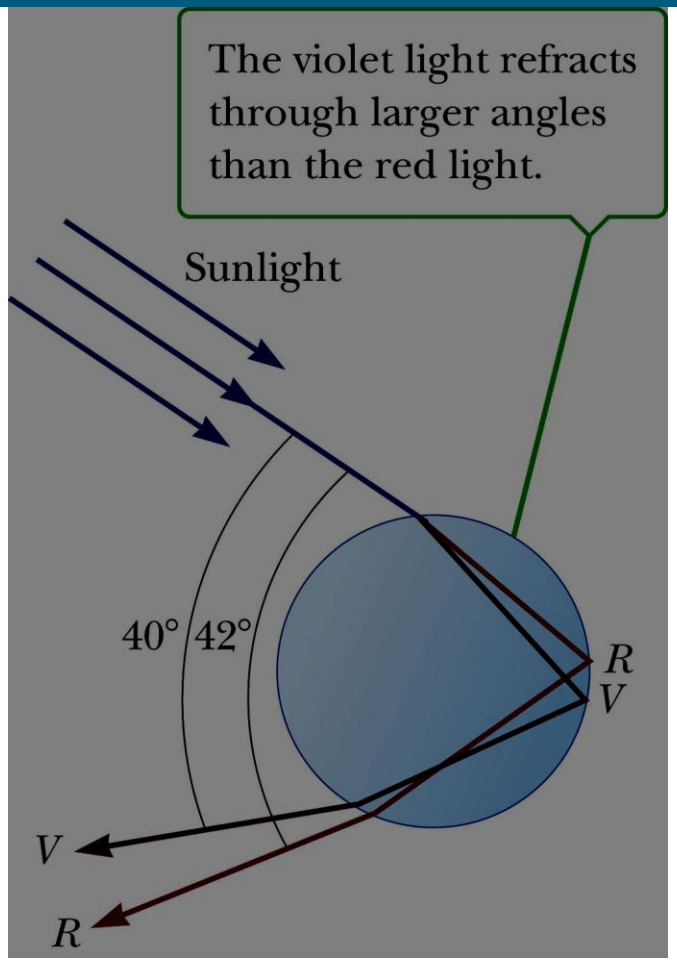
- All hot, low pressure gases emit their own characteristic spectra
- The particular wavelengths emitted by a gas serve as "fingerprints" of that gas.
- Some uses of spectral analysis
  - Identification of molecules
  - Identification of elements in distant stars
  - Identification of minerals

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.

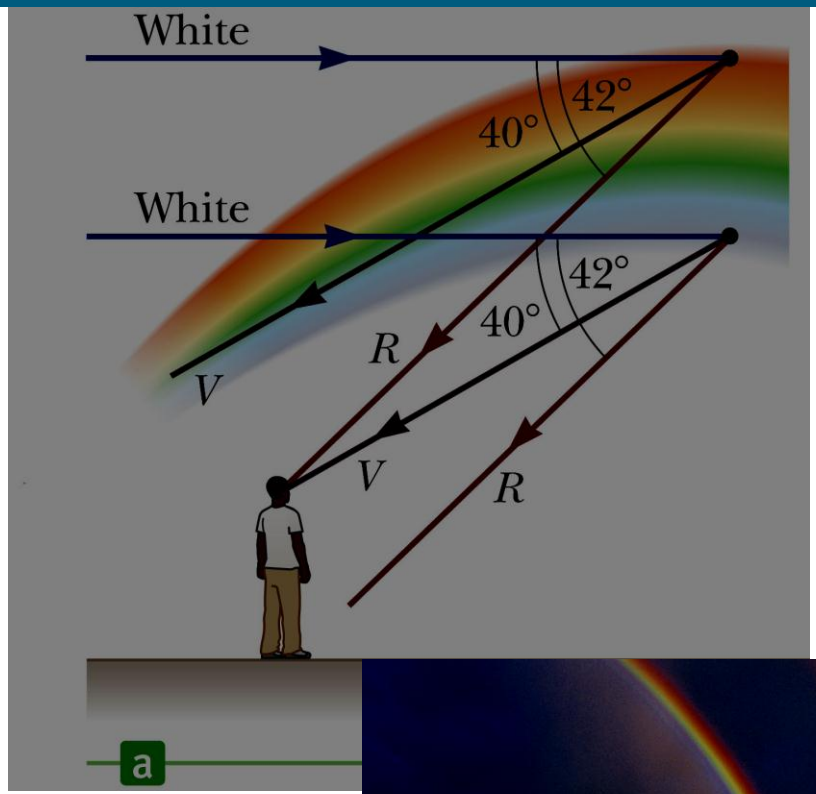
The Rainbow, 2

- 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 violet ray is 40°
  - The angle between the white light and the red ray is 42°



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.



Christian Huygens

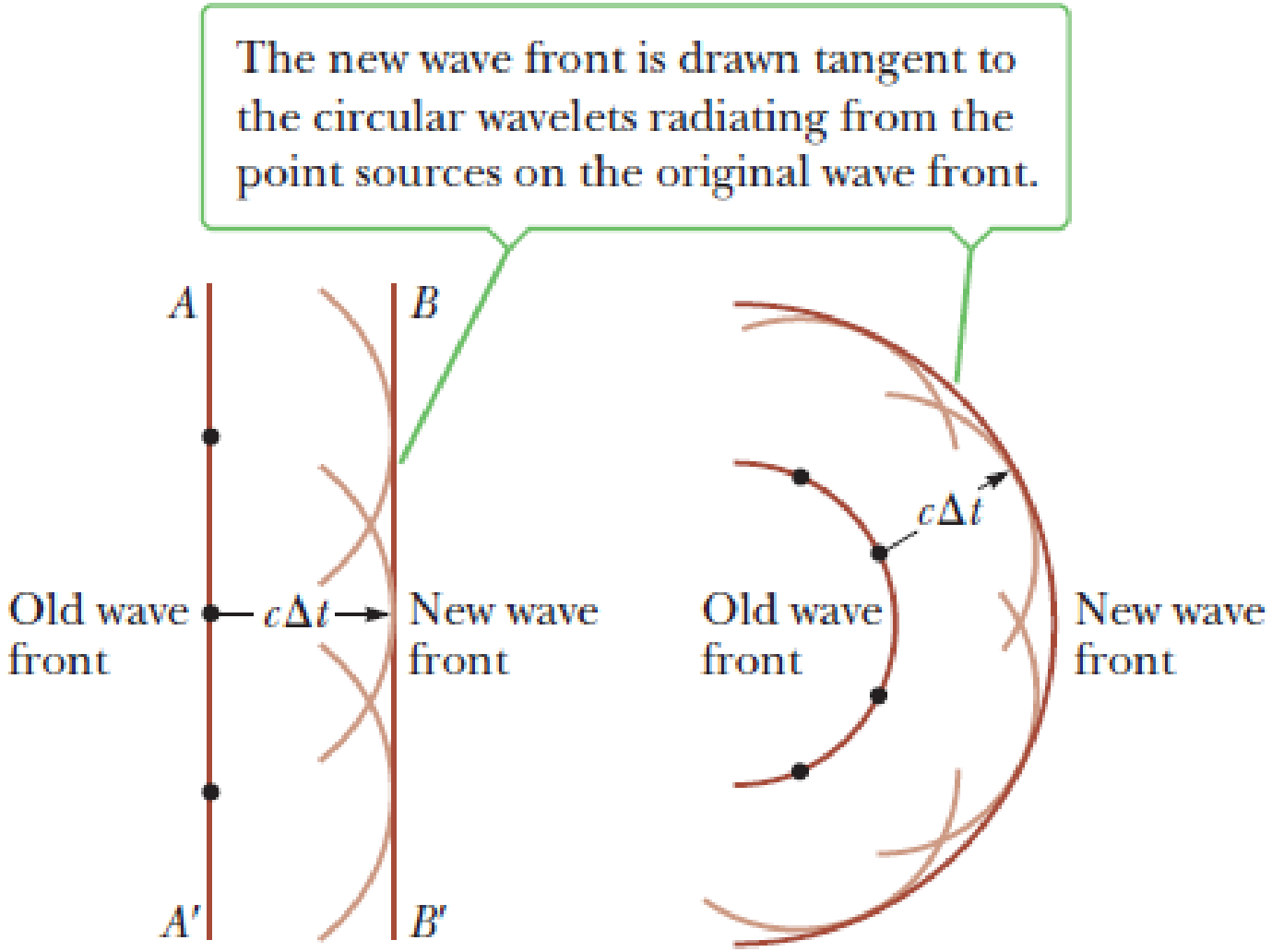
- 1629 – 1695
- Best known for contributions to fields of optics and dynamics
- Deduced the laws of reflection and refraction
- Explained double refraction

Huygen's Principle

- Huygen assumed that light is a form of wave motion rather than a stream of particles.
- Huygen'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.

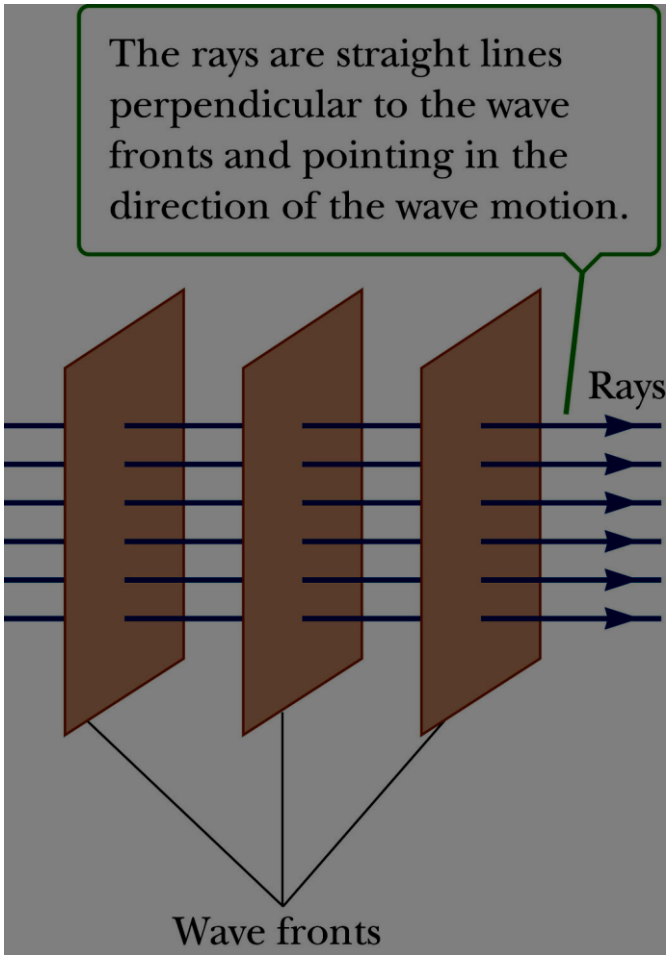
Huygen's Principle, Cont.

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


The new wave front is drawn tangent to the circular wavelets radiating from the point sources on the original wave front.
A
B
A′
B′
Old wave front
cΔt
New wave front
cΔt
Old wave front
New wave front

Huygen's Construction for a Plane Wave

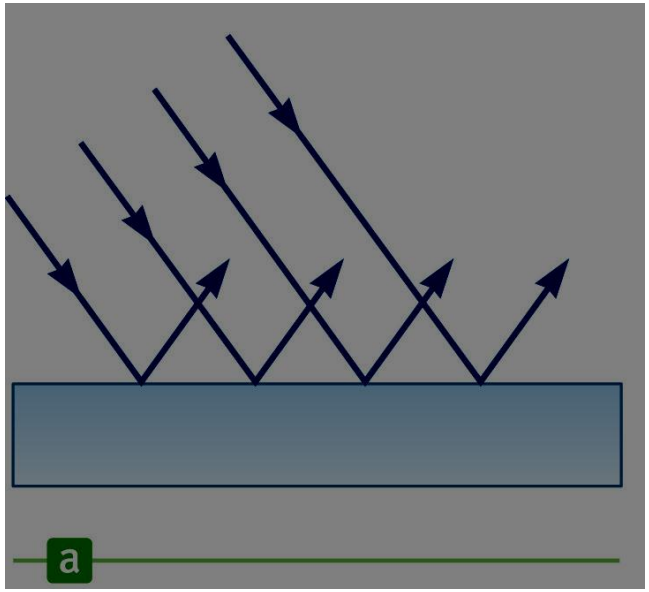
- At t = 0, the wave front is indicated by the plane AA'
- The points are representative sources for the wavelets.
- After the wavelets have moved a distance cΔt, a new plane BB' can be drawn tangent to the wavefronts.



Huygen's Construction for a Spherical Wave

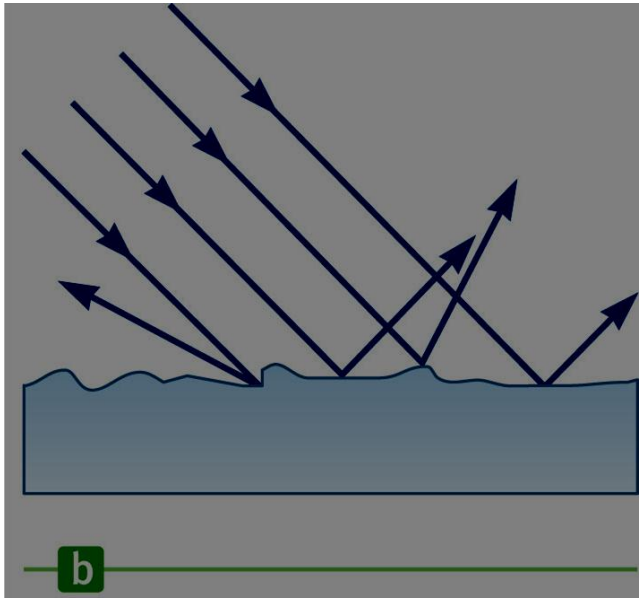
- The inner arc represents part of the spherical wave.
- The points are representative points where wavelets are propagated.
- The new wavefront is tangent at each point to the wavelet.

Huygen's Principle and the Law of Reflection

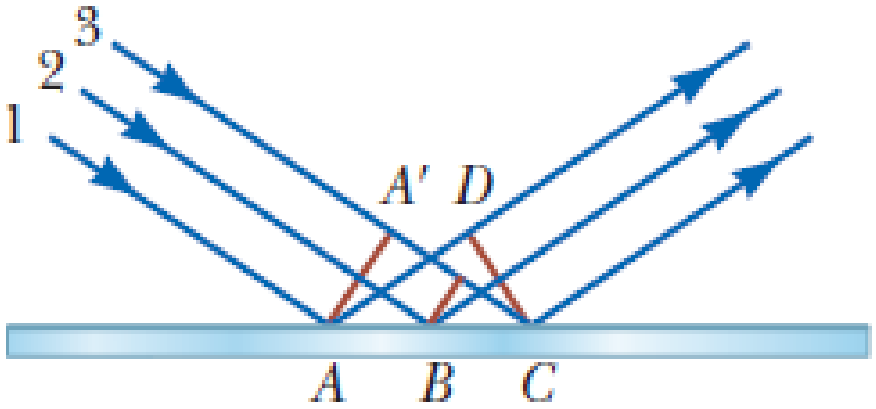


- The Law of Reflection can be derived from Huygen's Principle.
- AA' is a wave front of incident light.
- The reflected wave front is CD.

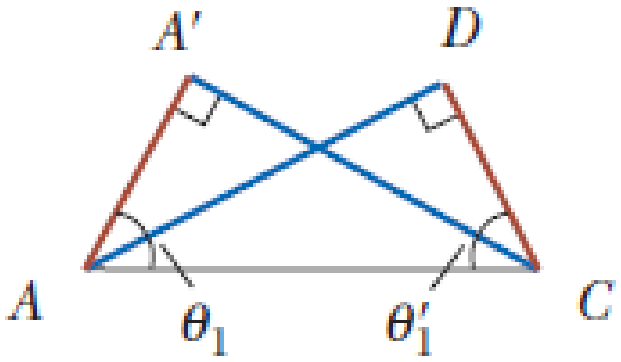
Huygen's Principle and the Law of Reflection, Cont.



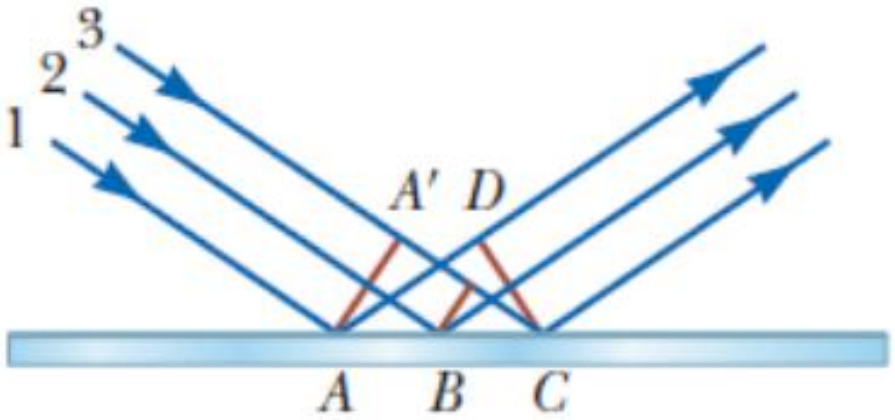
- Triangle ADC is congruent to triangle AA'C.
- $\theta_1 = \theta_1'$
- This is the Law of Reflection.



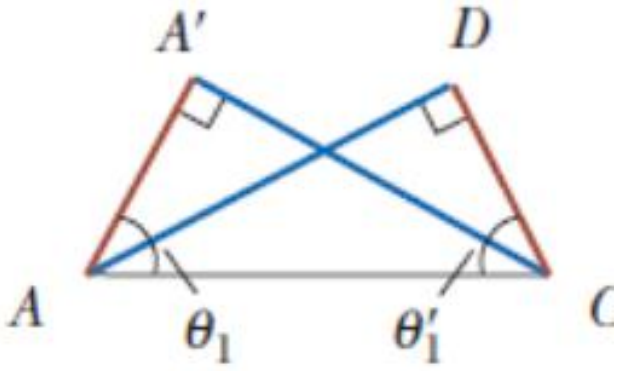
a



b



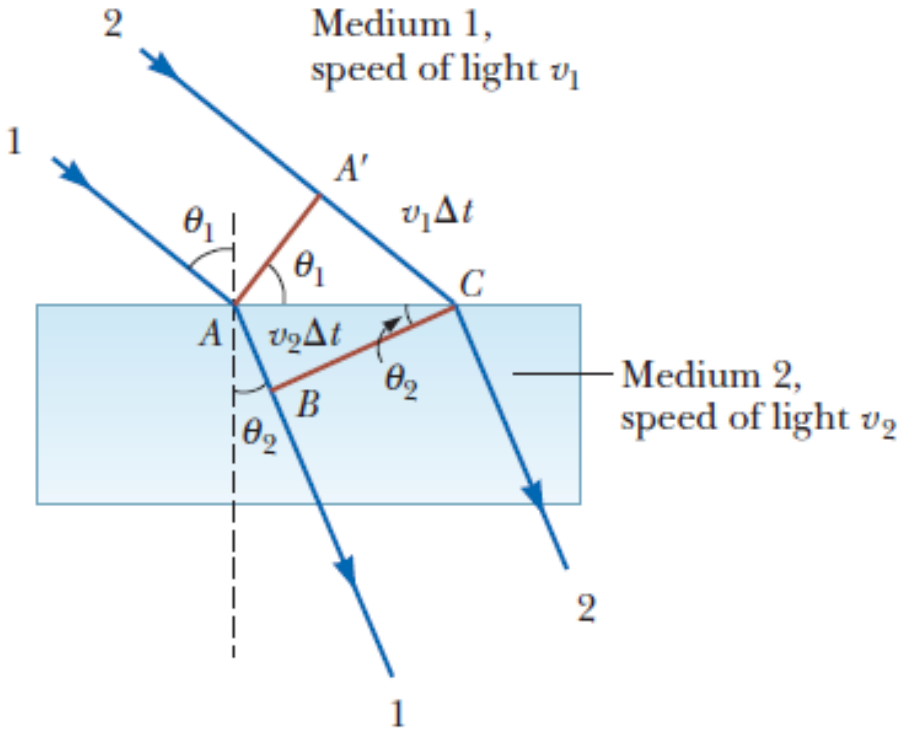
a

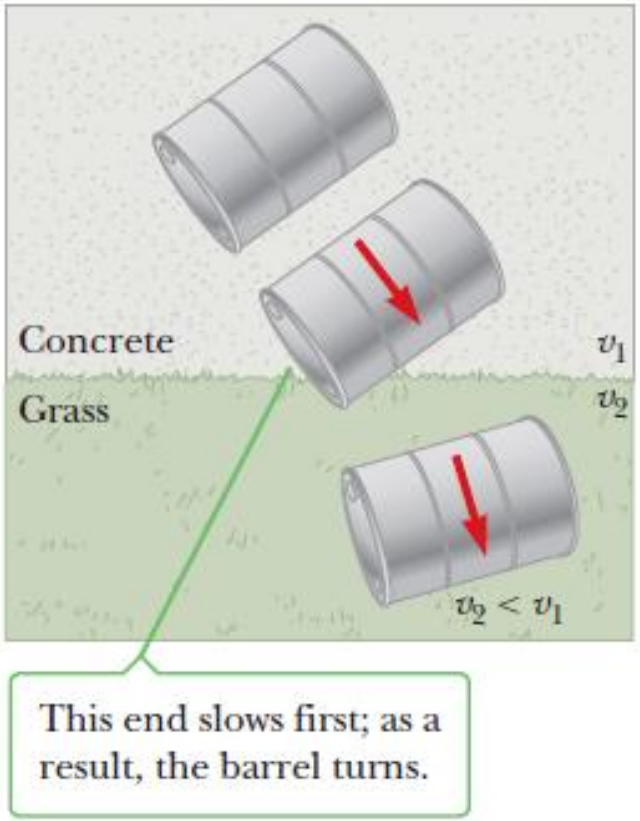


b

$\sin\theta_1 = A'C/AC$; $\sin\theta_2 = AD/AC$

Since $A'C = AD$, $\sin\theta_1 = \sin\theta_2$ or $\theta_1 = \theta_2$


2
Medium 1,
speed of light v_1
1
A'
$v_1\Delta t$
θ_1
θ_1
C
A
$v_2\Delta t$
θ_2
Medium 2,
speed of light v_2
B
θ_2
2
1


Concrete
v_1
Grass
v_2
$v_2 < v_1$
This end slows first; as a result, the barrel turns.

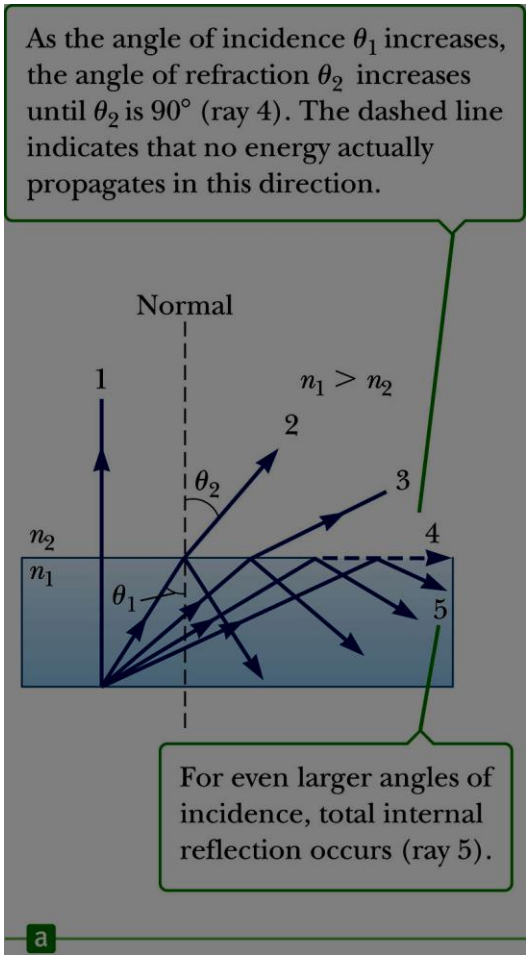
Huygen's Principle and the Law of Refraction

- In time Δt, ray 1 moves from A to B and ray 2 moves from A' to C.
- From triangles AA'C and ACB, all the ratios in the Law of Refraction can be found.
  - $n_1 \sin \theta_1 = n_2 \sin \theta_2$

Total Internal Reflection

- *Total internal reflection* can occur when light attempts to move from a medium with a higher index of refraction to one with a lower index of refraction.

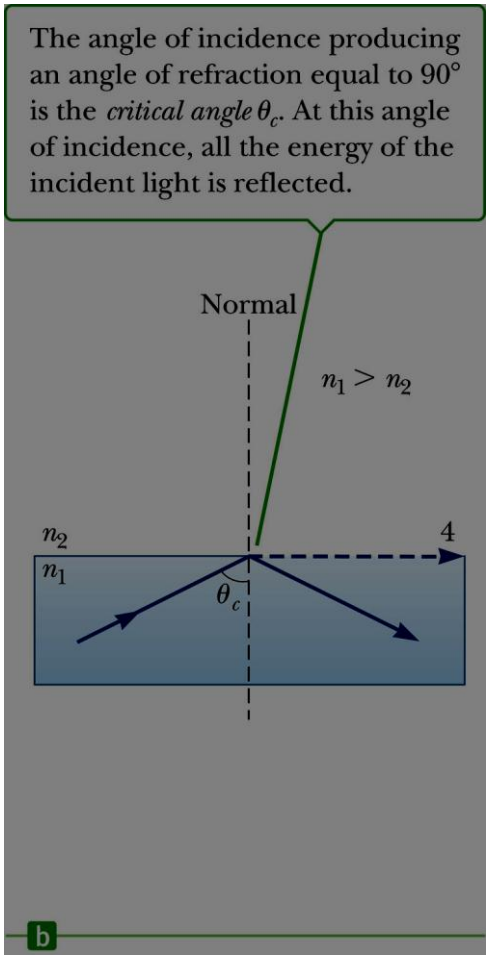
–Ray 5 shows internal reflection



Critical Angle

- A particular angle of incidence will result in an angle of refraction of 90°
  - –This angle of incidence is called the *critical angle.*

$$\sin\theta_c = \frac{n_2}{n_1} \quad \text{for } n_1 > n_2$$



Courtesy of Henry Leap and Jim Lehman

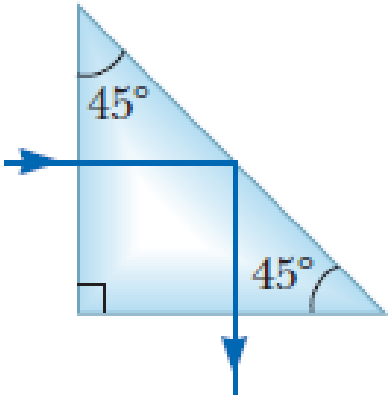
This photograph shows nonparallel light rays entering a glass prism. The bottom two rays undergo total internal reflection at the longest side of the prism. The top three rays are refracted at the longest side as they leave the prism.

Critical Angle, Cont.

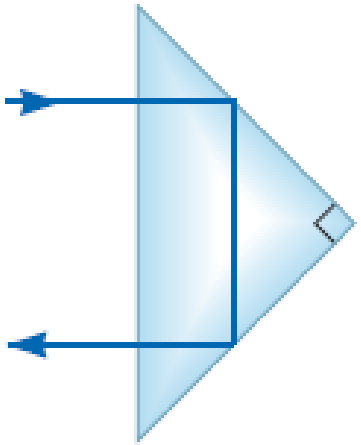
- For angles of incidence *greater* than the critical angle, the beam is entirely reflected at the boundary.
  - This ray obeys the Law of Reflection at the boundary.
- Total internal reflection occurs only when light is incident on the boundary of a medium having a lower index of refraction than the medium in which it is traveling.

$$n_1 \sin \theta_c = n_2 \sin 90^\circ = n_2$$

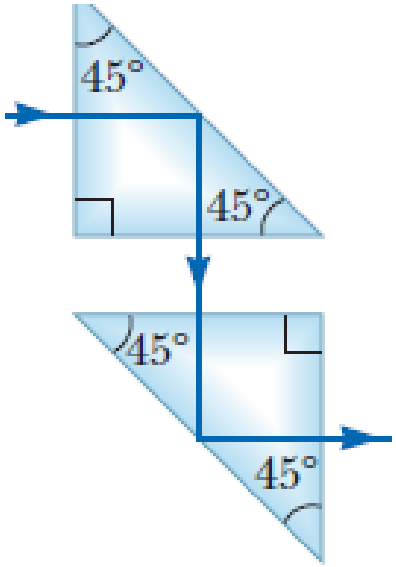
$$\sin \theta_c = \frac{n_2}{n_1} \qquad \text{for } n_1 > n_2$$



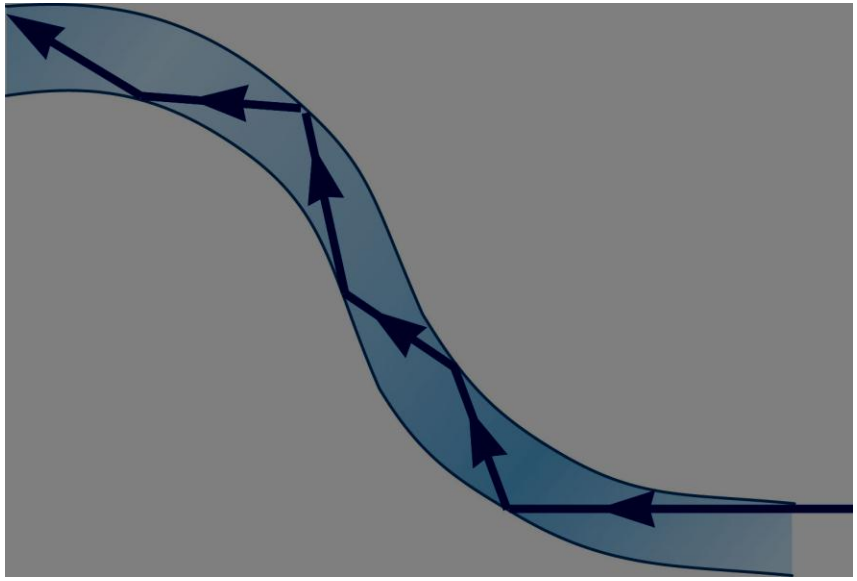
a



b



c

Fiber Optics

- An application of internal reflection
- Plastic or glass rods are used to “pipe” light from one place to another.
- Applications include
  - Medical use of fiber optic cables for diagnosis and correction of medical problems
  - Telecommunications