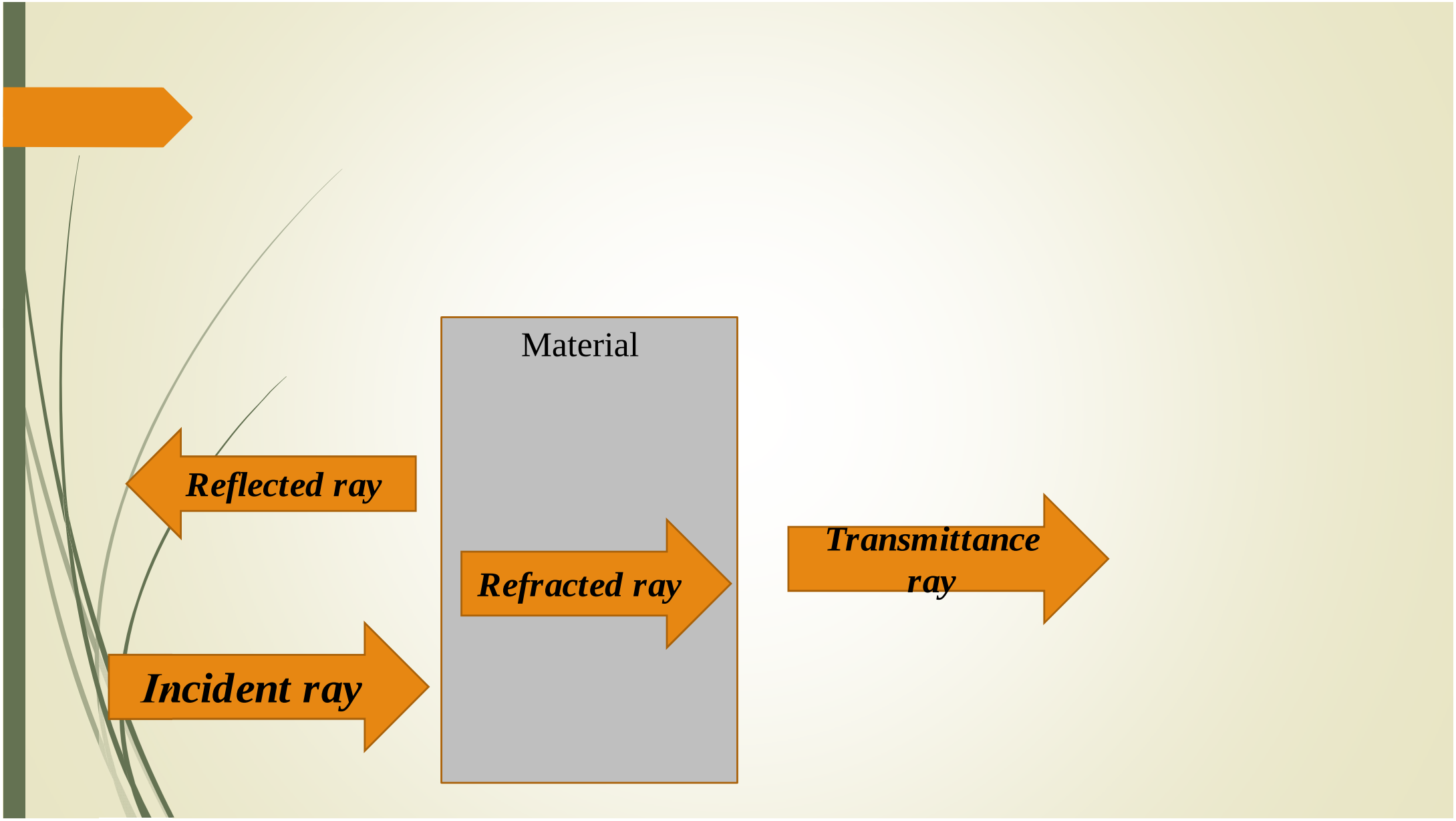
Refraction

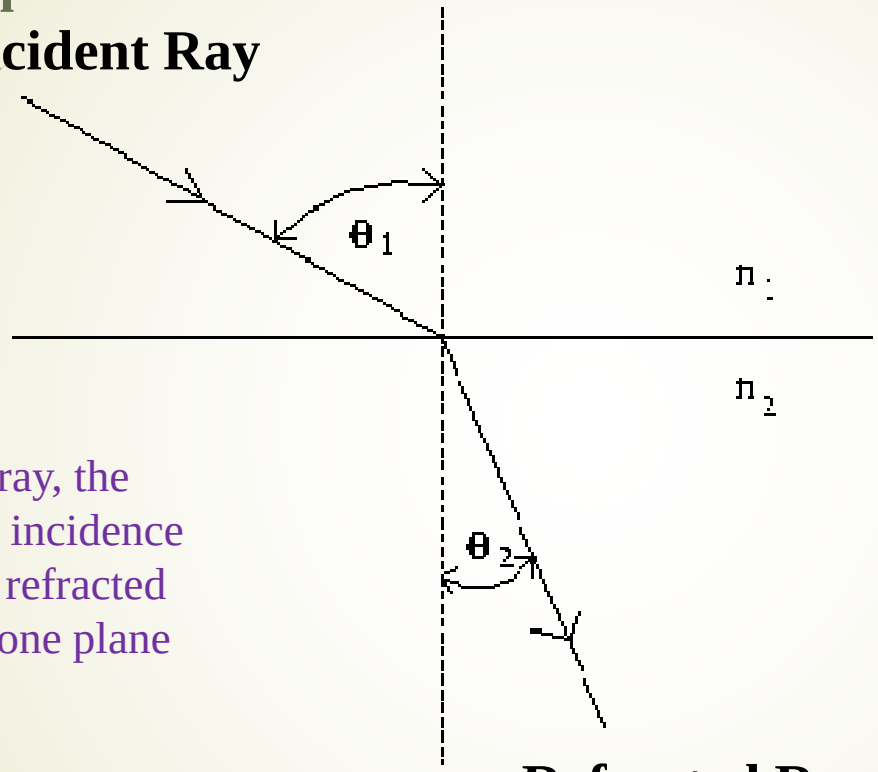
Definition:

When a wave crosses a boundary between Medium 1 and Medium 2:

- ✓ the wave changes direction because it changes velocity.
- ✓ Frequency remains constant.
- ✓ Velocity changes as a result of wavelength change.


Material
Reflected ray
Refracted ray
Transmittance ray
Incident ray

When light travels from one material to another it usually changes direction
The bending of light that occurs at the borderline of two materials is called **refraction**



The incident ray, the normal to the incidence point and the refracted ray are all in one plane

When the incident ray travels from a **less optically dense medium (low n)** to a **more optically dense medium (higher n)** then the **refracted ray bends towards the normal.**

Index of Refraction (**n**)

the amount of bending depends on the optical properties of the two materials -->

characterized by their **index of refraction: n**

n is a number: n=1 for vacuum, n=1.33 for water, n=2.42 for diamond, n=1.5-1.9 for different types of glass …….

when the amount of bending is bigger, the difference in n is bigger for the two materials

$$n = c / v$$

- **c :** the speed of light in a vacuum, 3×10^8 m/sec
- **v :** speed of light in the medium.
- **n** : medium's index of refraction

- **n>1 (Why?)**

Indices of Refraction

Vacuum	1.00
Air	1.0003
Water	1.33
Ethanol	1.36
Crown glass	1.52
Quartz	1.52
Diamond	2.42

- The speed of light has a lower speed in a more optically dense medium.

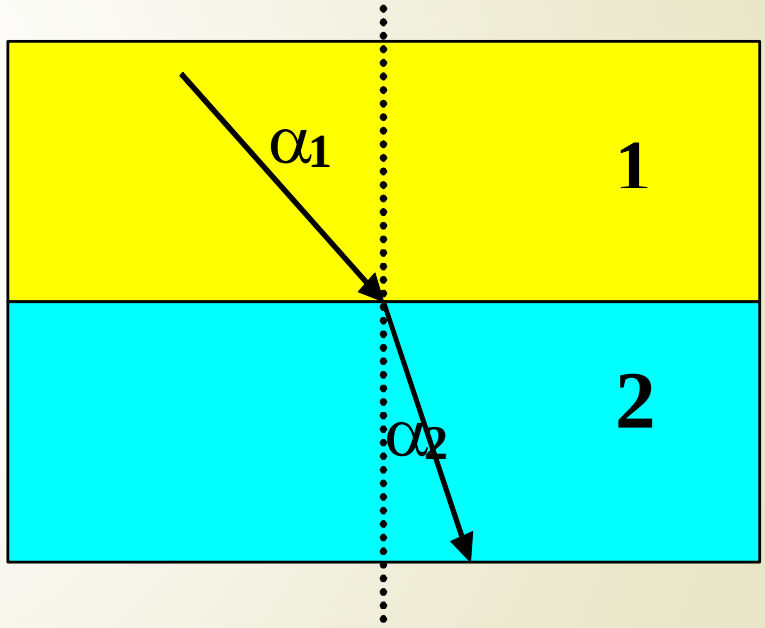
Snell's Law

If light travels from material 1 with index of refraction n_1 to material 2 with index of refraction n_2 the following laws determine the direction of the refracted ray:

$$\sin(\alpha_1)n_1 = \sin(\alpha_2)n_2$$

$$\frac{Sin\alpha_1}{Sin\alpha_2} = \frac{\lambda_1}{\lambda_2}$$

$$\frac{\lambda_1}{\lambda_2} = \frac{V_1 / f}{V_2 / f} = \frac{V_1}{V_2} = \frac{c/n_1}{c/n_2} = \frac{n_2}{n_1}$$



Dispersion

The index of refraction of a medium depends in a slightly manner on the frequency of the light-beam

Different color rays deflect in different manner during refraction: violet light is deflected more than red…..

By refraction we can decompose the white color in its constituents

A prism separates white light into the colors of the rainbow.

We can do the opposite effect too…..recombining the rainbow colors in white light

Atmospheric dispersion of light: **rainbow** (dispersion on tinny water drops) or **halos** (dispersion on tiny ice crystals)

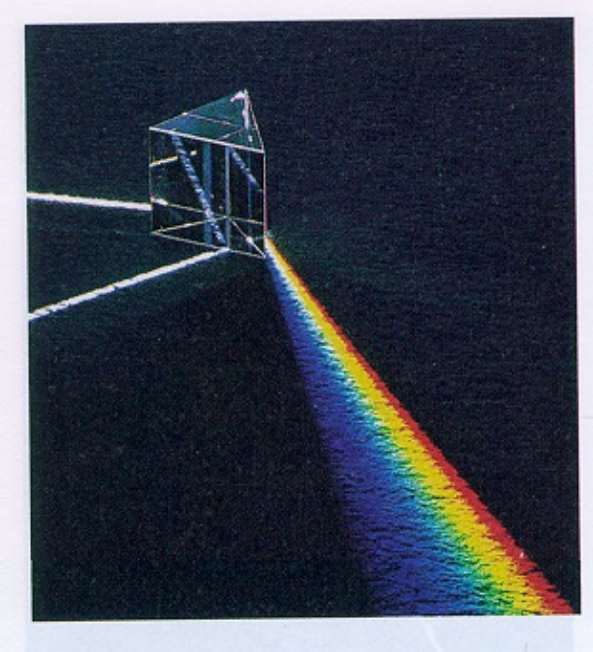
For a given material, the index of refraction varies with the wavelength of the light passing through the material

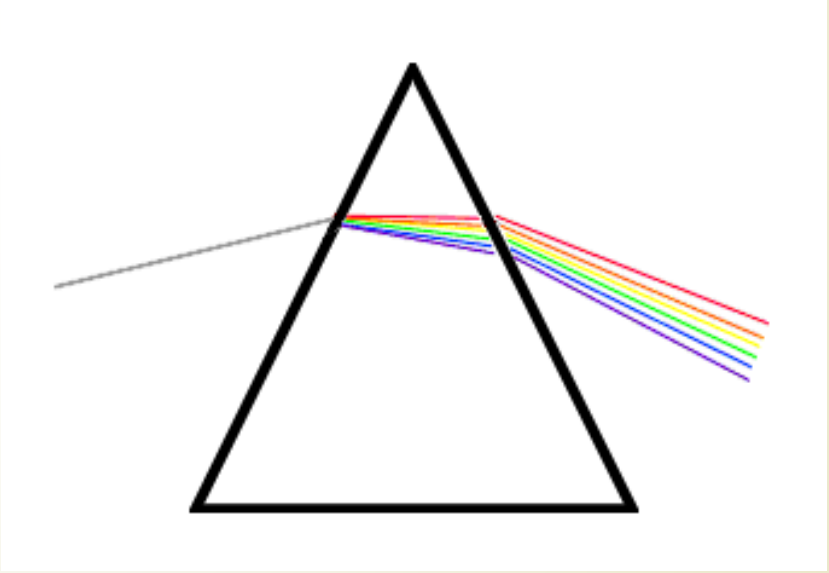
This dependence of *n* on λ is called *dispersion*

Snell's law indicates light of different wavelengths is bent at different angles when incident on a refracting material

The index of refraction of glass is different for the colors that make up white light because the speed of light is slightly different in glass for each frequency of light. (In vacuum all colors have speed $c=3 \times 10^8$ m/s.)

Video





Total Internal Reflection

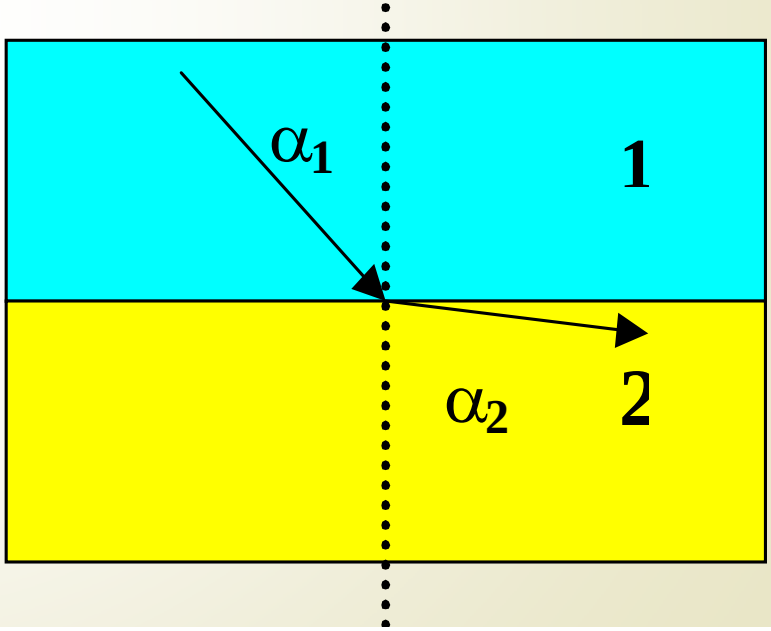
At the border of two materials usually both reflection and refraction appears. In some peculiar situations however the refracted light is also reflected. **reflection is total.**

- Can occur when ray goes from **higher** n to **lower** n.
- Above a Critical angle (of incidence) the ray is reflected, not refracted
- For problems, set the angle of refraction to 90, and solve for critical angle

$$\sin\alpha_1\, n_1 = \sin\alpha_2\, n_2 \rightarrow \frac{\sin\alpha_1}{\sin\alpha_2} = \frac{n_2}{n_1}$$

$$\alpha_2 = 90^\circ \rightarrow \sin\alpha_1 = \frac{n_2}{n_1}$$

$$\alpha_1 = Critical\ angle$$



Example 5. Find the critical angle of incidence from water to air.

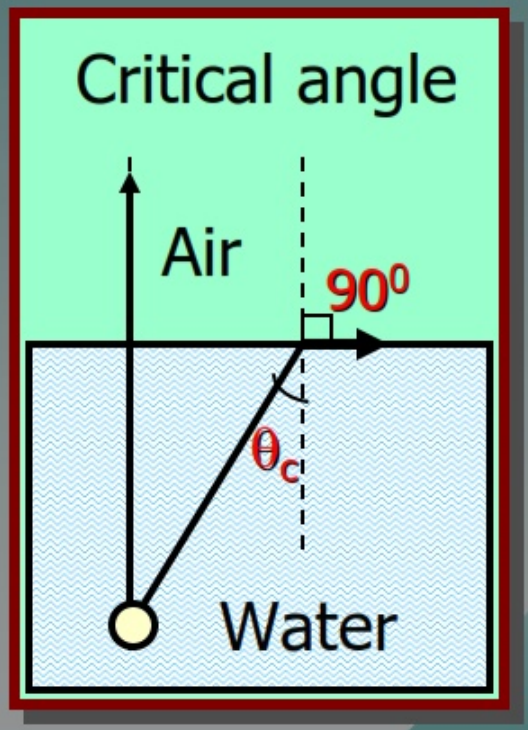
For critical angle, $\theta_A = 90^0$

$n_A = 1.0$; $n_W = 1.33$

$$n_W \sin\theta_C = n_A \sin\theta_A$$

$$\sin\theta_C = \frac{n_A \sin 90^0}{n_w} = \frac{(1)(1)}{1.33}$$

Critical angle: $\theta_c = 48.8^0$



In general, for media where $n_1 > n_2$ we find that:

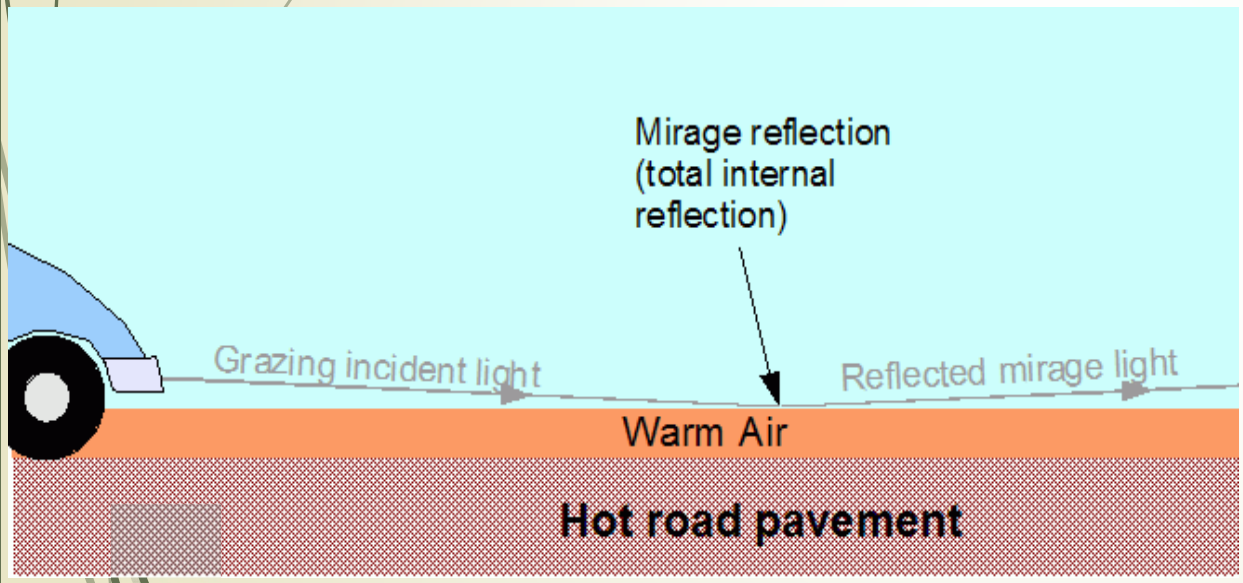
$$\sin\theta_C = \frac{n_1}{n_2}$$

Total refraction in everyday life:

- Mirage
- Rainbow
- Optical fibers
- Porro prism

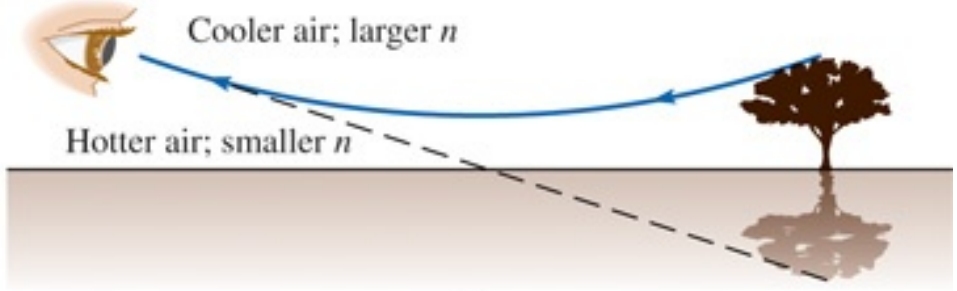
Mirage

Total internal reflection occurs because hot air has a lower n, than cold air.

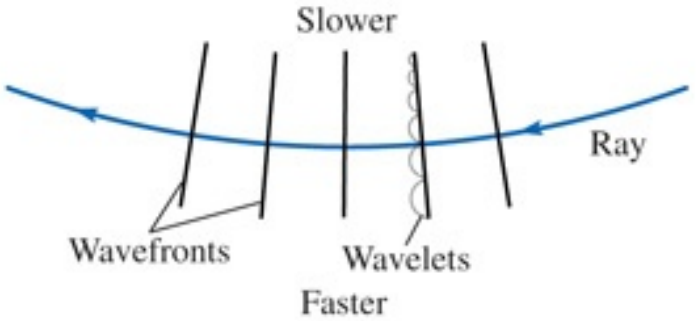


Mirage

(a)



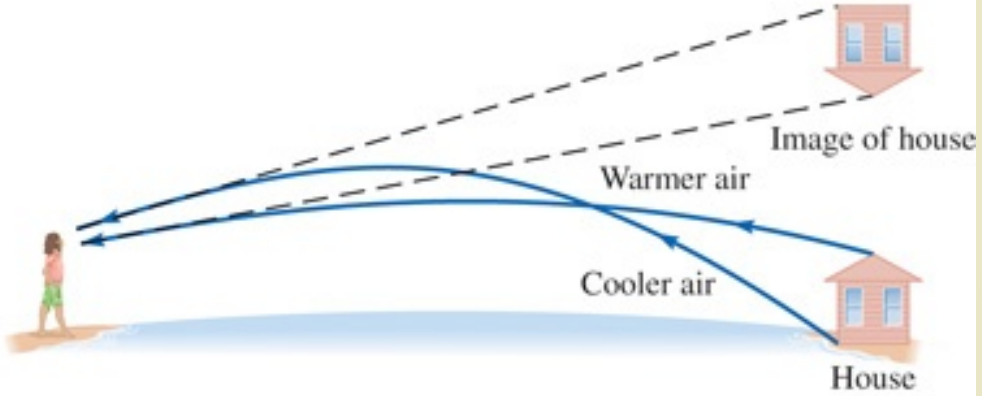
(b)



(c)

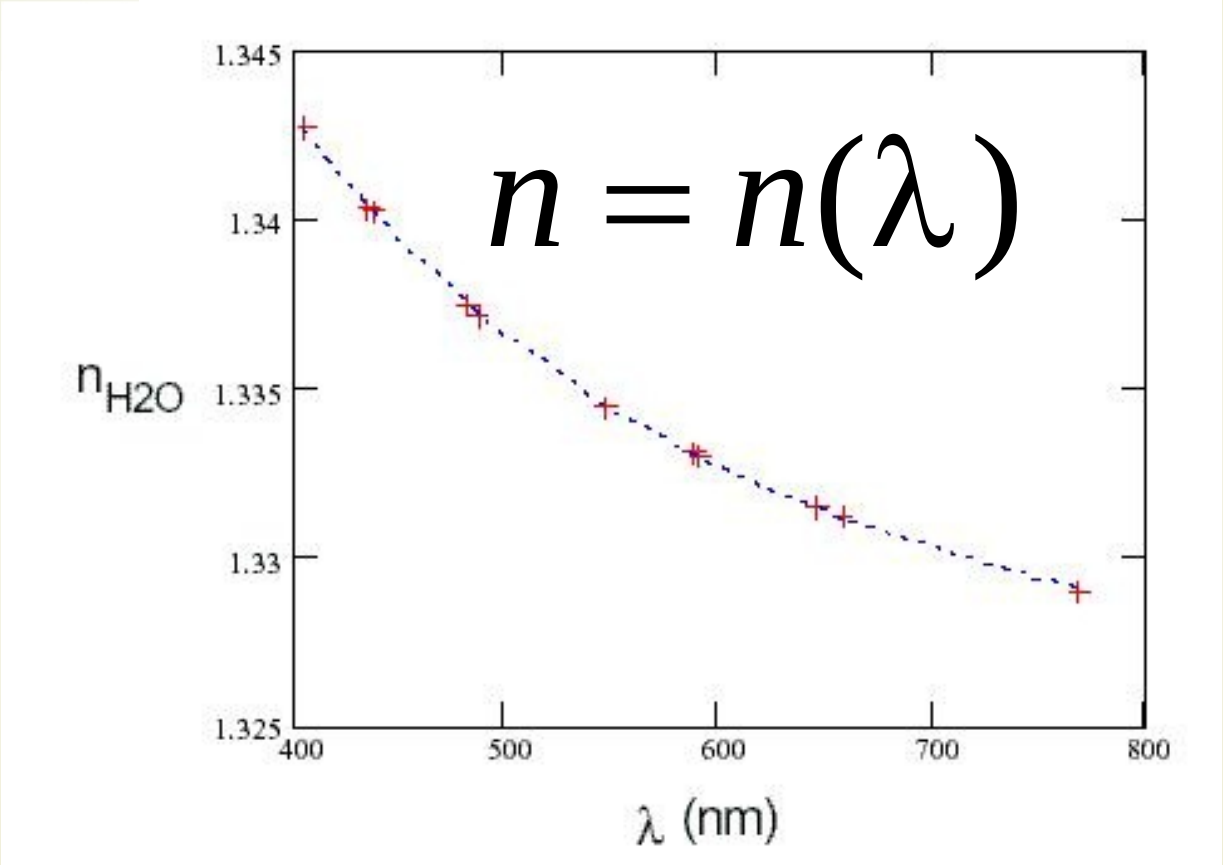
Mirage

(a)

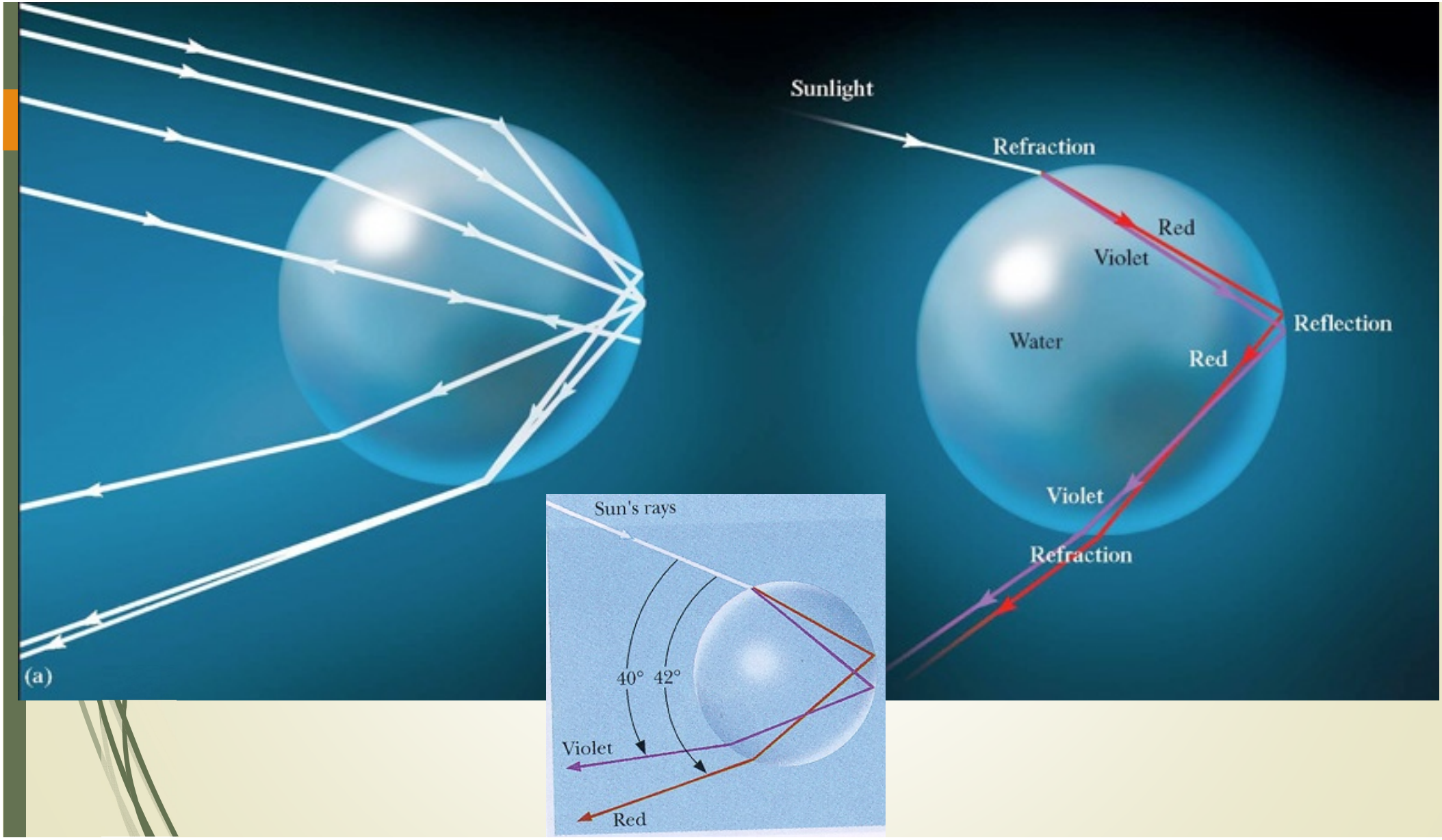


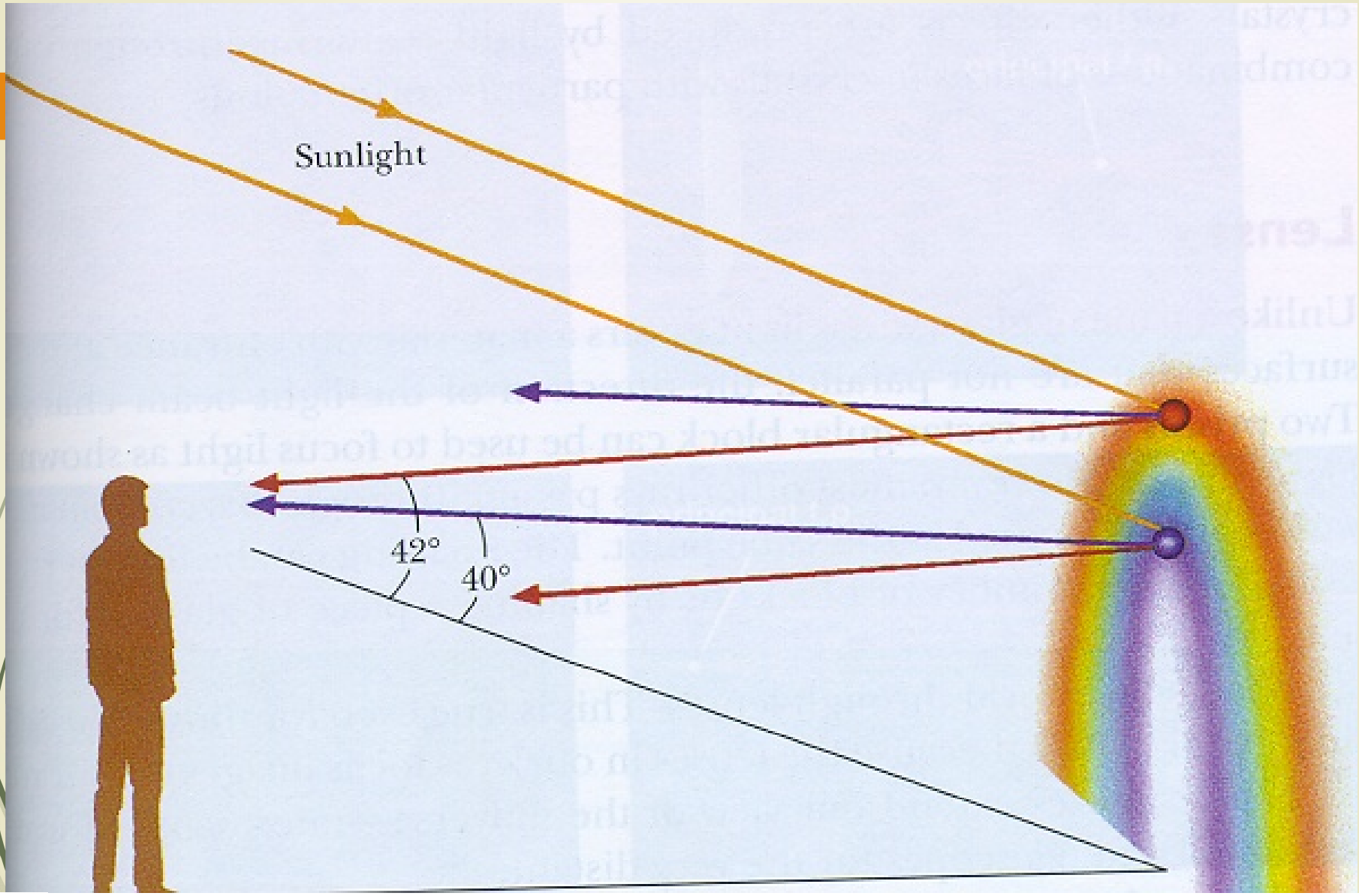
(b)

Rainbow



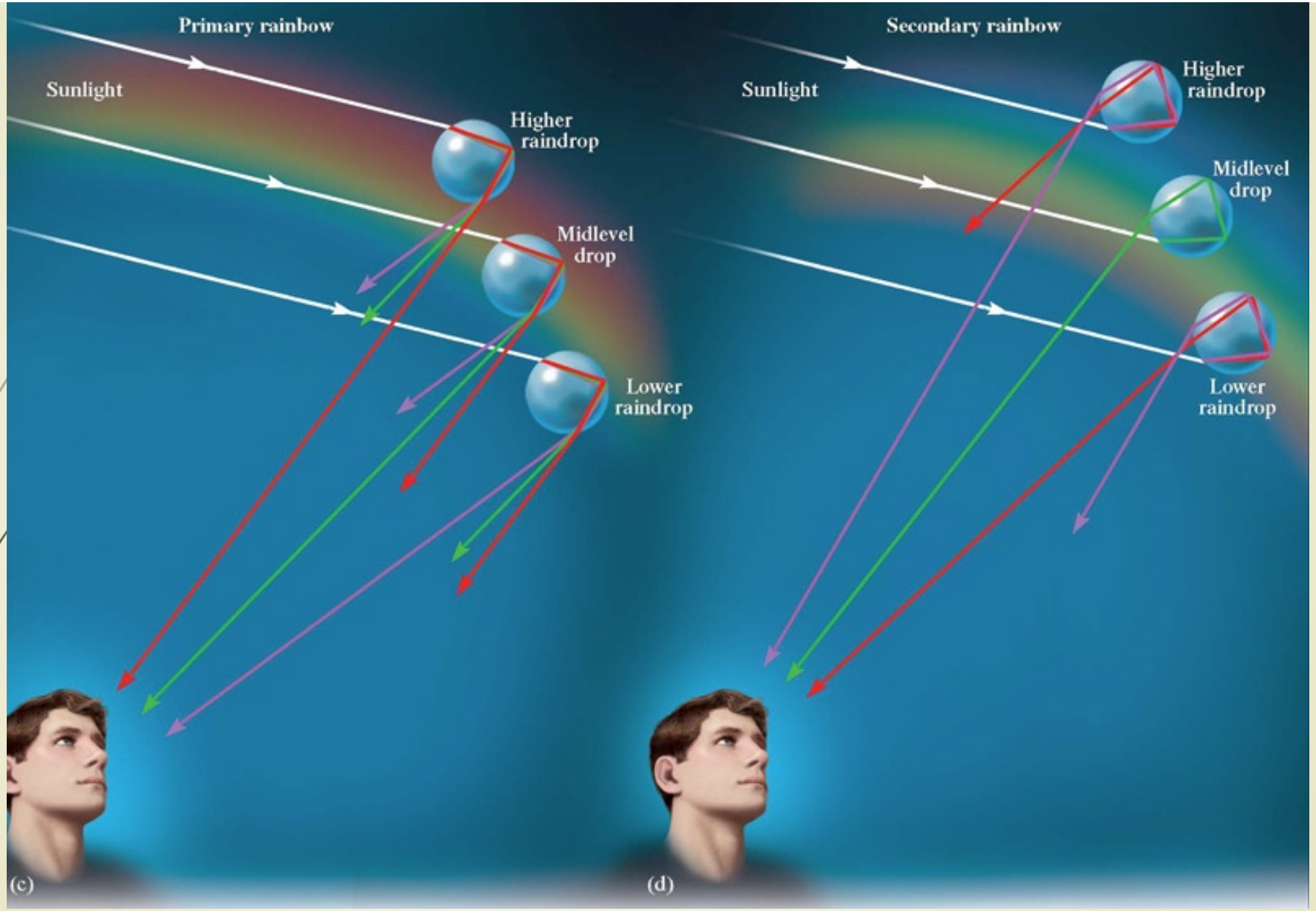
Refractive Index Function of Wavelength


Sunlight
Refraction
Red
Violet
Reflection
Water
Red
Violet
Refraction
(a)
Sun's rays
40°
42°
Violet
Red


Sunlight
42°
40°

Double Rainbow

- The secondary rainbow is fainter than the primary
- 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


Primary rainbow
Sunlight
Higher raindrop
Midlevel drop
Lower raindrop
(c)
Secondary rainbow
Sunlight
Higher raindrop
Midlevel drop
Lower raindrop
(d)

Atmospheric refraction

- the atmosphere made up of layer with different density and temperature

→ these layers different index of refraction

→ light refracted

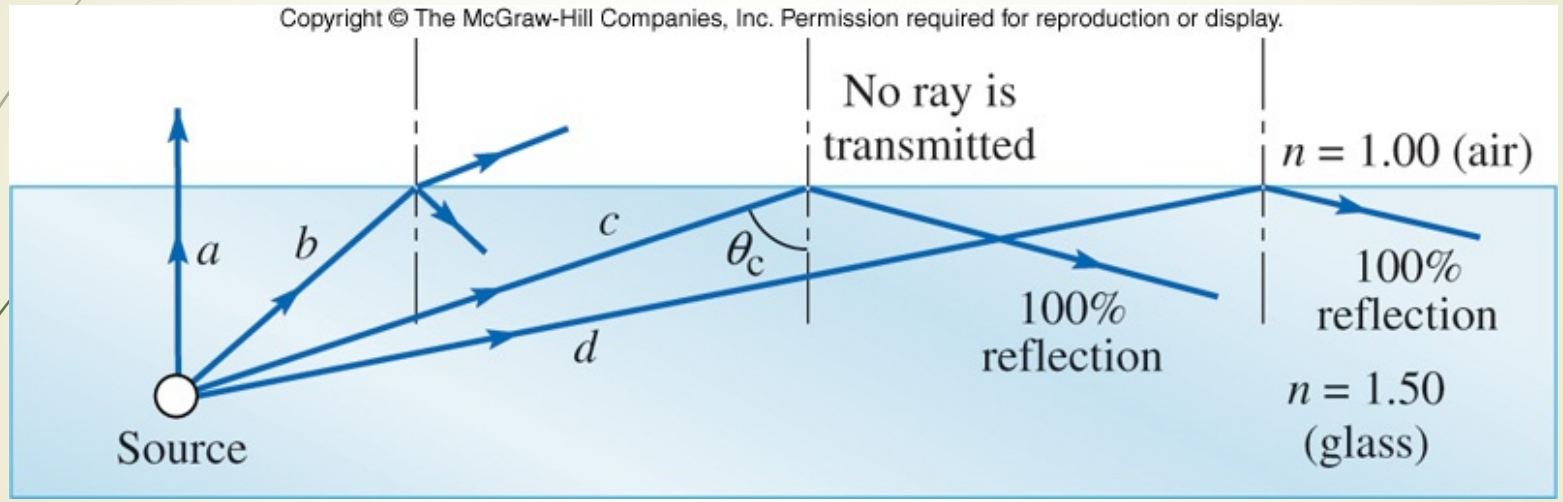
→ distortion of the shape of Moon or Sun at horizon

→ apparent position of stars different from actual one

if light goes from layers with higher n to layers with lower --> total refraction: -mirages, looming

Light guides:

optical fibers: used in communication, medicine, science, decorative room lighting, photography etc…..



- 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

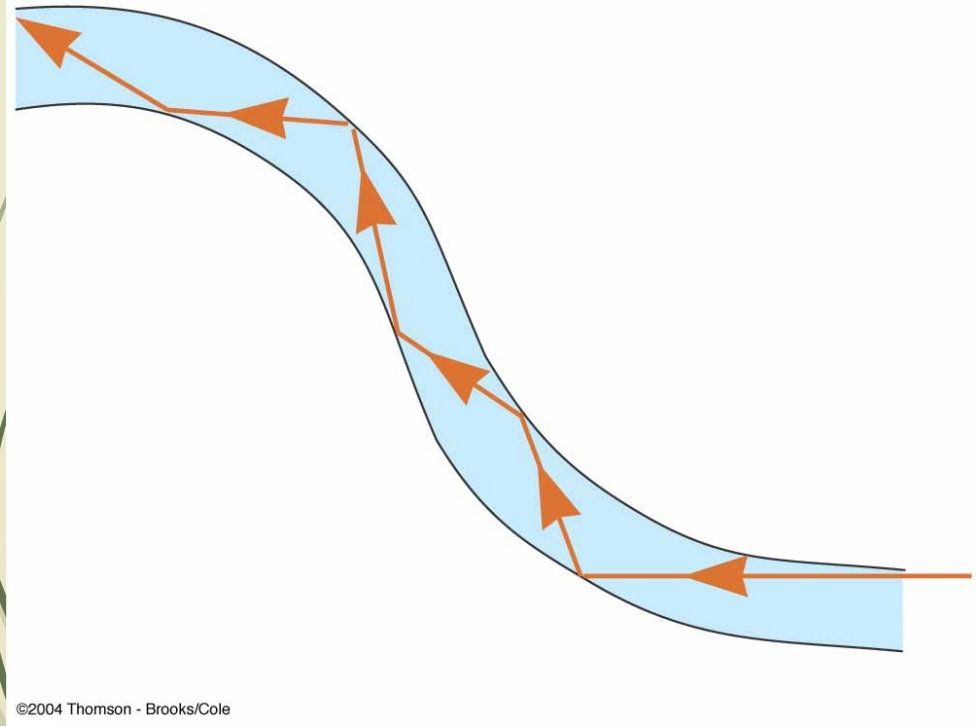
Critical angle:

$$\theta_c = \sin^{-1}\frac{n_t}{n_i}$$

no transmitted ray for $\theta_i \geq \theta_c$

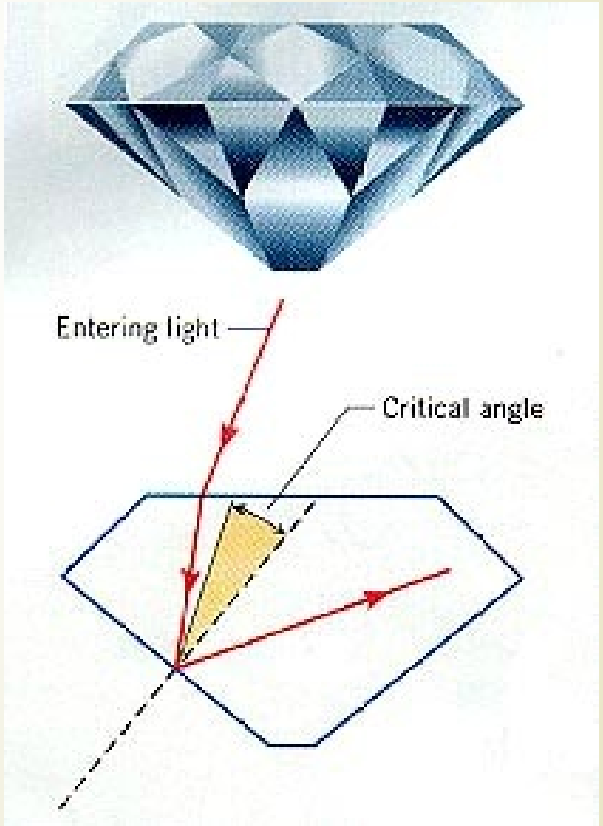
Fiber Optics

- 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



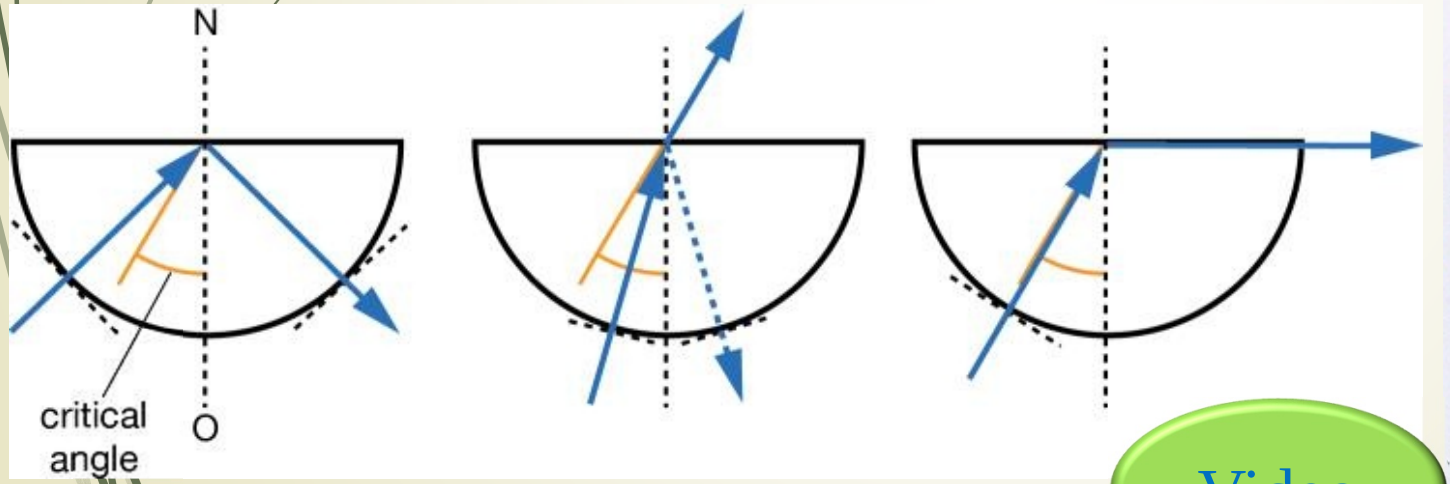
Internal Reflection in Diamond

- The critical angle for diamond in air is 24.5^{o}.
- Any ray which strikes the inside surface at an angle greater than 24.5^{o} will be totally internally reflected.

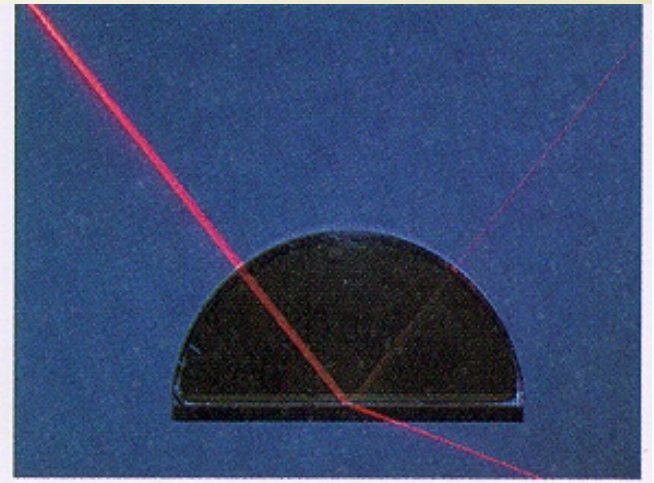


Total internal reflection

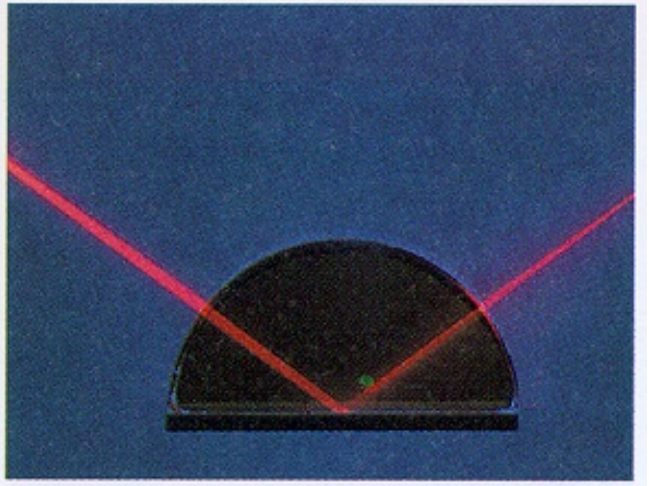
Going from a slower medium (e.g. glass) to a faster medium (e.g. air), when the angle of incidence is greater than a critical angle, **all** of the light is internally reflected.



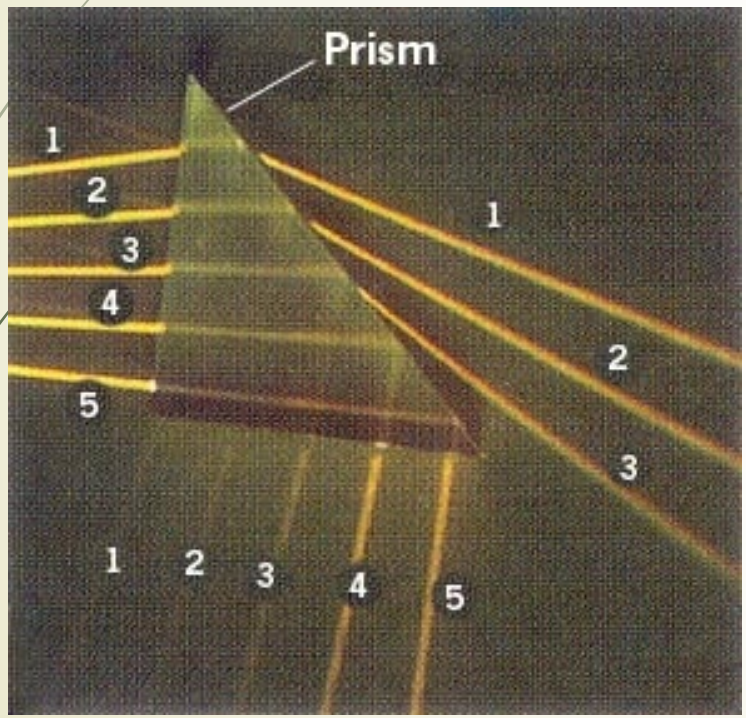
Video



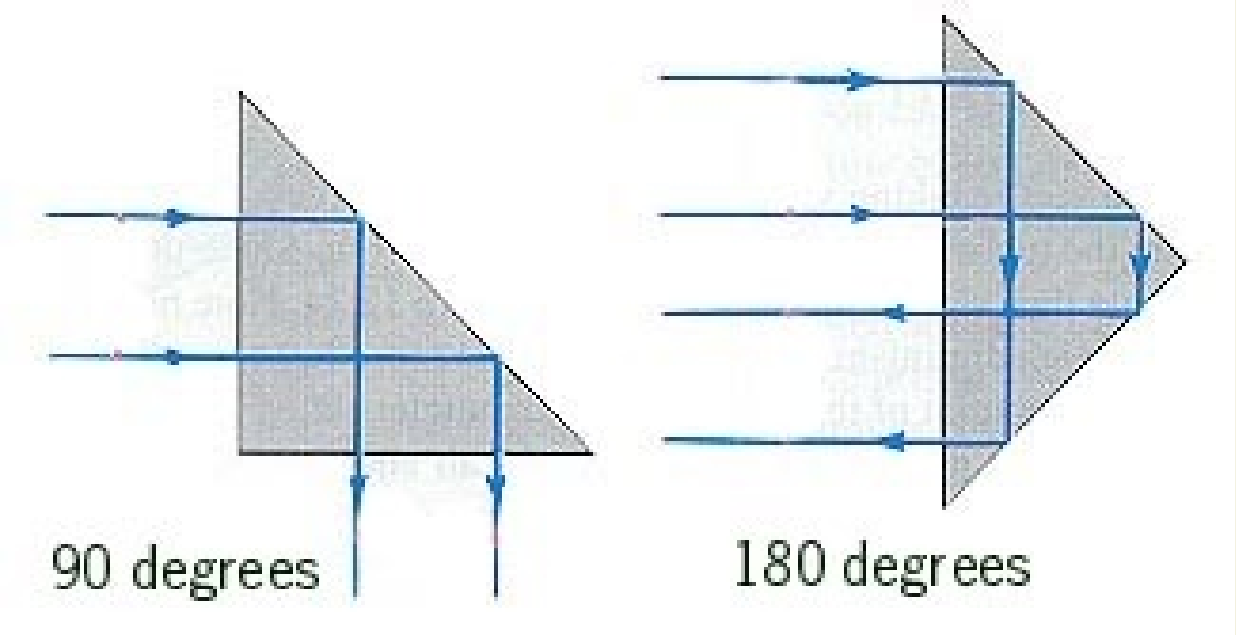
(a)



Porro Prism



- All rays reflect internally, but the top three rays reflect only a small percentage internally; most energy leaves the prism.
- The fourth and fifth rays are reflected 100 % internally


90 degrees
180 degrees