Lecture 7

Chapter 22 Reflection and refraction of light

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

Light

* Wave or particle?

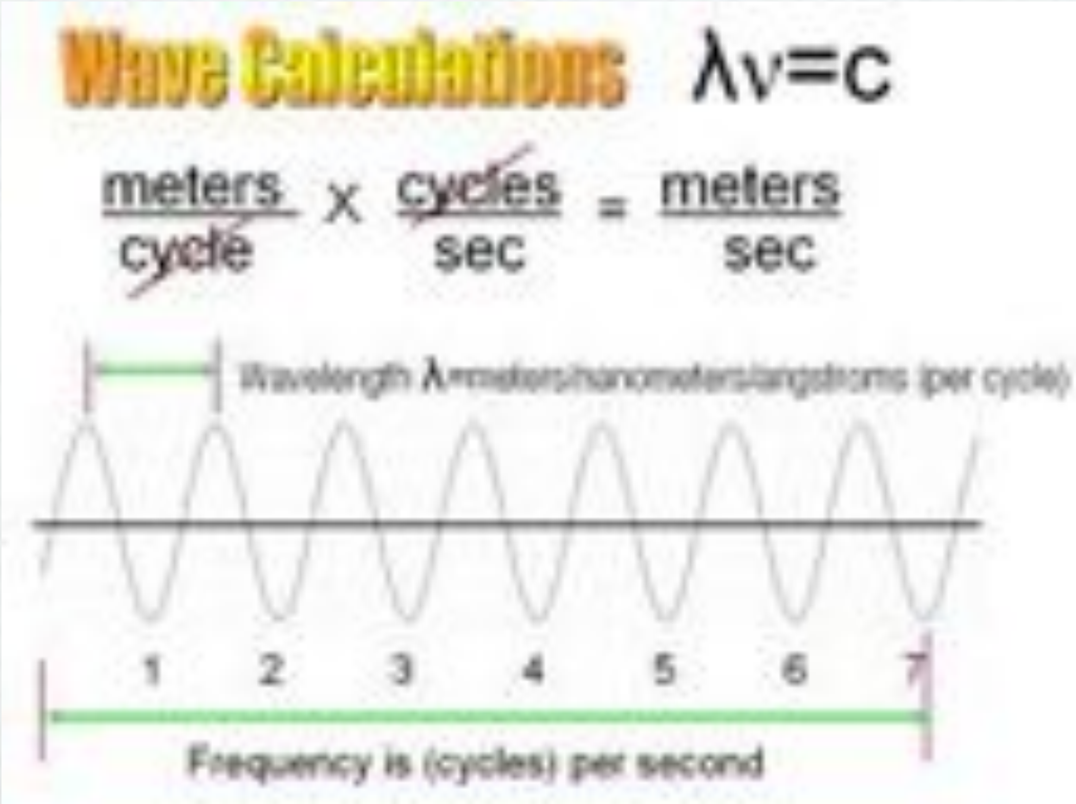
Dual Nature of Light

- 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.

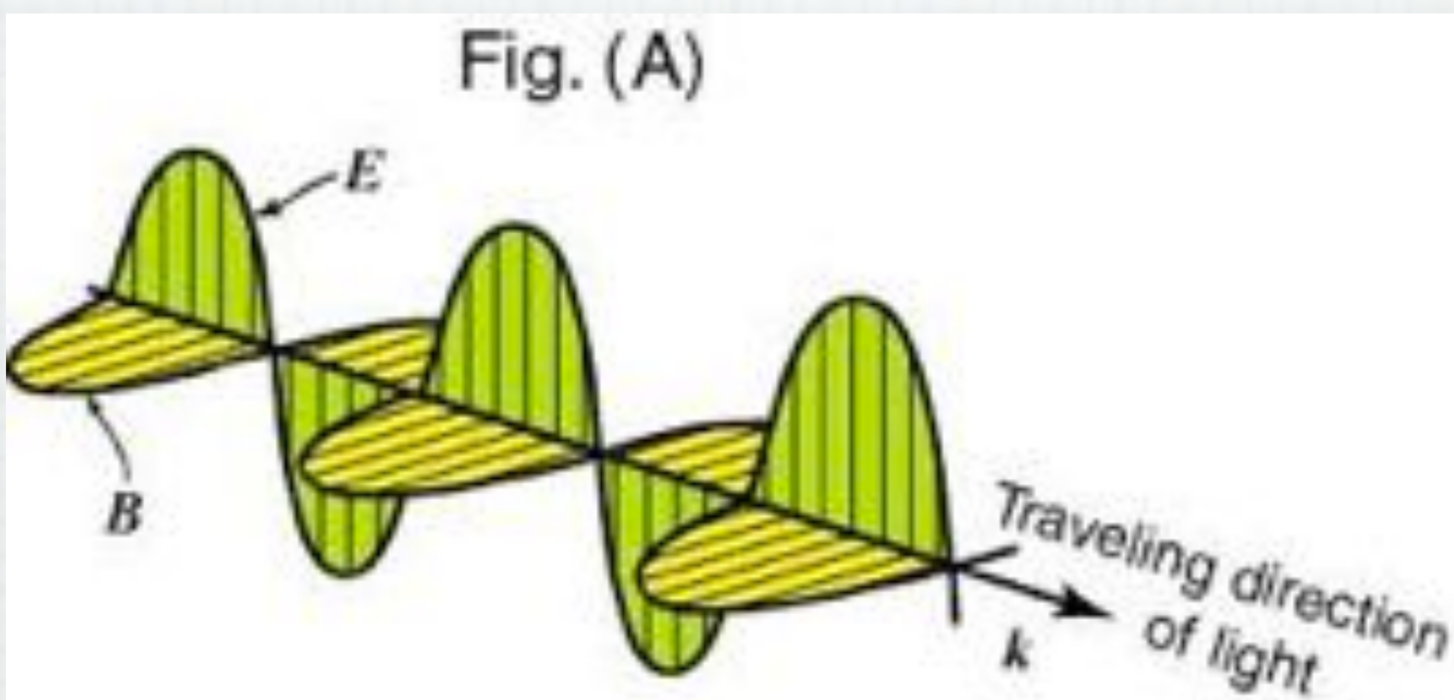
Light acts like a wave or a particle

The wave nature requires $\lambda f = c$

where c is the speed of light or 3 x 10^8 m/s



Light propagates as a wave



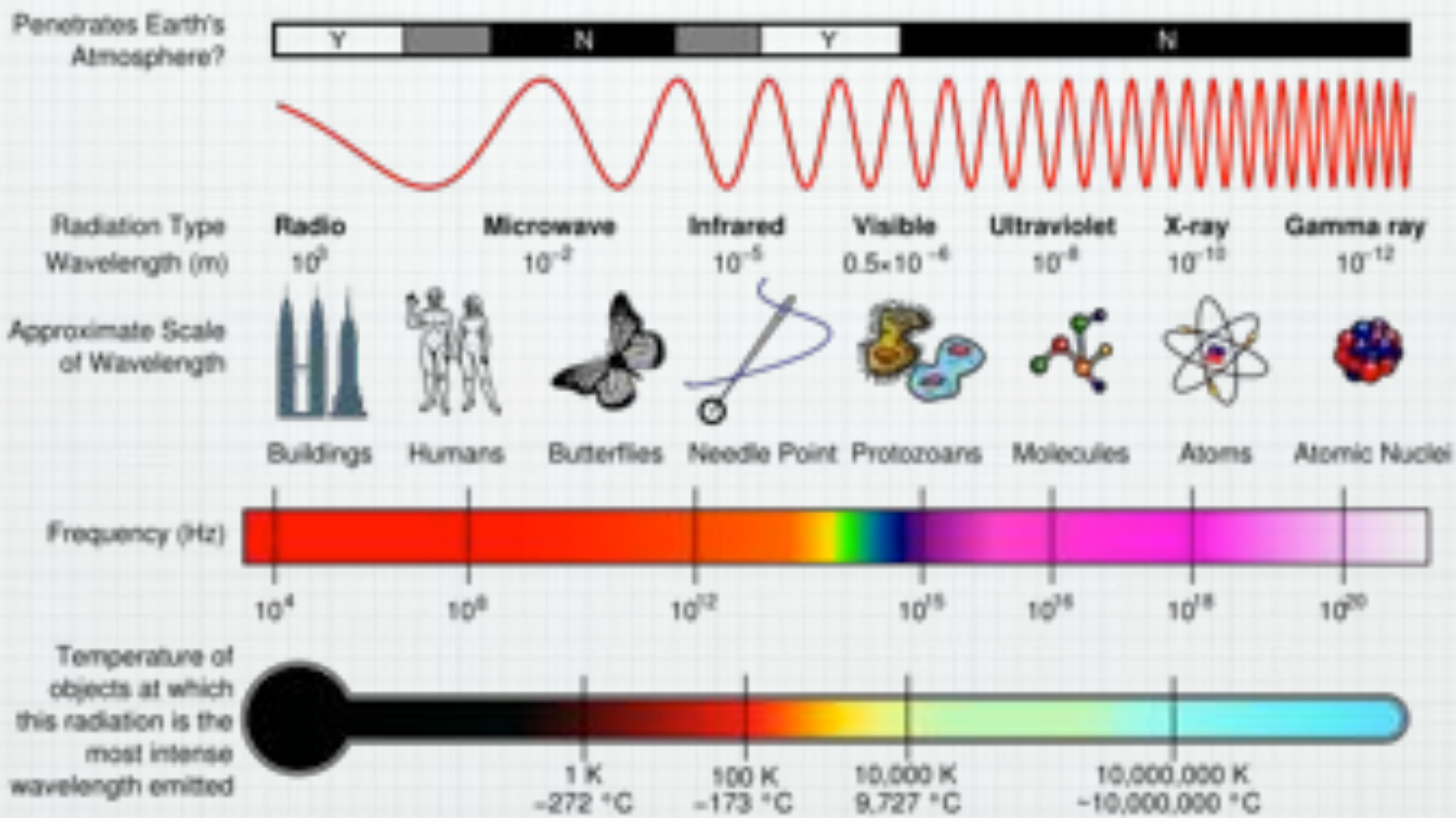
Light also behaves like a particle

The Particle Nature of Light

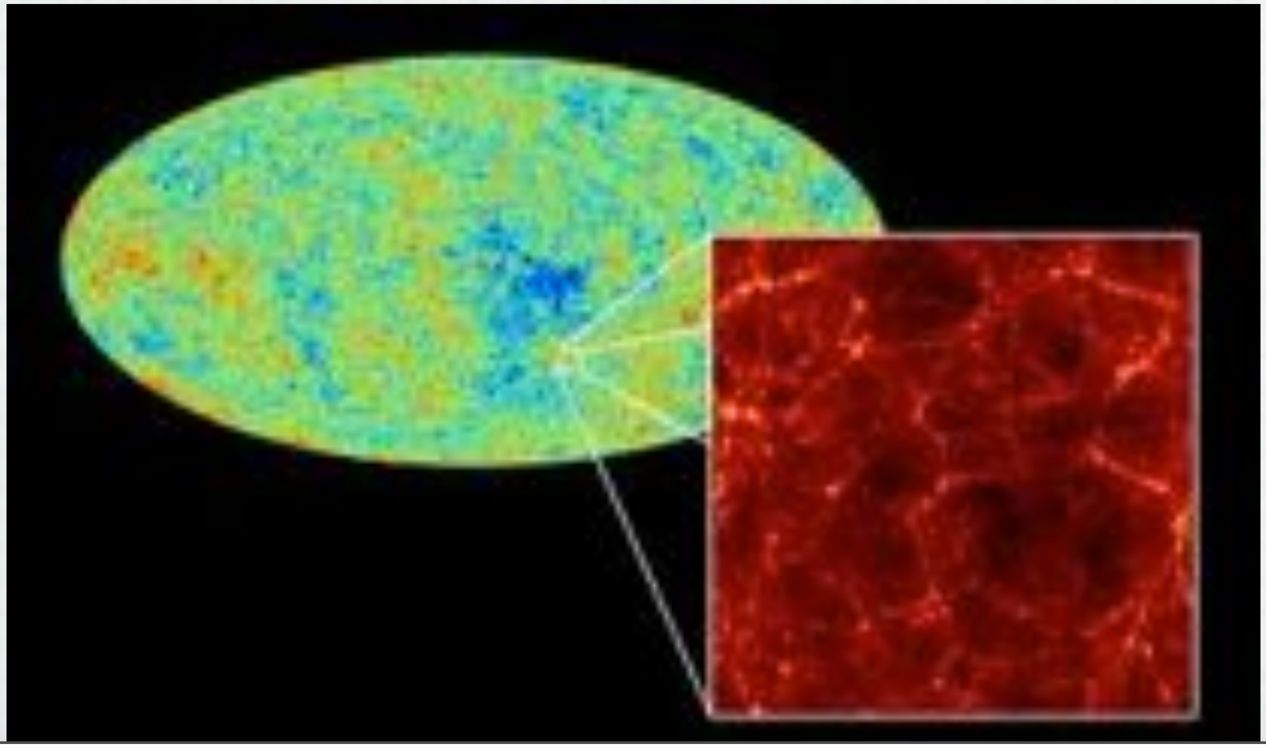
- "Particles" of light are called *photons.*
- Each photon has a particular energy.
  - $E = h f$
  - h is *Planck's constant*
    - $h = 6.63 \times 10^{-34}$ J s
  - Encompasses both natures of light
    - Interacts like a particle
    - Has a given frequency like a wave

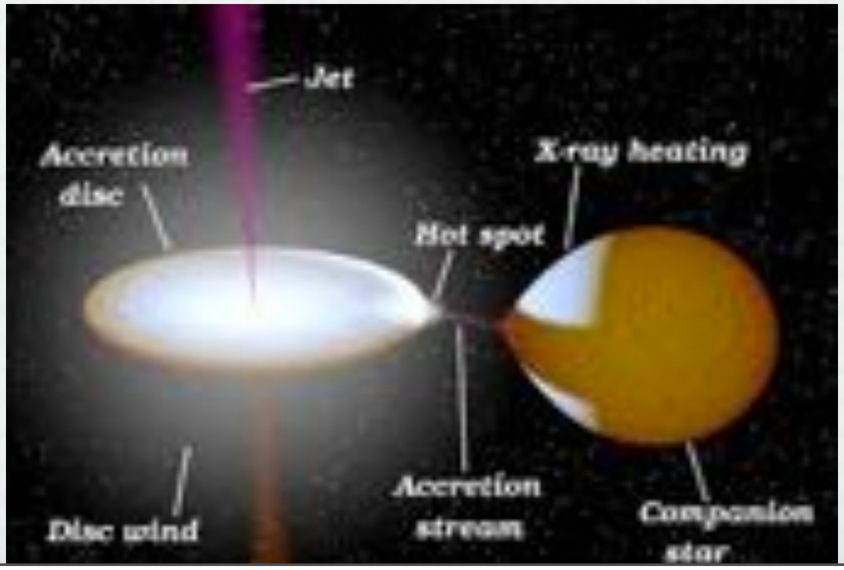
Shorter wavelength or higher frequency

* Means more energy



All objects emit light, even you
The wavelength emitted depends on the temperature





According to the photon energy formula, tripling the frequency of the radiation from a monochromatic source will change the energy content of the individually radiated photons by what factor?

a.0.33
b.1.0
c.1.73
d.3.0

Tripling the wavelength of the radiation from a monochromatic source will change the energy content of the individually radiated photons by what factor?

a.0.33
b.1.0
c.1.73
d.3.0

Photon A has an energy of 2.0×10^{-19} J. Photon B has 4 times the frequency of Photon A. What is the energy of Photon B?

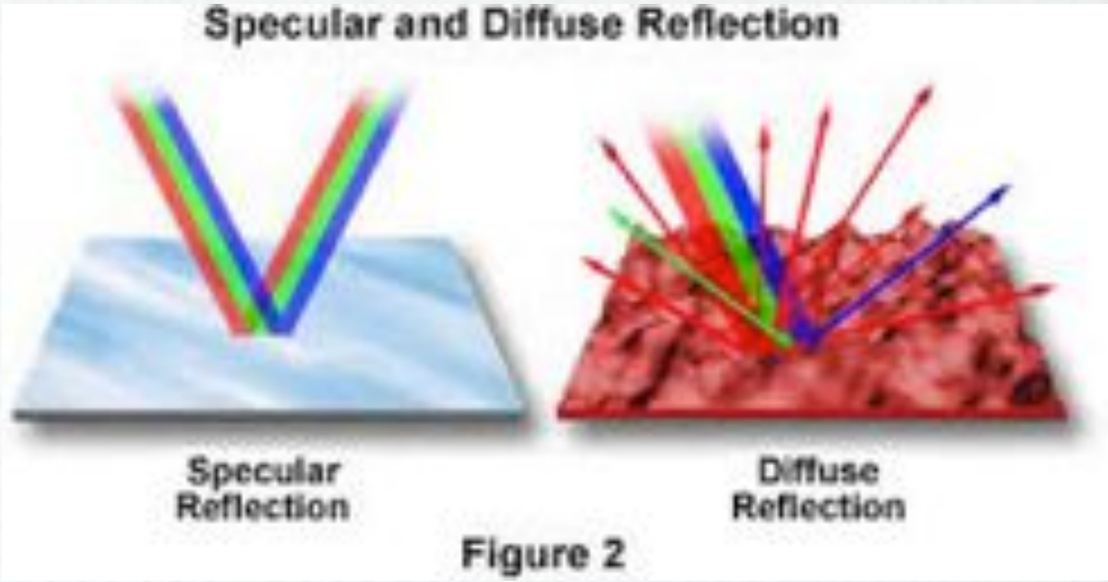
a.0.50×10^{-19} J
b.1.0×10^{-19} J
c.8.0×10^{-19} J
d.32×10^{-19} J

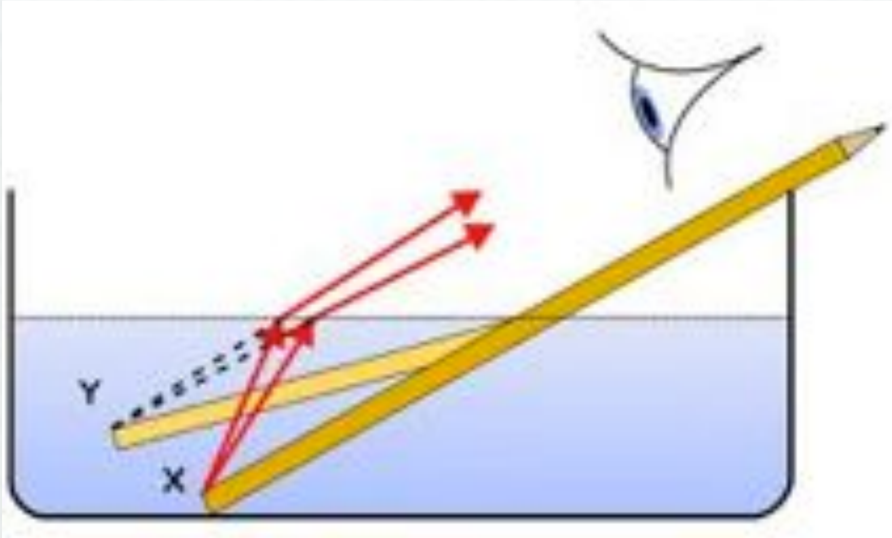
Reflection and Refraction

- 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.

Section 22.2

Bouncing/Bending



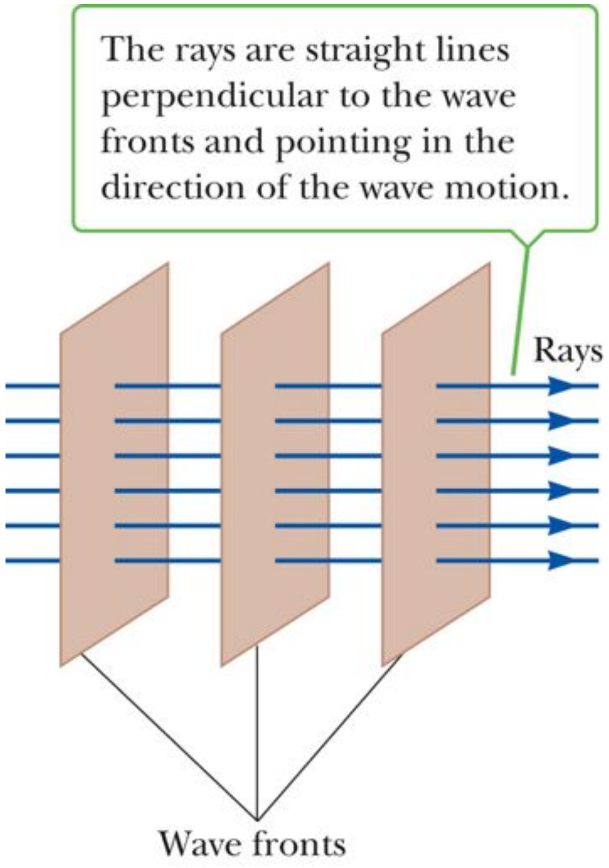


Geometric Optics – Using a Ray Approximation

- 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.



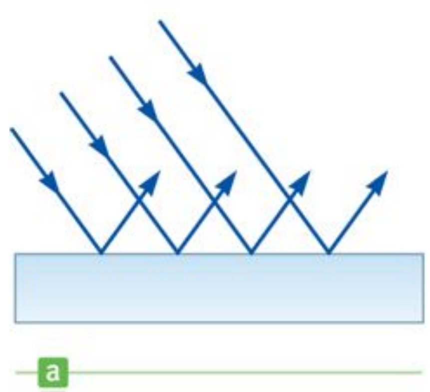
Reflection of Light

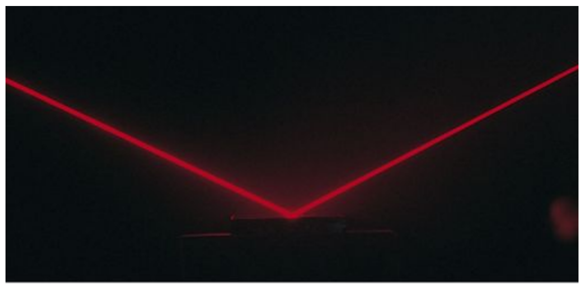
- A ray of light, the *incident ray*, travels in a medium.
- When it encounters a boundary with a second medium, part of the incident ray is *reflected* back into the first medium.
  - This means it is directed backward into the first medium.

Section 22.2

Specular Reflection

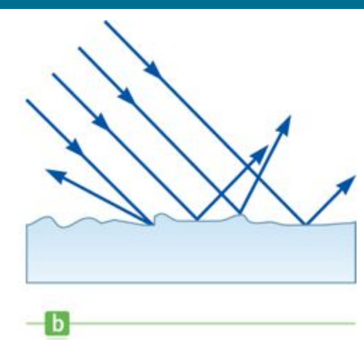
- *Specular reflection* is reflection from a smooth surface.
- The reflected rays are parallel to each other.
- All reflection in this text is assumed to be specular.

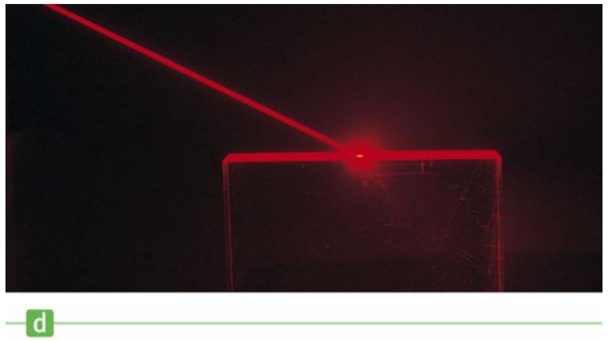




Diffuse Reflection

- *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.

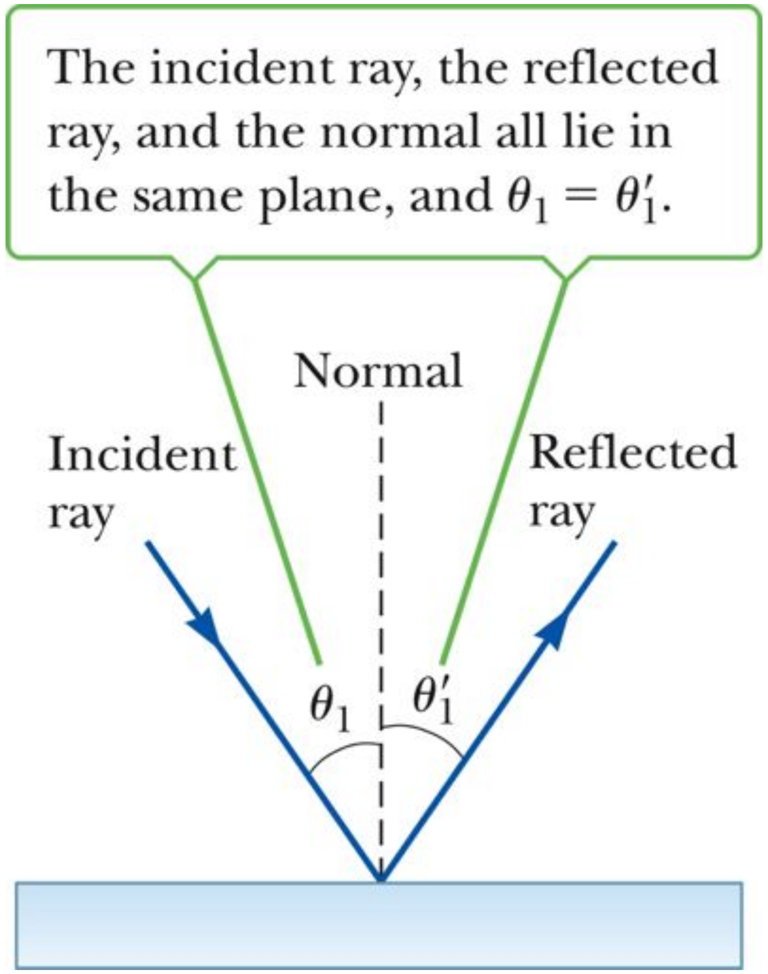




Section 22.2

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.
- $\theta_1 = \theta_1'$

As the angle of incidence is increased for a ray incident on a reflecting surface, the angle between the incident and reflected rays ultimately approaches what value?

a.zero

b.45°

c.90°

d.180°

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.*

Section 22.2

The index of refraction of light is given by n

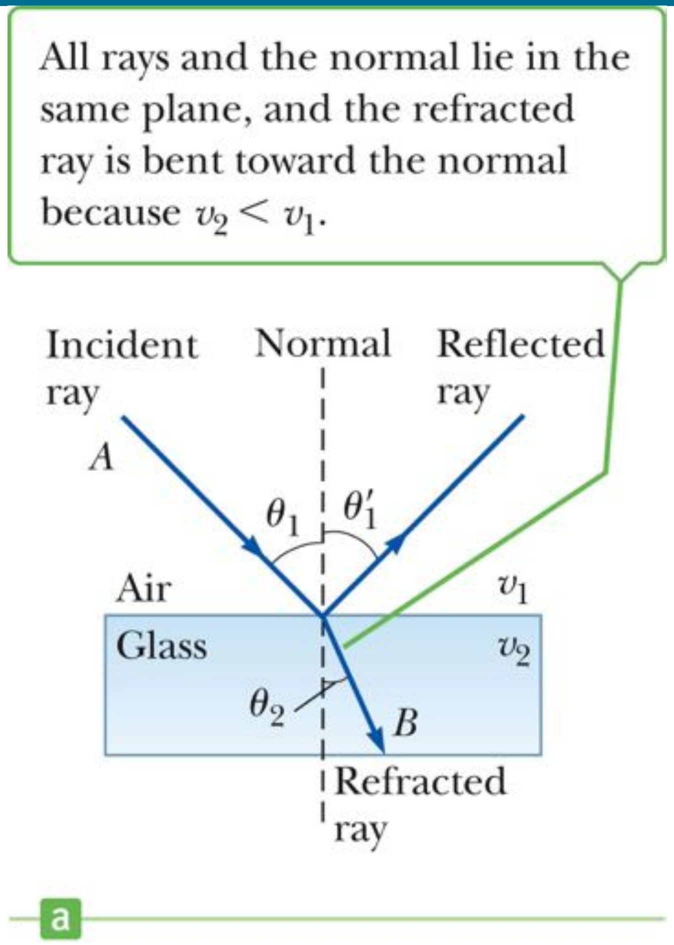
The Index of Refraction

- 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

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

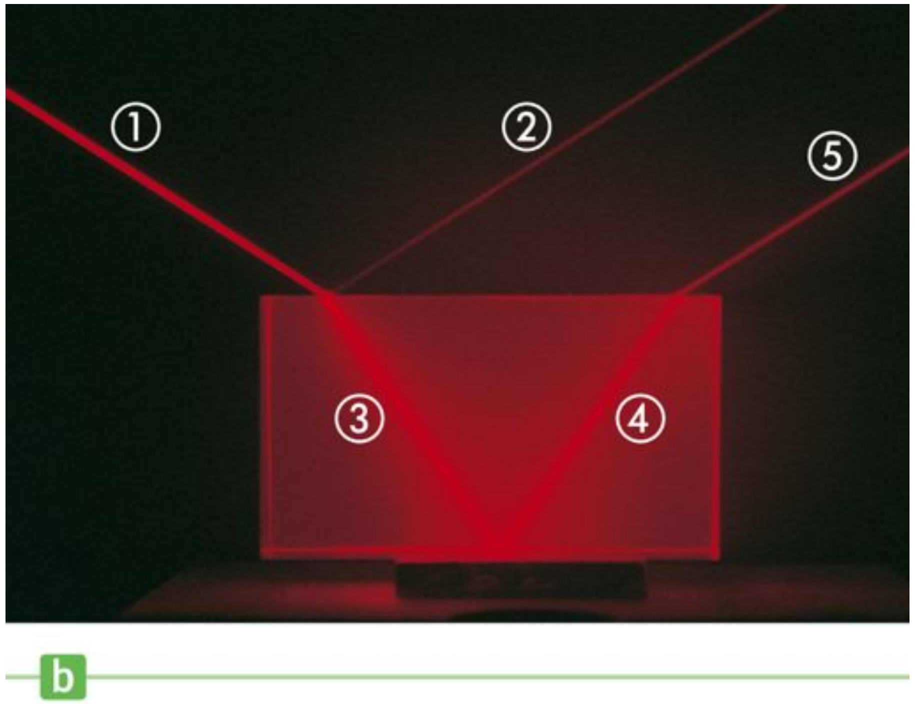
Refraction of Light, Cont.

- 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.

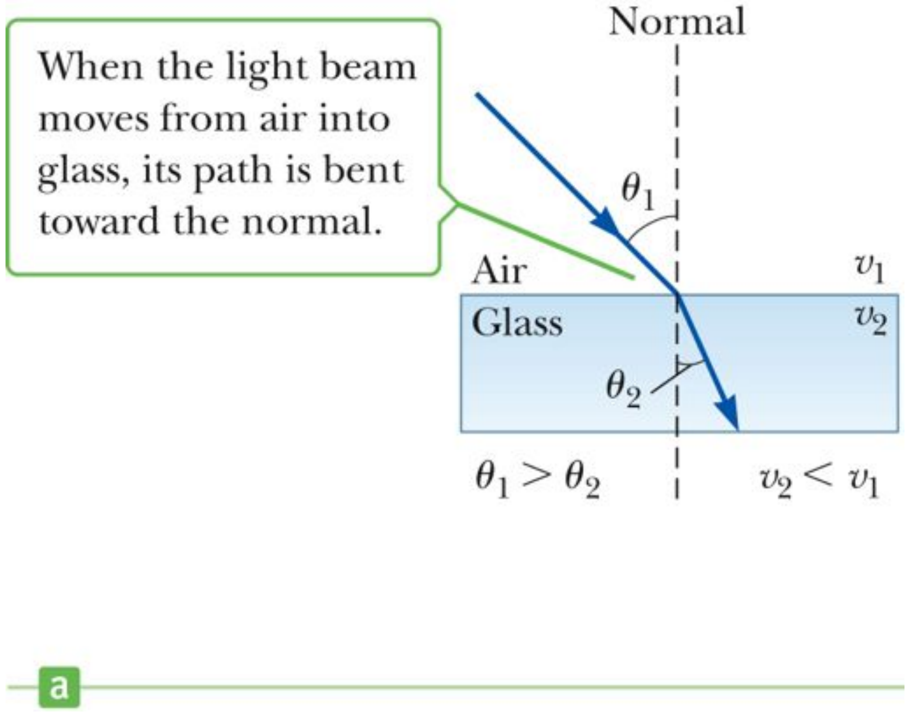
or $$n_1 sin(\theta_1) = n_2 sin(\theta_2)$$

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).

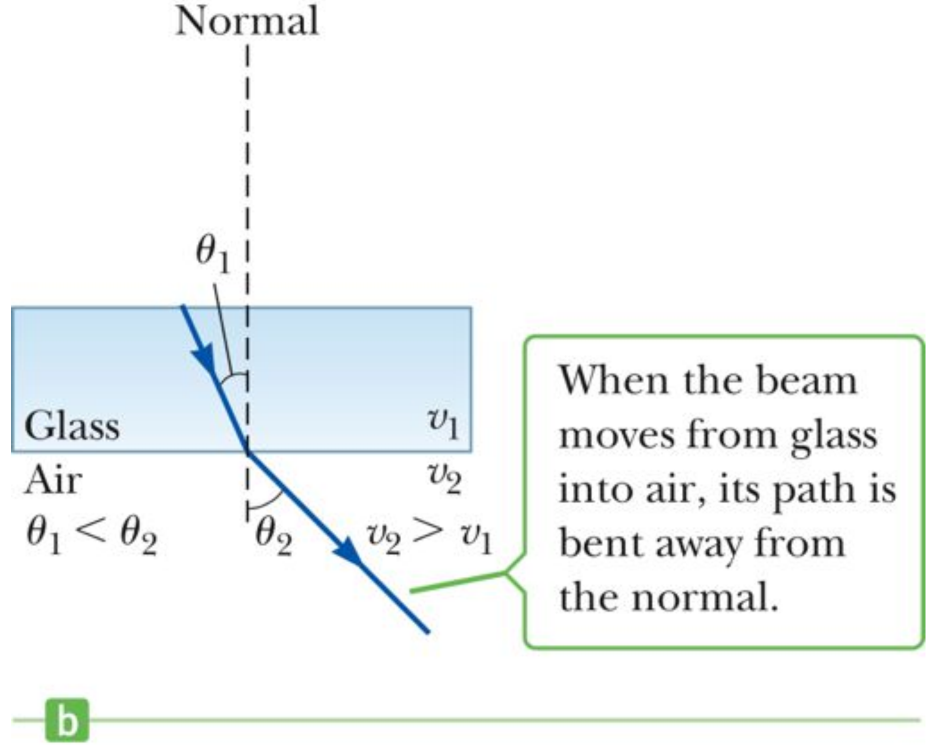
Refraction Details, 1

- 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.

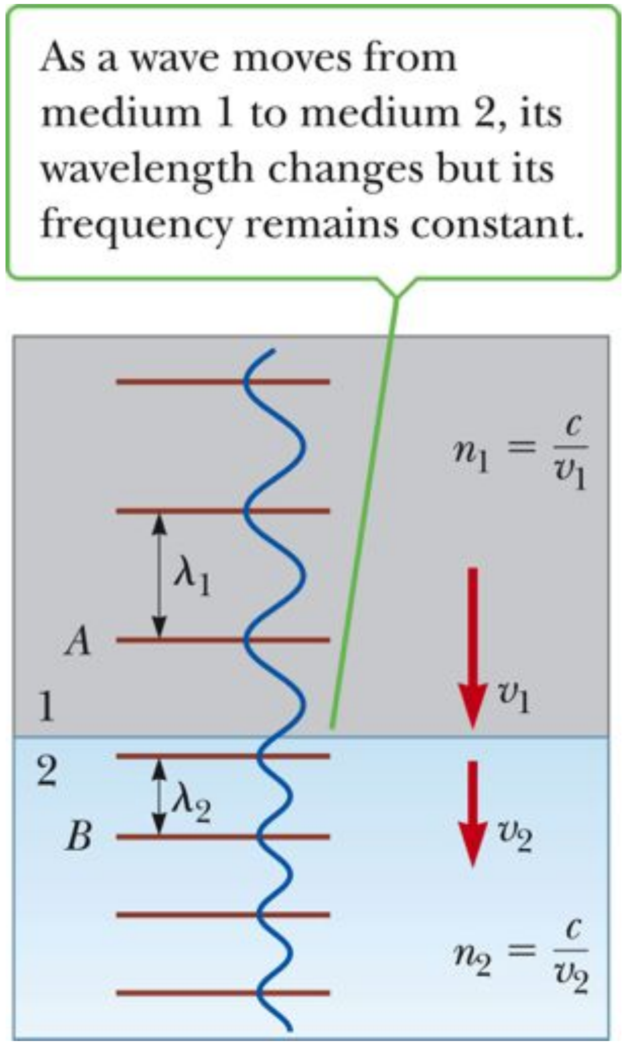


Index of Refraction, Cont.

- 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.



Section 22.3

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 λ_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

Water has an index of refraction of 1.333. What is the speed of light through it? ($c = 3.00 \times 10^8$ m/s)

a. 4.00×10^8 m/s

b. 2.25×10^8 m/s

c. 4.46×10^8 m/s

d. 1.46×10^8 m/s

A ray of light strikes a thick sheet of glass ($n = 1.5$) at an angle of 25° with the normal. Find the angle of the refracted ray within the glass with respect to the normal.

a. 56°

b. 46°

c. 25°

d. 16°

A light ray in air is incident on an air-to-glass boundary at an angle of 30.0° and is refracted in the glass at an angle of 21.0° with the normal. Find the index of refraction of the glass.

a. 2.13

b. 1.74

c. 1.23

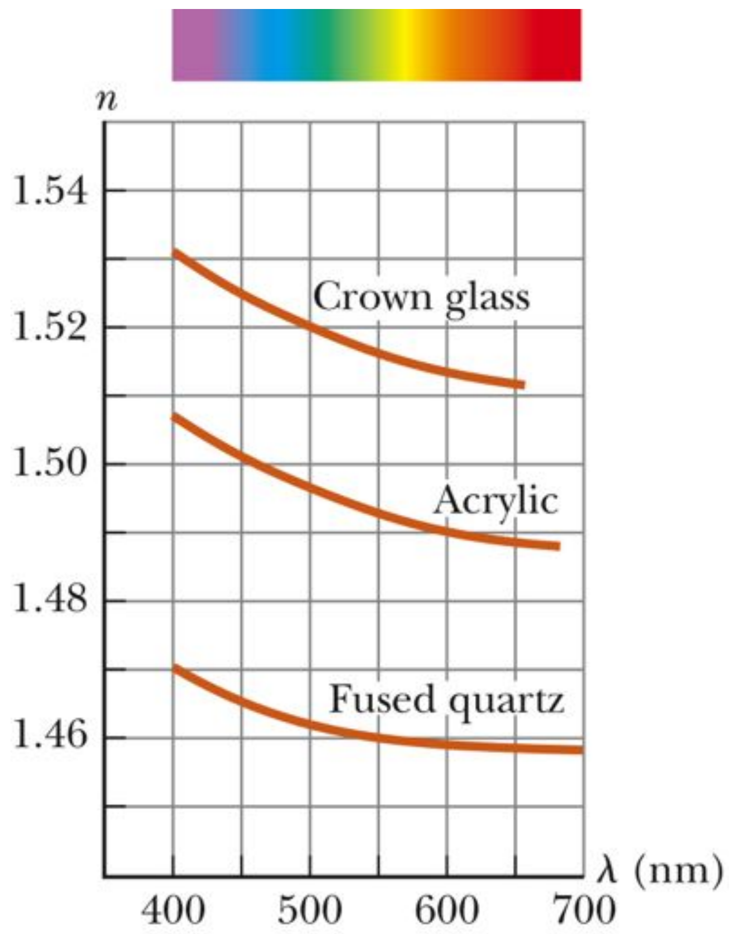
d. 1.40

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.

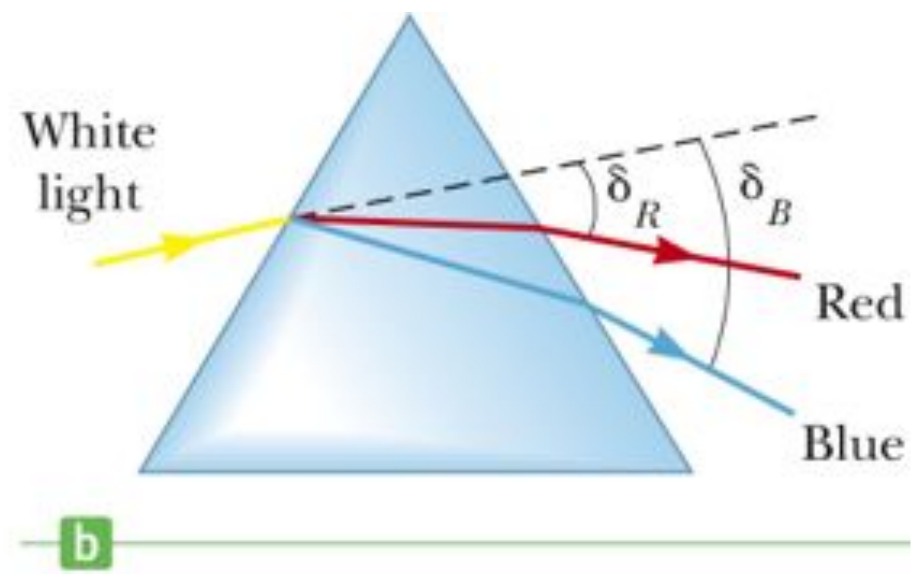
Variation of Index of Refraction with Wavelength

- 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.



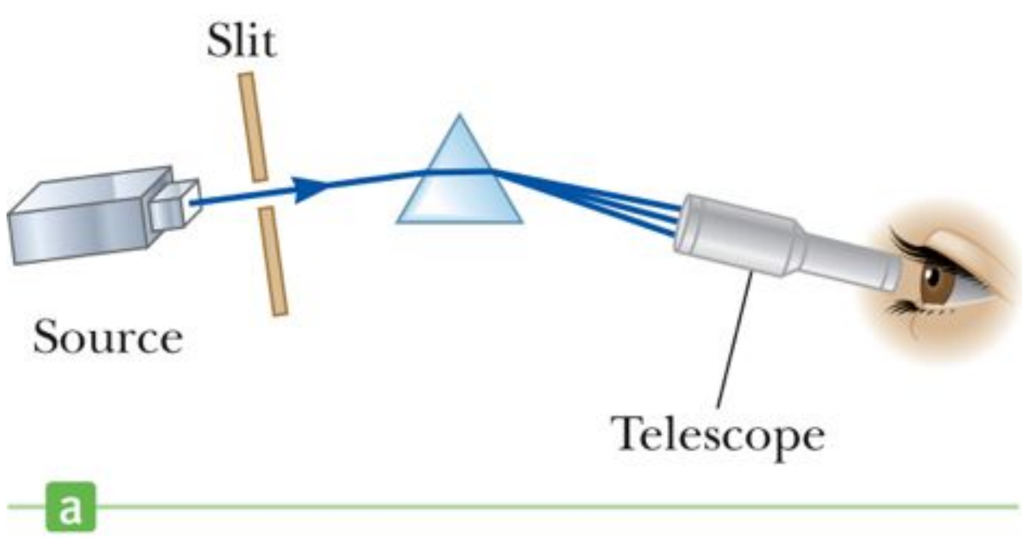
Refraction in a Prism

- 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.



Section 22.4

Prism Spectrometer



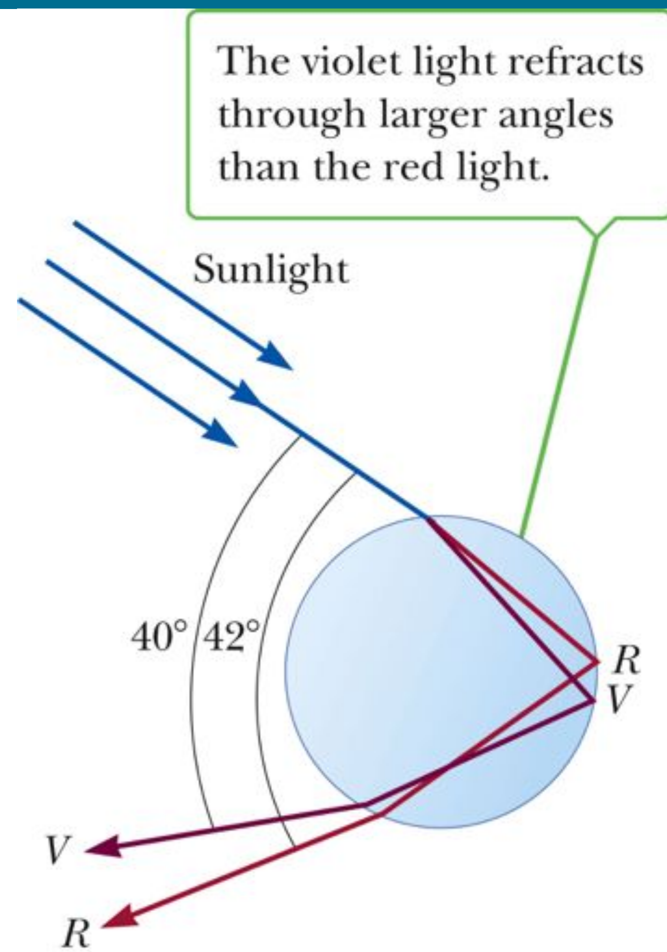
- A prism spectrometer uses a prism to cause the wavelengths to separate.
- The instrument is commonly used to study wavelengths emitted by a light source.

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

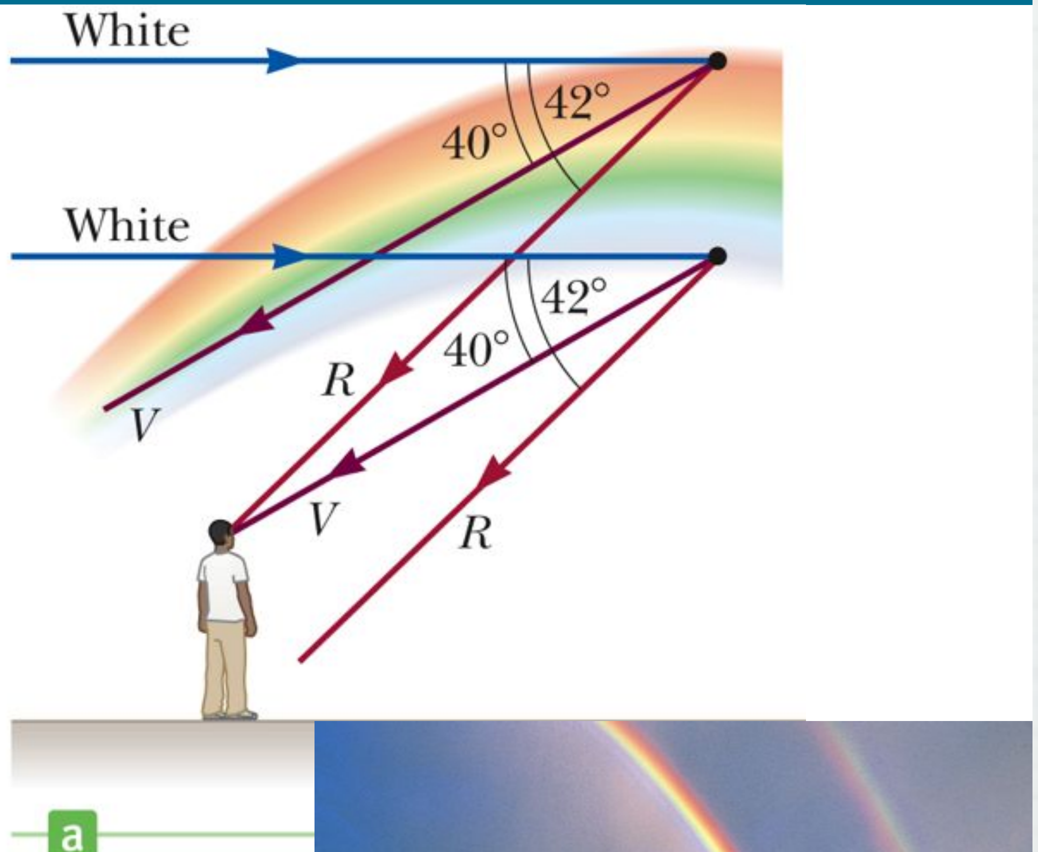
- At the back surface the light is reflected.
- It is refracted again as it returns to the front surface and moves into the air.
- The rays leave the drop at various angles.
  - The angle between the white light and the violet ray is 40°
  - The angle between the white light and the red ray is 42°



Section 22.5

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.



A certain kind of glass has n_{blue} = 1.650 for blue light and n_{red} = 1.610 for red light. If a beam of white light (containing all colors) is incident at an angle of 30.0°, what is the angle between the red and blue light inside the glass?
a.0.22°
b.0.45°
c.1.90°
d.1.81°

Huygen' s Principle

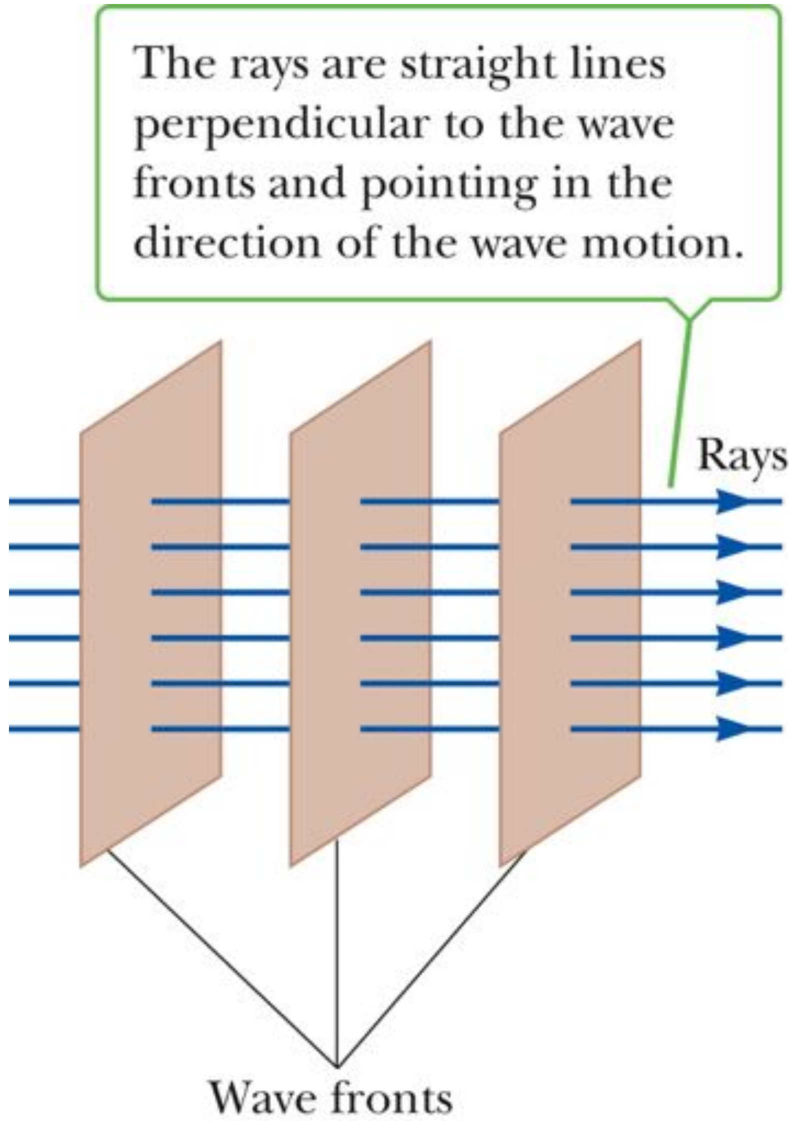
- Huygen assumed that light is a form of wave motion rather than a stream of particles.
- Huygen' s Principle is a geometric construction for determining the position of a new wave at some point based on the knowledge of the wave front that preceded it.

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.

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 $c\Delta t$, 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.

Section 22.6

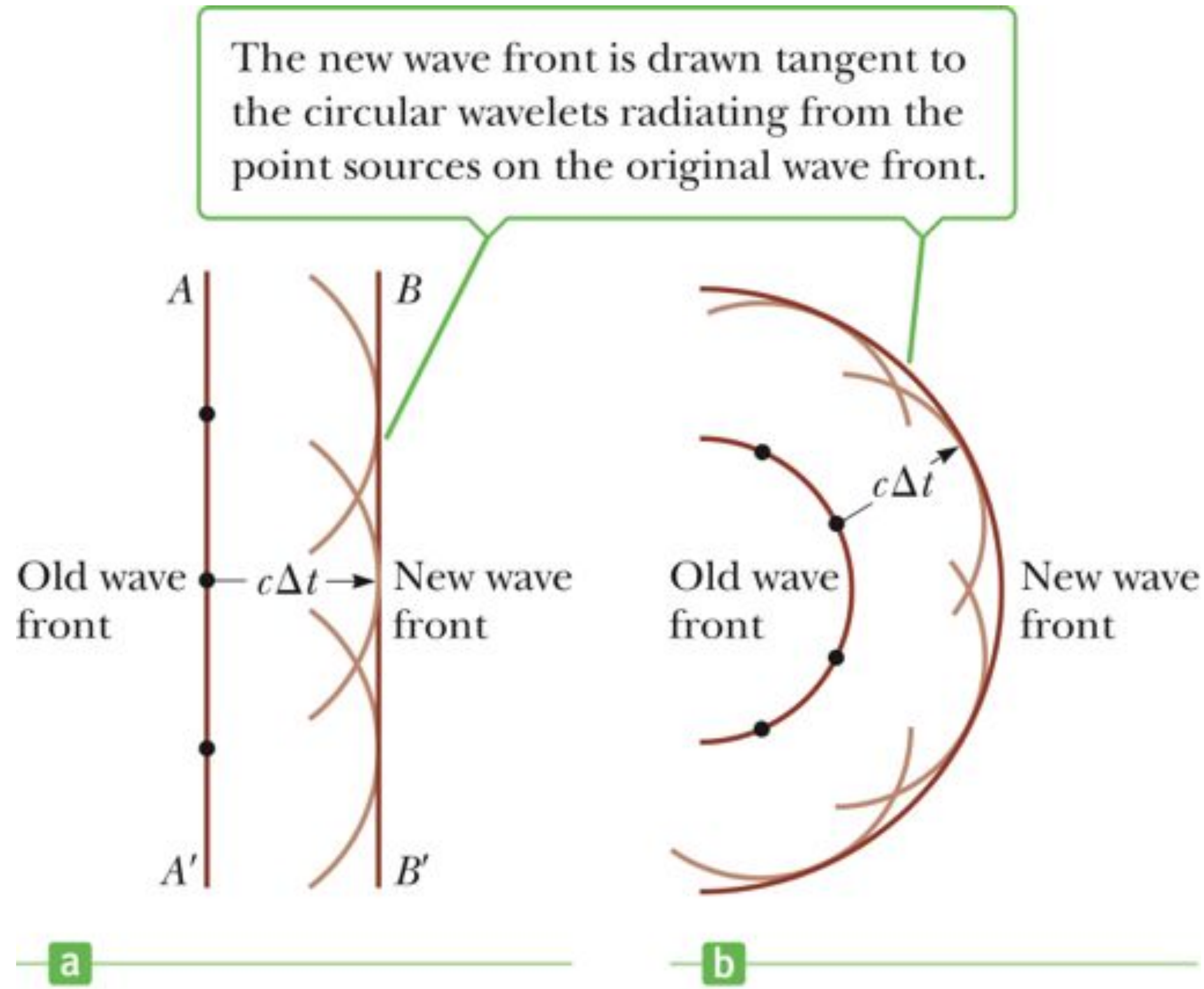
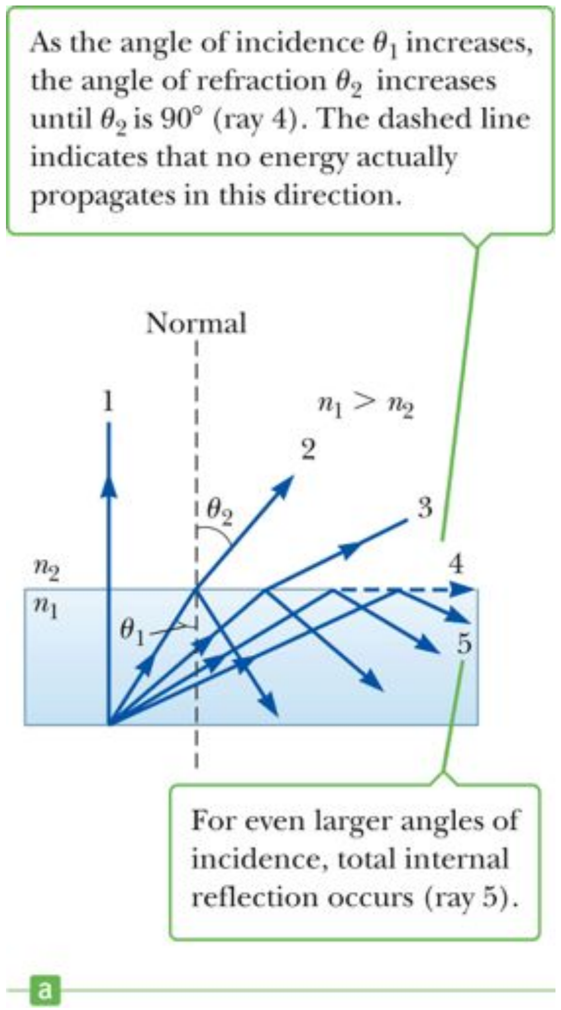


Fig. 22-21, p. 775

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

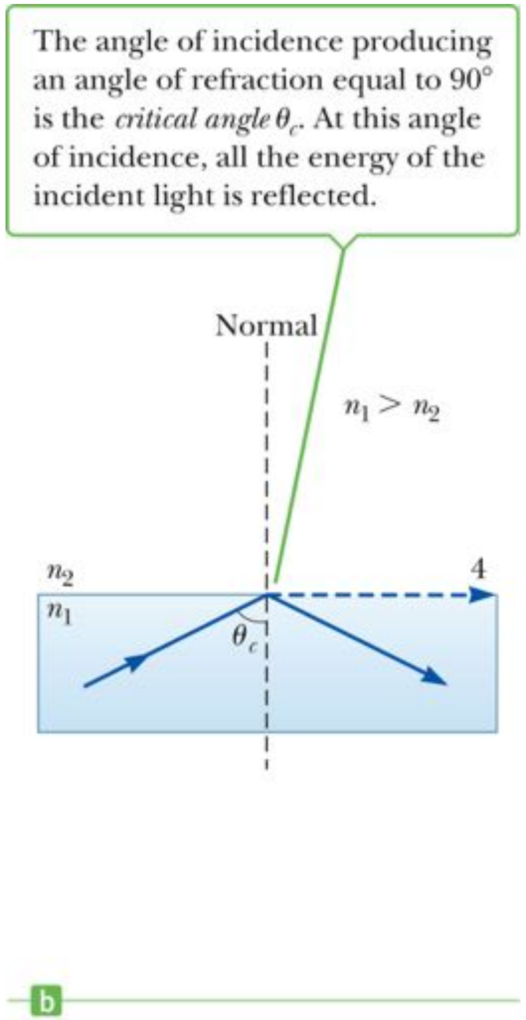


Critical Angle

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

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

$$for\ n_1 > n_2$$

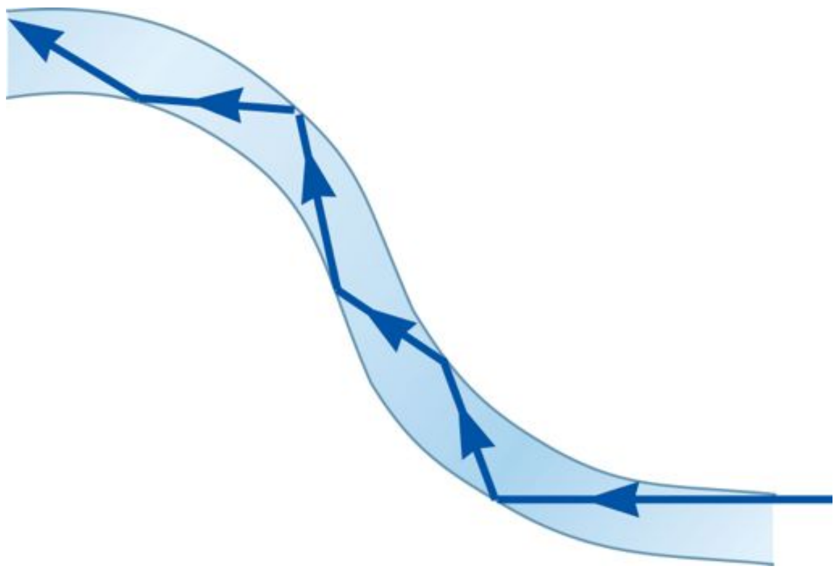


Critical Angle, Cont.

- 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.

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



Diamond has an index of refraction of 2.419. What is the critical angle for internal reflection inside a diamond that is in air?

a.24.4°

b.48.8°

c.155°

d.131°

Key Concepts

* For reflection, the angle of incidence equals the angle of reflection wrt the normal of the surface
* both the velocity and wavelength of light change when propagating into materials with different refractive indices
* The index of refraction is wavelength dependent
* All sources on a wavefront are point sources for the creation of spherical wavefronts
* There is a critical angle for which light will be reflected back into a medium when attempting to propagate from one refractive index to another

Prisms

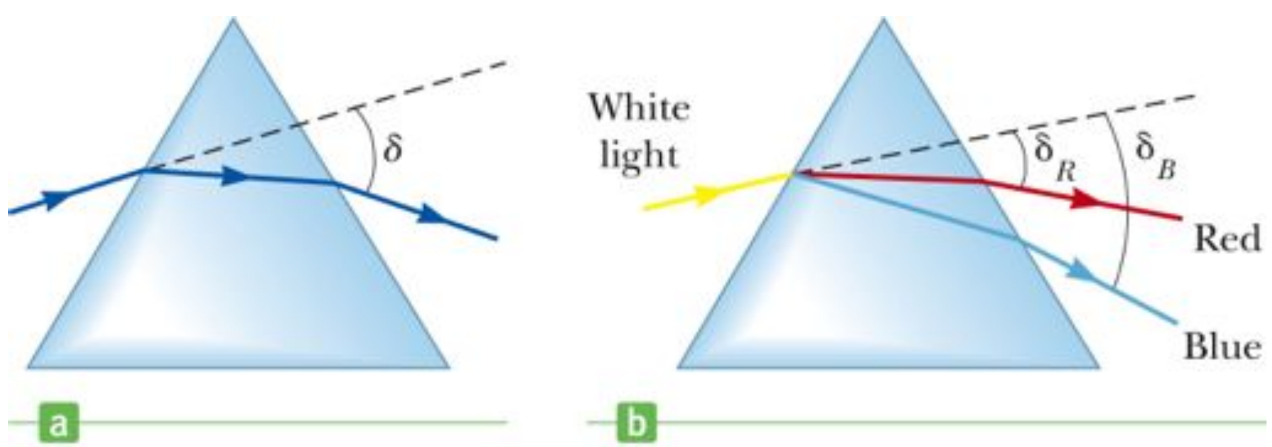


Fig. 22-14ab, p. 771

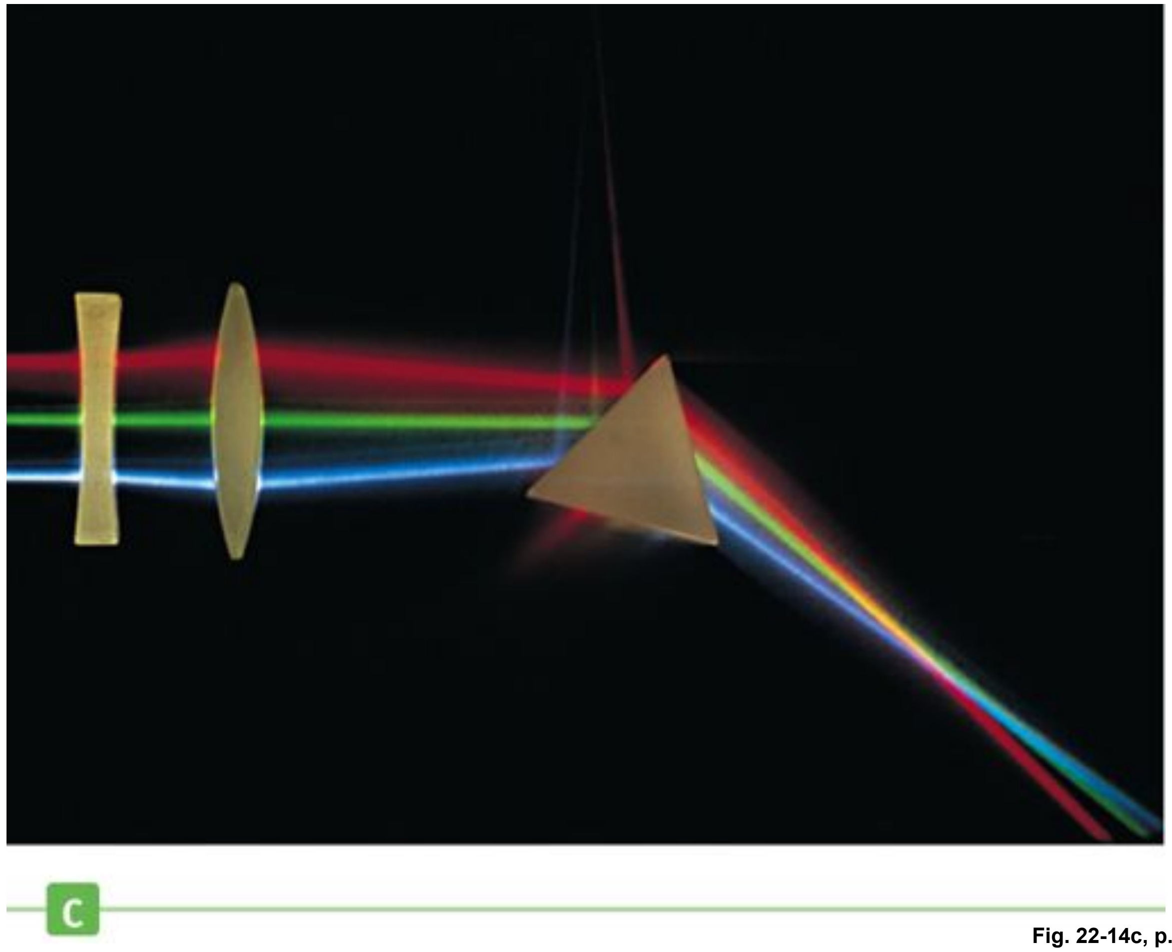


Fig. 22-14c, p. 771

Key Equations

$$E = hf$$

$$\theta_i = \theta_r$$

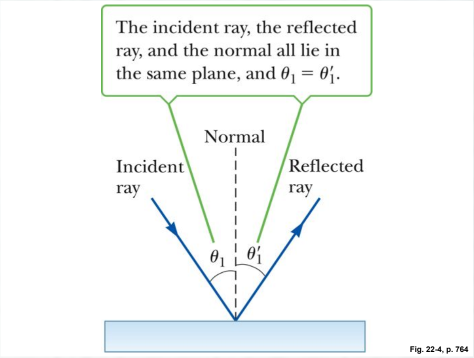


Fig. 22-4, p. 764

$$n = \frac{c}{v}$$

$$n = \frac{\lambda_0}{\lambda_n}$$

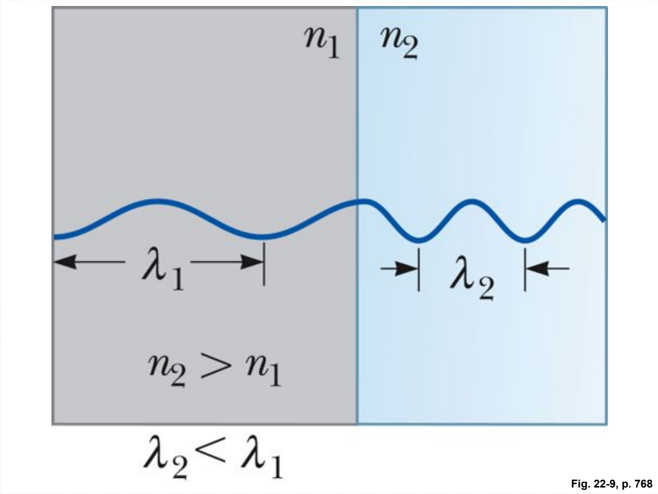


Fig. 22-9, p. 768

$$n_1 sin(\theta_1) = n_2 sin(\theta_2)$$

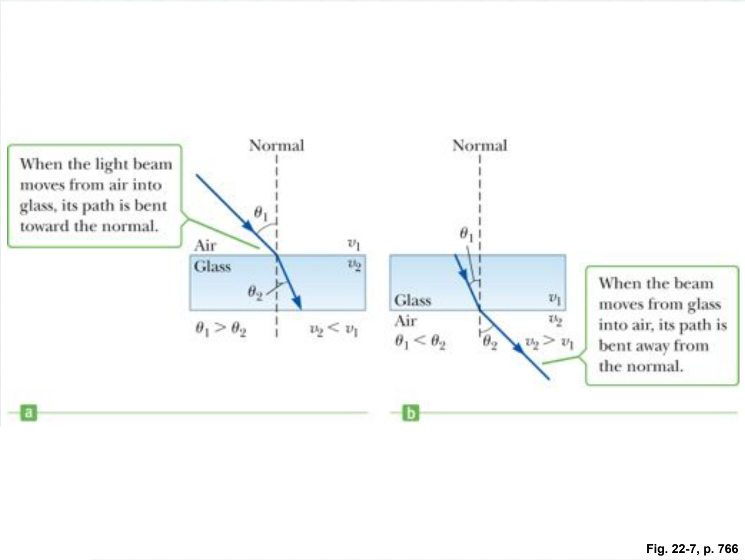


Fig. 22-7, p. 766

$$sin(\theta_c) = \frac{n_2}{n_1} \rightarrow (n_1 > n_2)$$

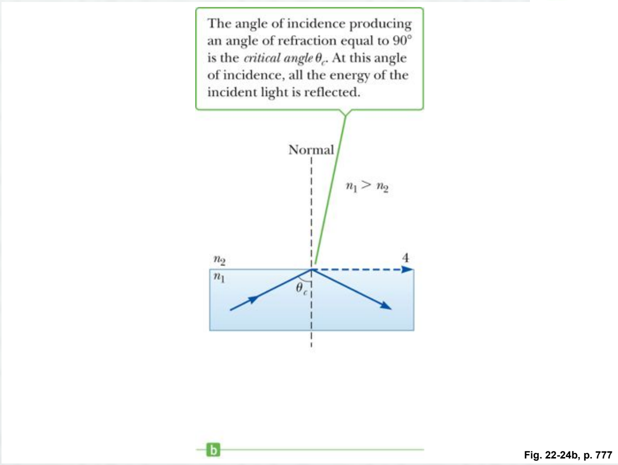


Fig. 22-24b, p. 777