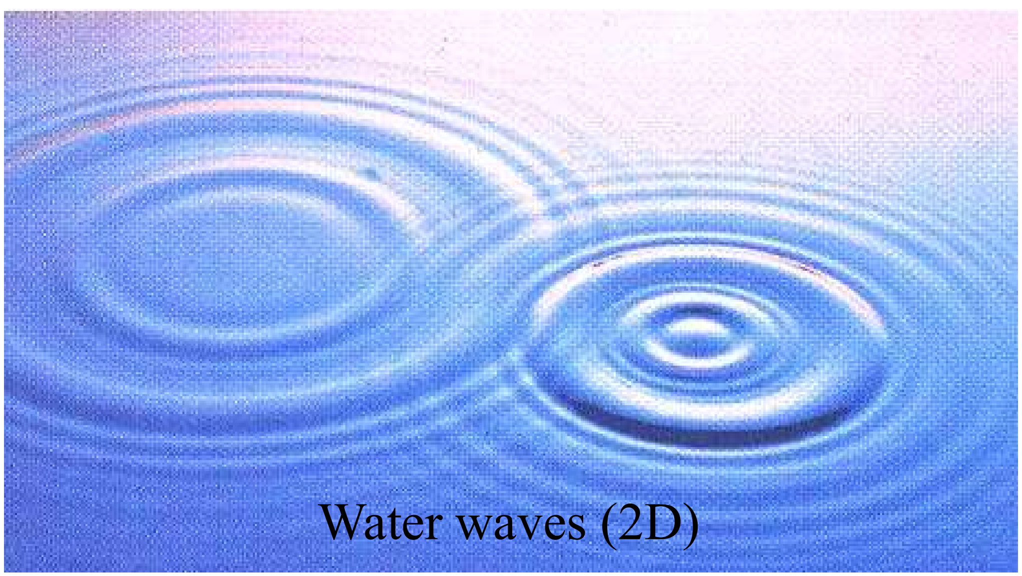
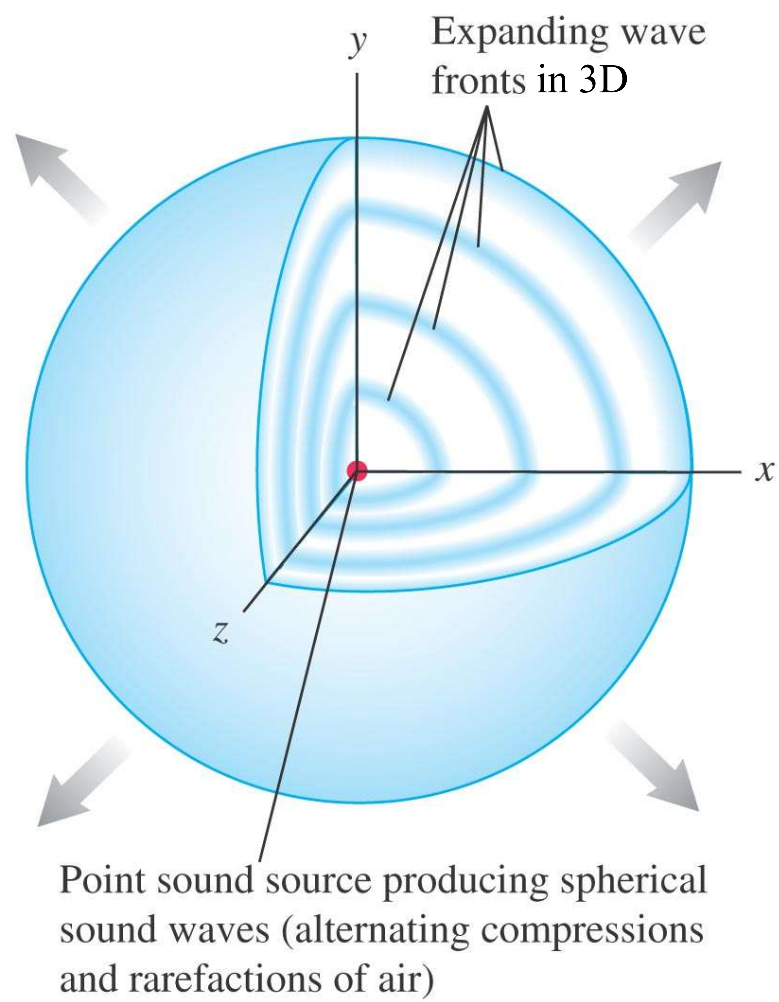
Propagation of Light: Waves and Wave Fronts

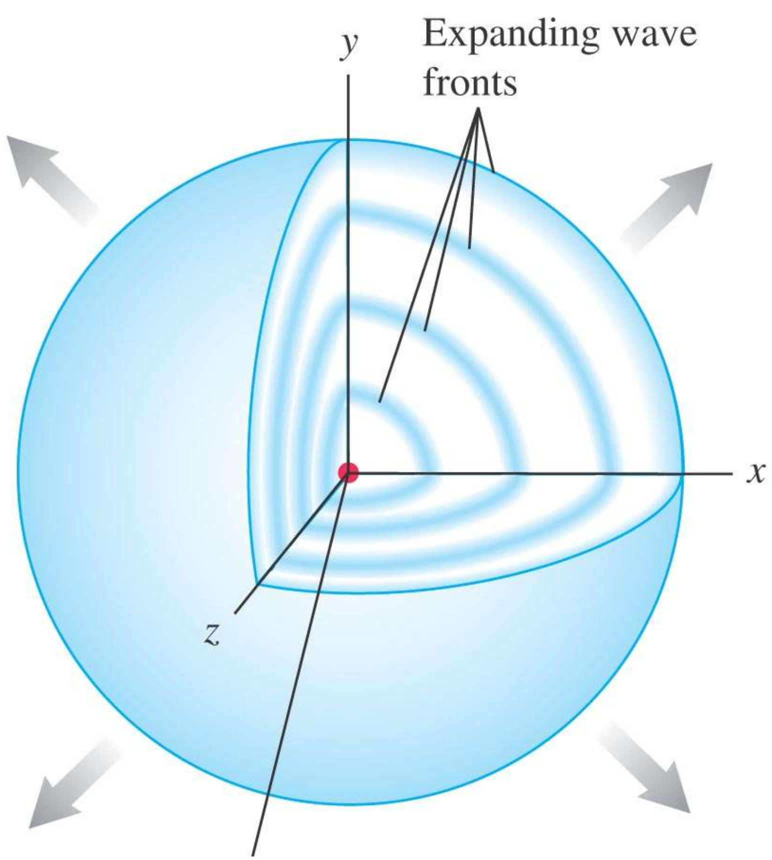
Propagating waves are usually visualized as a sequence of expanding **wave fronts** in space.

Wave front: the locus of points where the wave has the same phasic relation, e.g. crests, troughs.

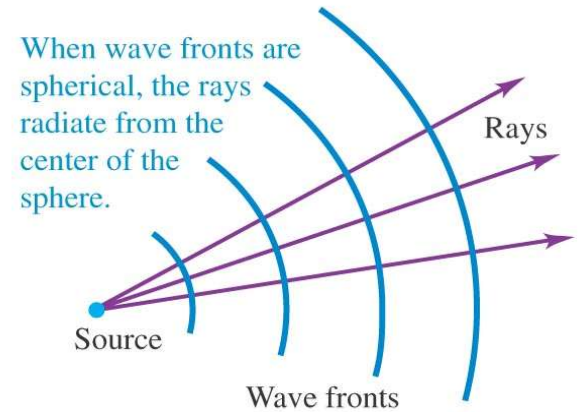




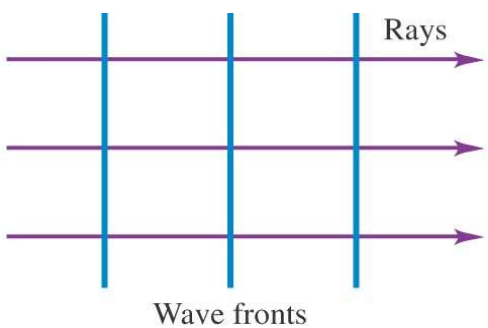
Waves, Wave Fronts, and Rays



Rays are always *perpendicular* to the wave fronts.



When wave fronts are planar (source is sufficiently far away), rays are perpendicular to the wave fronts and *parallel* to each other.



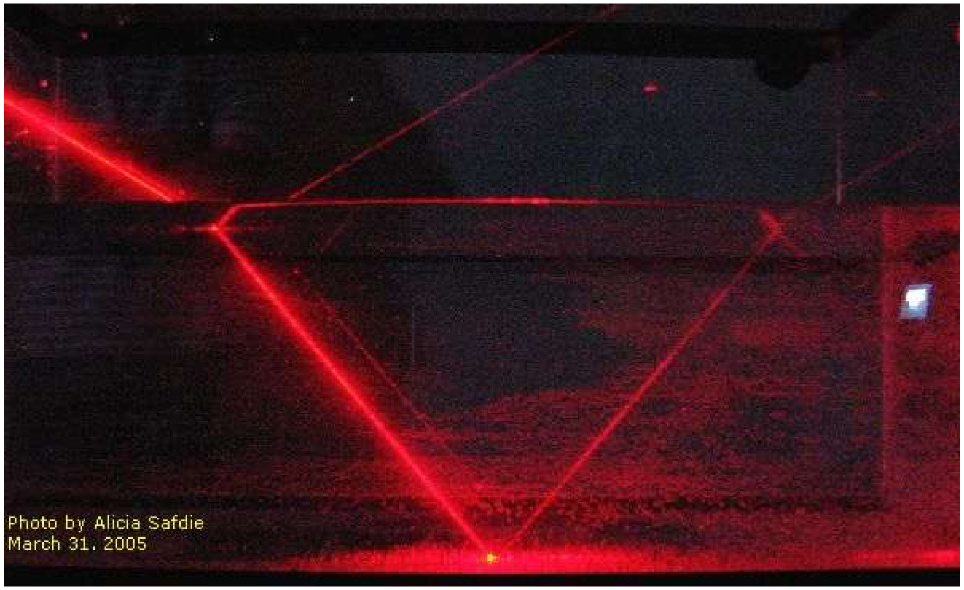
A ray indicates the direction of travel of the wave.

The Study of Light: Optics

- Geometric (or Rays) Optics:

Geometric Optics is the study of the propagation of light with the assumption that rays are *straight* lines in a *fixed* direction through an *uniform* medium.

- In most daily situations, light (rays) travel in a *straight* line in a *uniform* medium.
- At the boundary between two materials (air & glass), a ray's direction might change.
- Wave characteristics of light are not important.

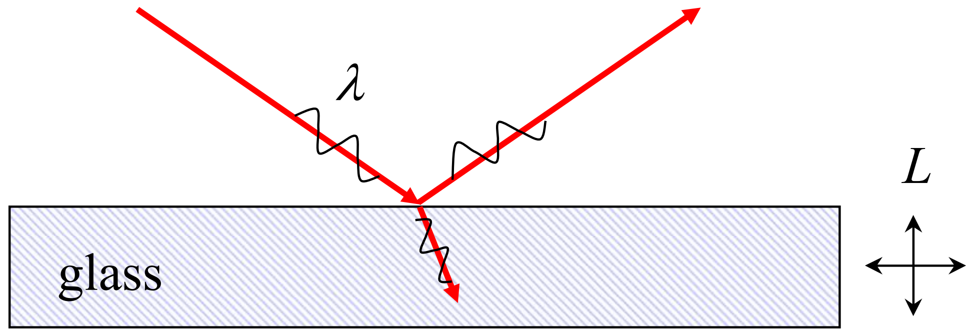


The Study of Light: Optics

- Condition for Rays Optics:

$$L >> \lambda$$

Relevant system size >> wavelength



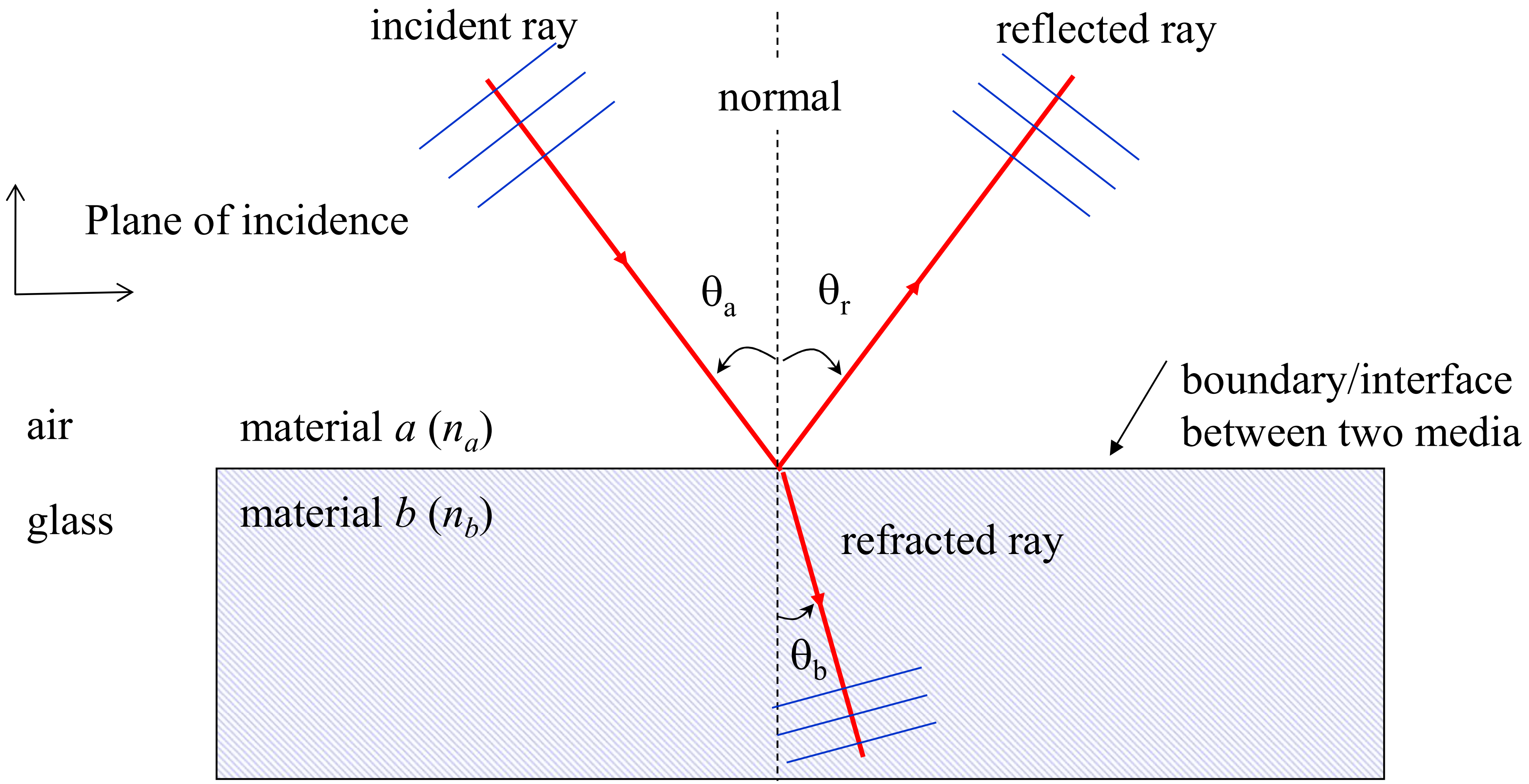
In this approximation, wave characteristic of light is not important and rays model of light gives accurate predictions.

(Visible light: $\lambda \sim 500$ nm $<< L$ → Rays Optics works well with typical optical instruments: mirror, lens, cameras, telescopes,…)

- Physical (Wave) Optics (Ch.35-36):

The study of light when wave properties of light are important (diffraction and interference). $L \approx \lambda$

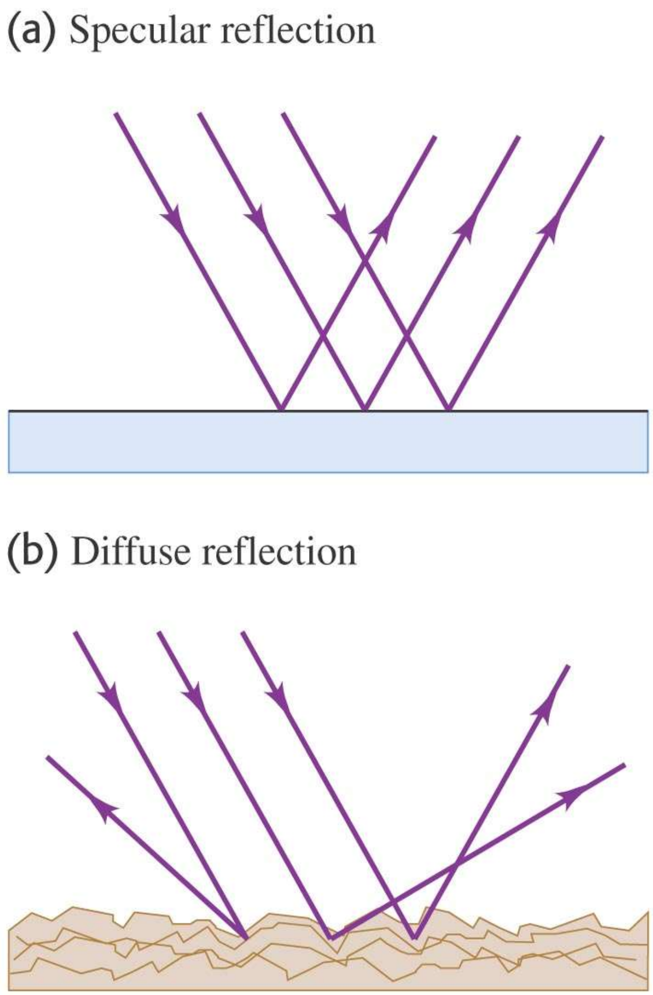
Reflection and Refraction



When light hits a *boundary*, typically a part of it will be *reflected* & a part of it will be *refracted*.

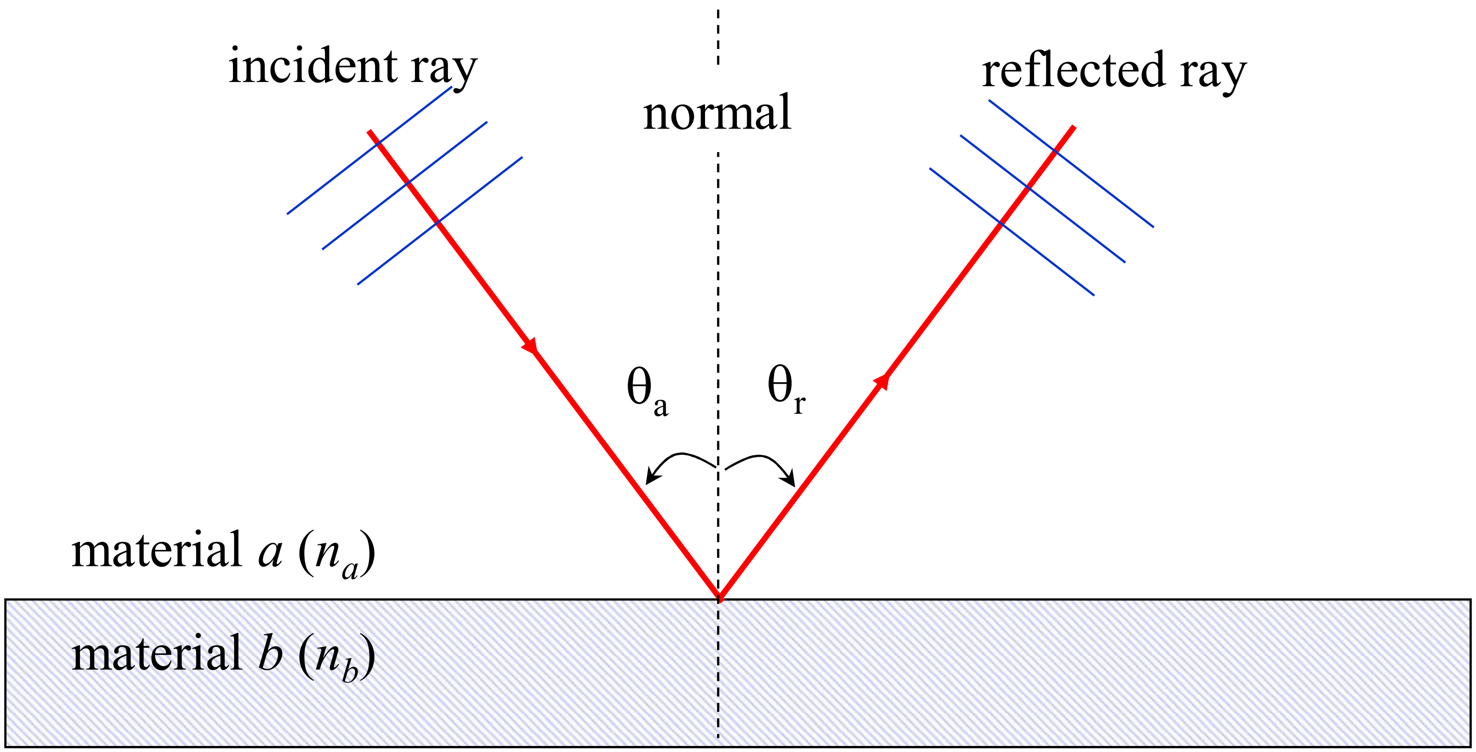
Reflection

- Specular Reflection
  - Reflection from a smooth surface
  - Reflected rays are parallel
- Diffused Reflection
  - Reflection from a rough surface
  - Reflected rays are in various directions



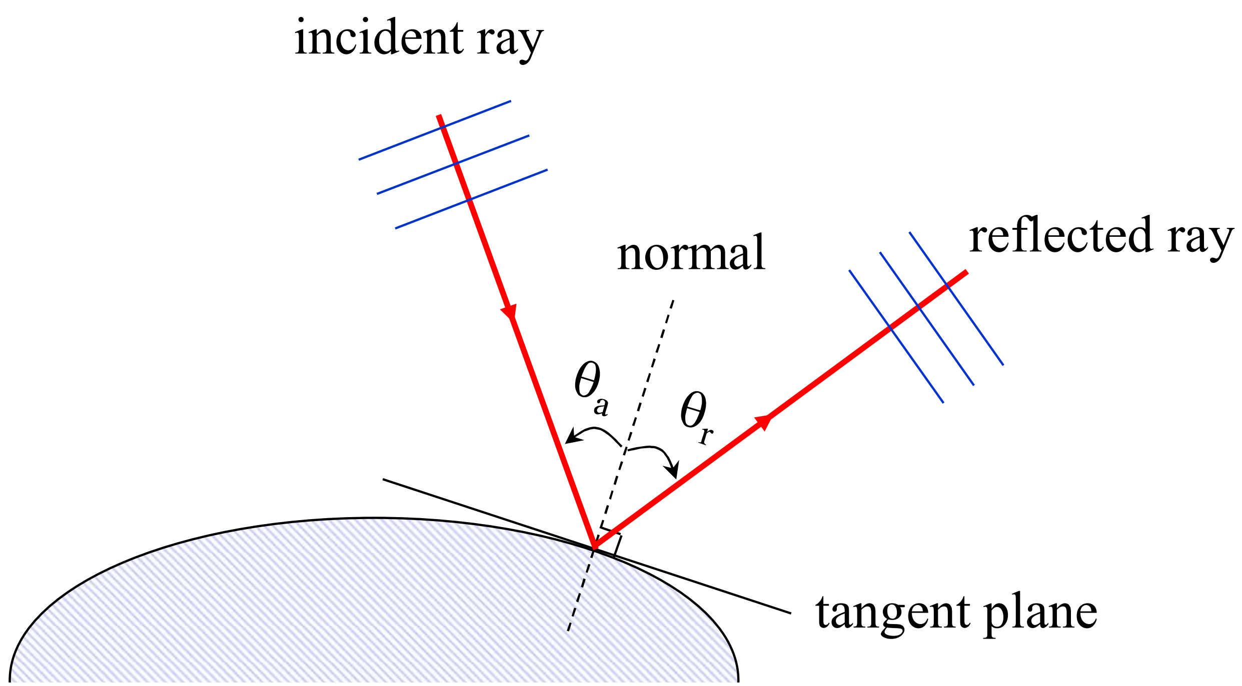
D magic mirror

Law of Reflection

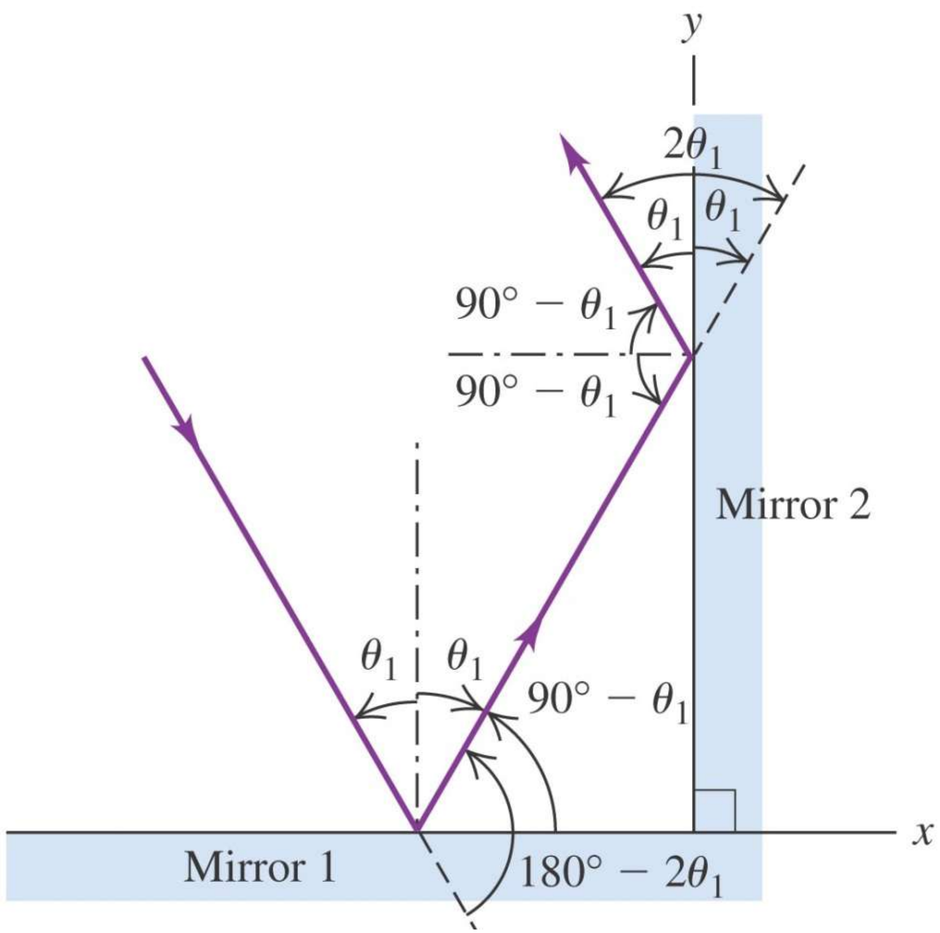


$$\theta_r \text{(angle of reflection)} = \theta_a \text{(angle of incidence)}$$

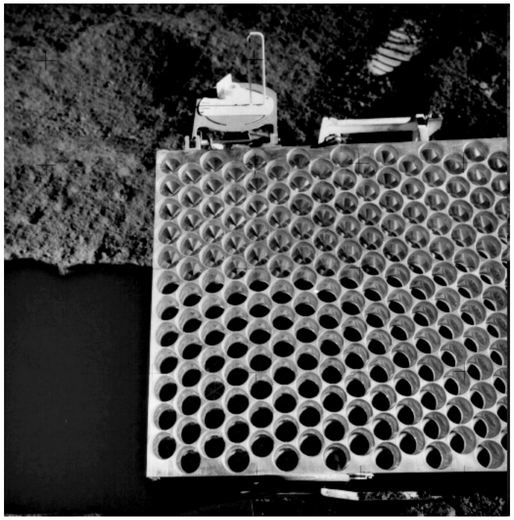
Law of Reflection (general interface)



Example 33.3 (Retroreflector)



Retroreflector on the moon



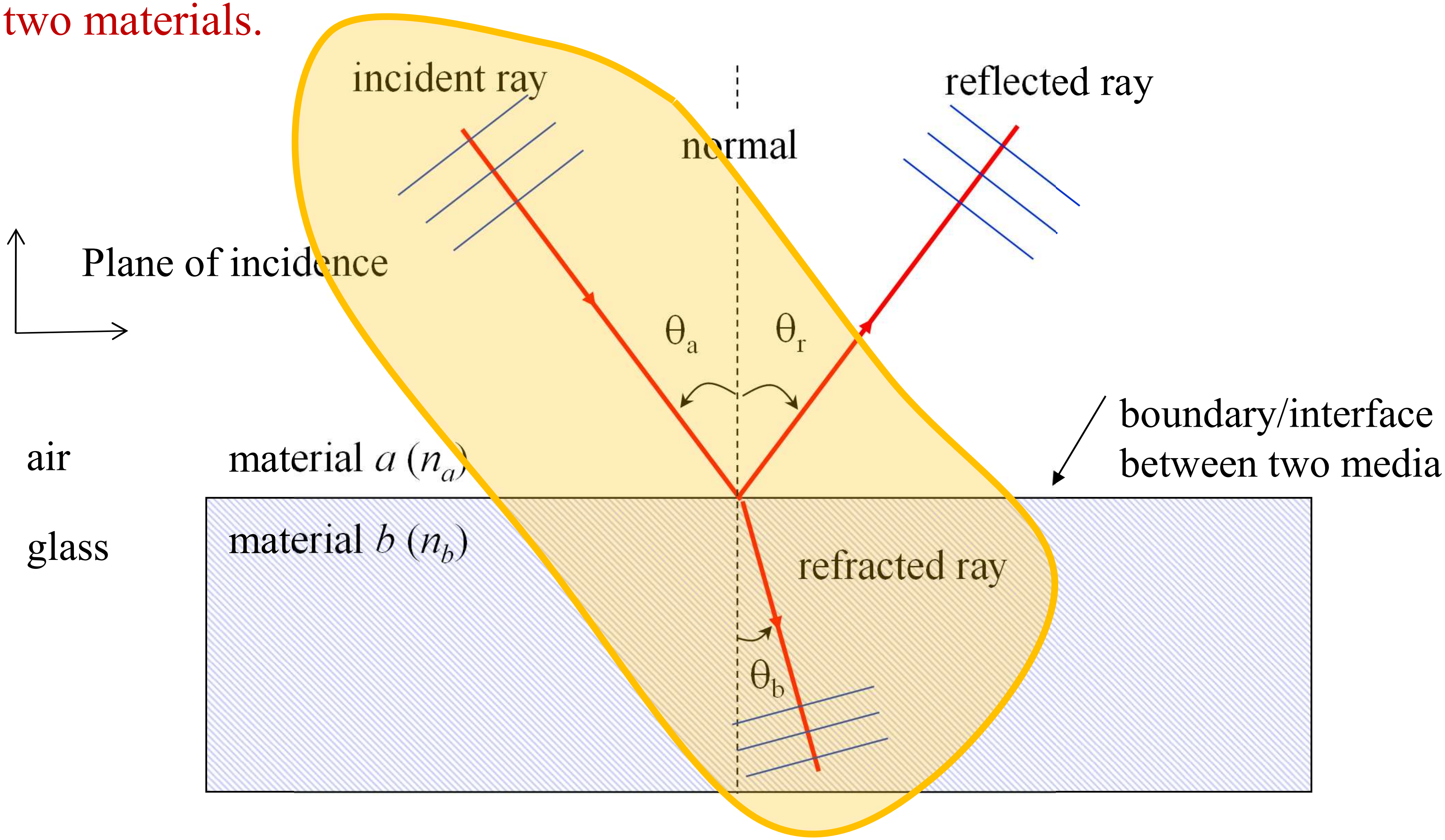
Reflected ray goes back in the same direction as incident ray independent of incident angel θ!

YouTube video of retroreflector: https://www.youtube.com/watch?reload=9&v=S4vYq31cpyc

$D_{\text{corner mirror}}$

Reflection and Refraction

Now, we will describe how light *refract* when it crosses a *boundary* between two materials.



Index of Refraction *n*:

- In materials, light interacts with atoms/molecules and travels *slower* than it can in vacuum, e.g.,

$$v_{water} \cong \frac{3}{4} c$$

- The optical property of transparent materials is called the **Index of Refraction**:

$$n \equiv \frac{c}{v_{material}} \quad \text{(Table 33.1)}$$

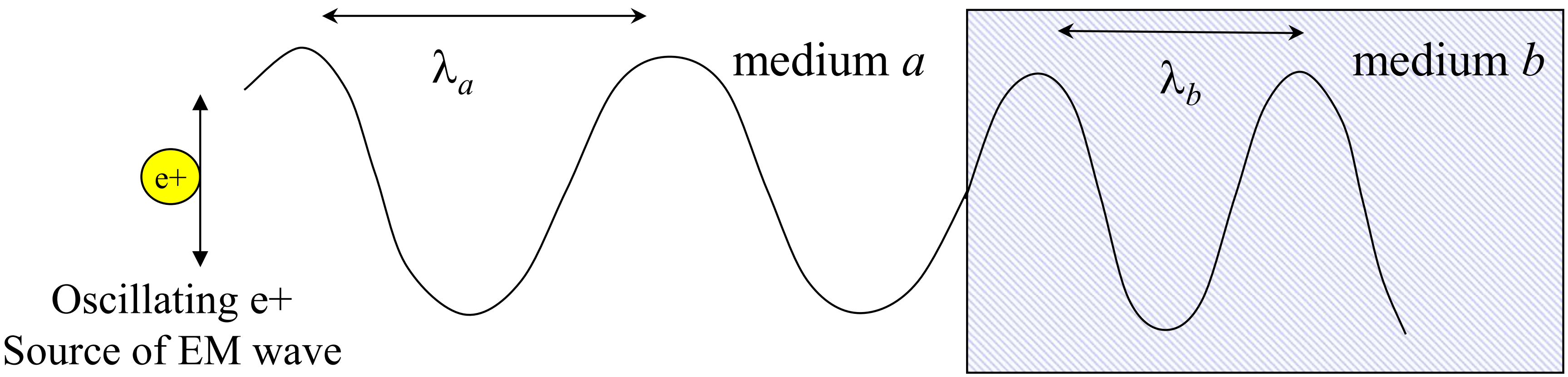
- Since $v_{\text{material}} < c$ always, $n > 1$!

Index of Refraction (n)

Table 33.1 Index of Refraction for Yellow Sodium Light $\lambda_0 = 589$ nm

Substance	Index of Refraction, n
Solids	
Ice (H_2O)	1.309
Fluorite (CaF_2)	1.434
Polystyrene	1.49
Rock salt (NaCl)	1.544
Quartz (SiO_2)	1.544
Zircon ($ZrO_2 \cdot SiO_2$)	1.923
Diamond (C)	2.417
Fabulite ($SrTiO_3$)	2.409
Rutile (TiO_2)	2.62
Glasses (typical values)	
Crown	1.52
Light flint	1.58
Medium flint	1.62
Dense flint	1.66
Lanthanum flint	1.80
Liquids at 20°C	
Methanol (CH_3OH)	1.329
Water (H_2O)	1.333
Ethanol (C_2H_5OH)	1.36
Carbon tetrachloride (CCl_4)	1.460
Turpentine	1.472
Glycerine	1.473
Benzene	1.501
Carbon disulfide (CS_2)	1.628

Index of Refraction and Wave Aspects of Light



$$n_a = \frac{c}{v_a} \qquad n_b = \frac{c}{v_b}$$

Note: *frequency* of the EM wave is dictated by the oscillations of the charge and the timing of this oscillation *can't change* for an observer in either medium *a* or *b*.

f does not change across media !

Index of Refraction and Wave Aspects of Light

Recall for a EM wave, we have: $v = f\lambda$

So, in the two medium, we have: $v_a = f\lambda_a$ and $v_b = f\lambda_b$

Dividing these two equations, we have:

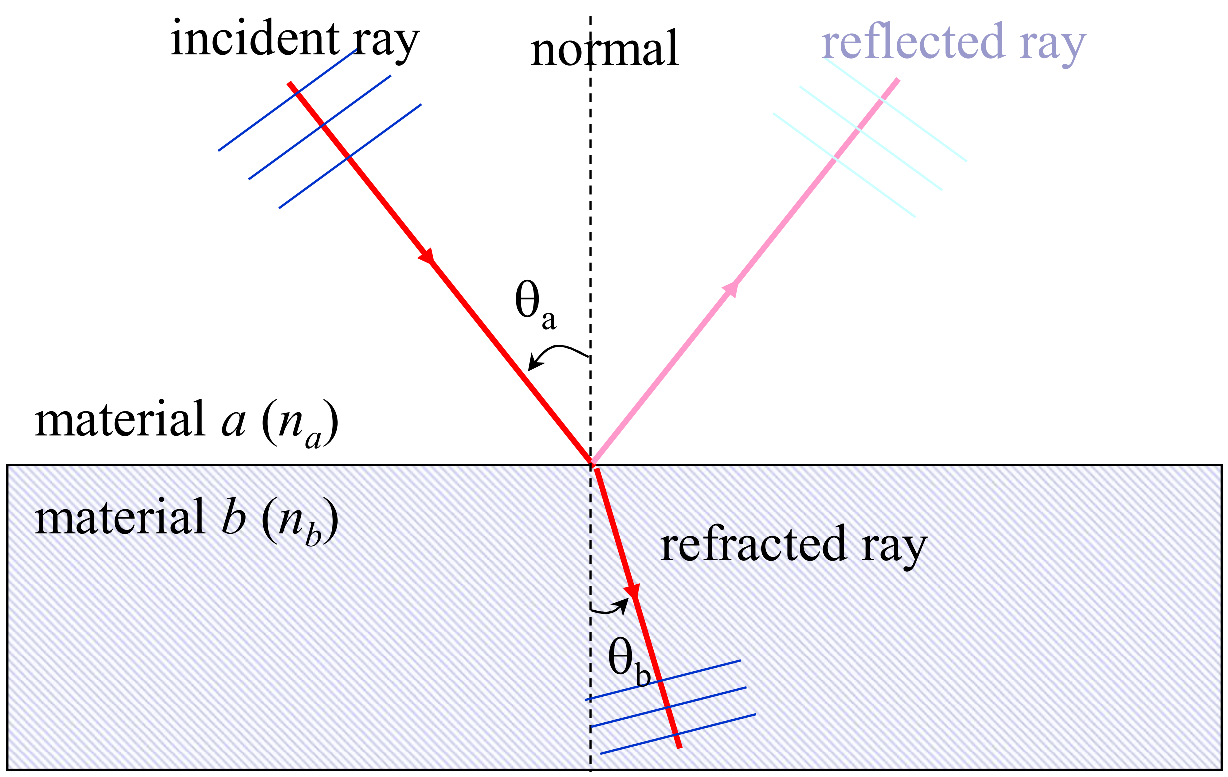
$$\frac{v_a}{v_b} = \frac{\not{f}\lambda_a}{\not{f}\lambda_b} = \frac{\lambda_a}{\lambda_b} \Rightarrow \frac{\lambda_a}{\lambda_b} = \frac{c/n_a}{c/n_b} \Rightarrow \frac{\lambda_a}{\lambda_b} = \frac{n_b}{n_a}$$

So, the wavelength of a light must change in different medium accordingly,

$$n_a\lambda_a = n_b\lambda_b$$

With one medium being a *vacuum*, we have $\lambda_n = \lambda/n$

Law of Refraction (Snell's Law)



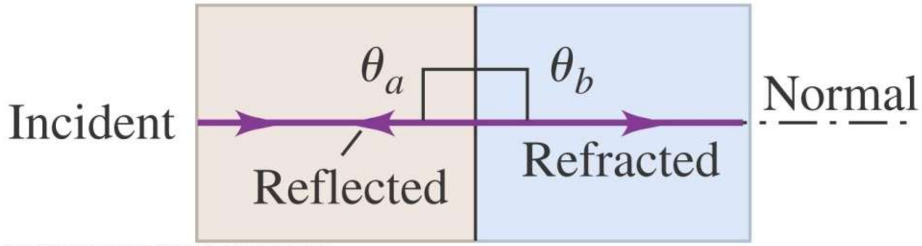
$$n_a \sin\theta_a = n_b \sin\theta_b$$

Snell's Law (3 cases)

$$n_a \sin\theta_a = n_b \sin\theta_b$$

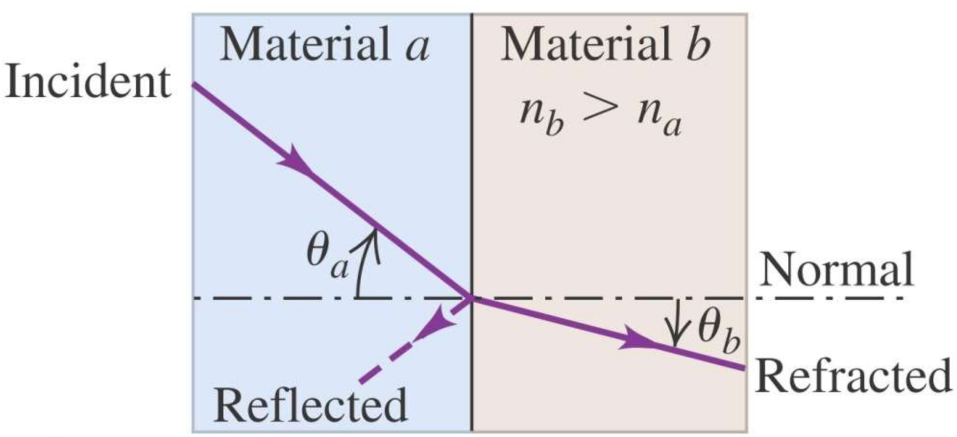
Recall
$$n = c / v$$

A ray oriented along the normal does not bend, regardless of the materials.

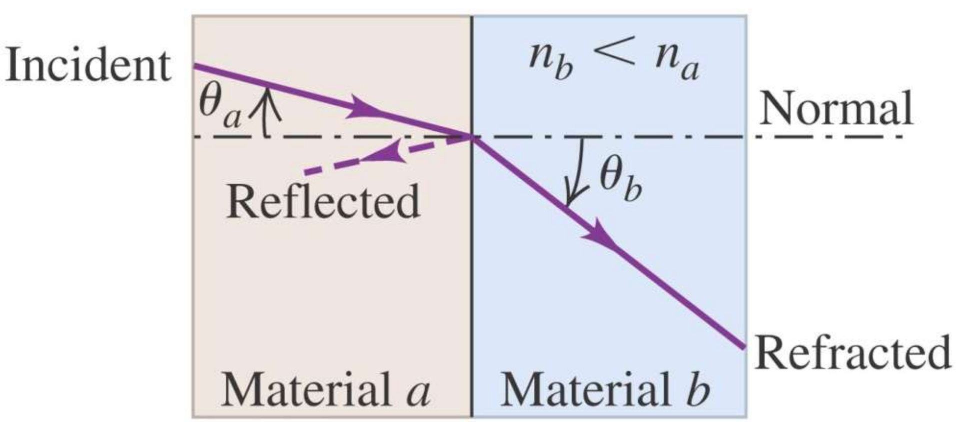


D_{pyrex_oil}

A ray entering a material of *larger* index of refraction bends *toward* the normal.

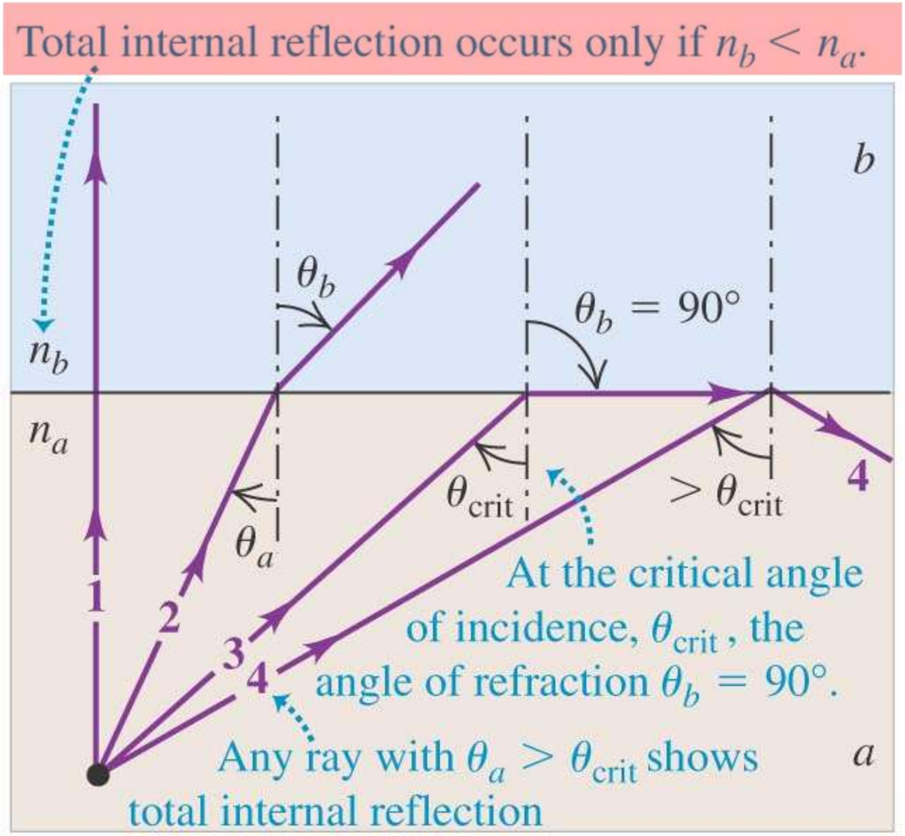


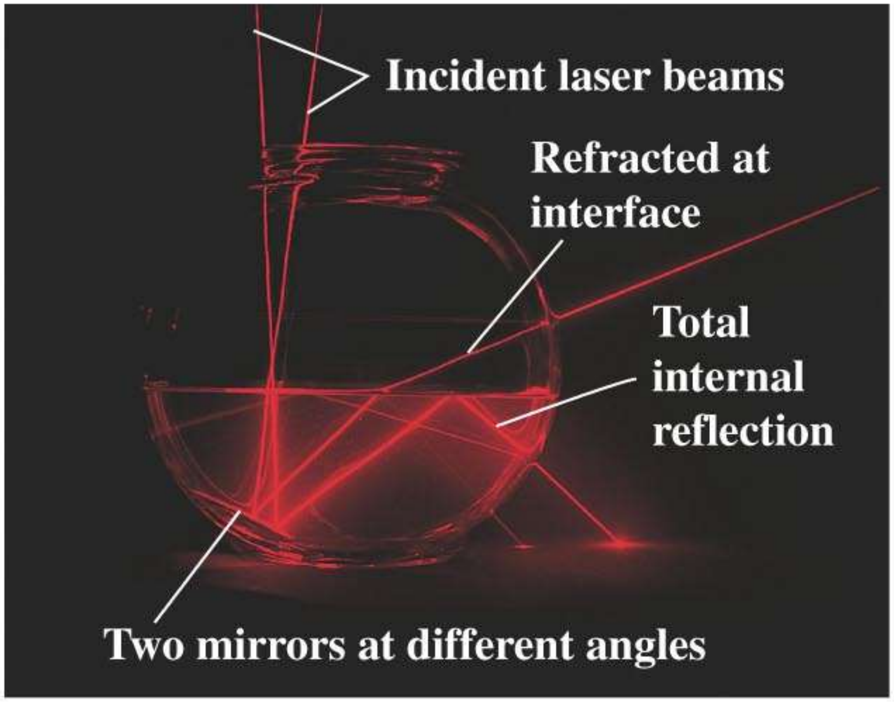
A ray entering a material of *smaller* index of refraction bends *away from* the normal.



Total Internal Reflection

- Light moves from a medium with a *larger n* to one with a *smaller n*.
- As the angle of incidence becomes more and more acute, the light ceases to be transmitted, only reflected.





Total Internal Reflection

- Critical Angle θ_{crit} is determined by the borderline case (ray 3).

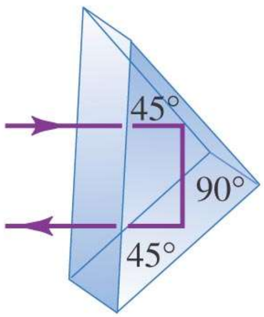
$$n_a \sin\theta_{crit} = n_b \sin 90^\circ \qquad \text{(from Snell's Law)}$$

$$\sin\theta_{crit} = \frac{n_b}{n_a}$$

(only valid for $n_a > n_b$)

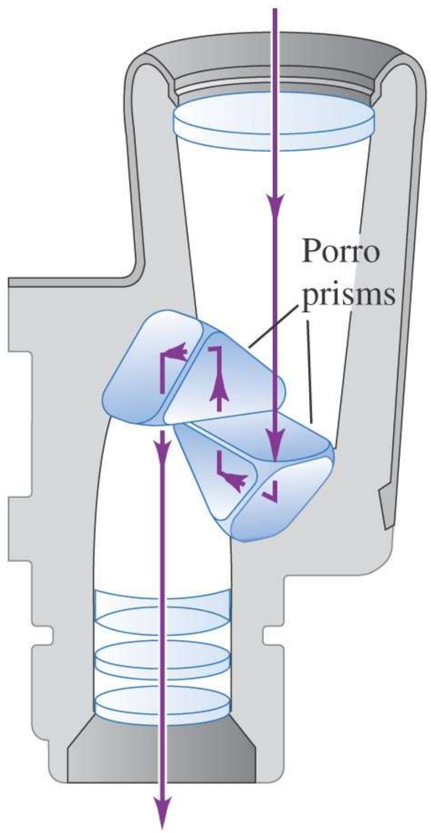
Applications of Internal Reflection

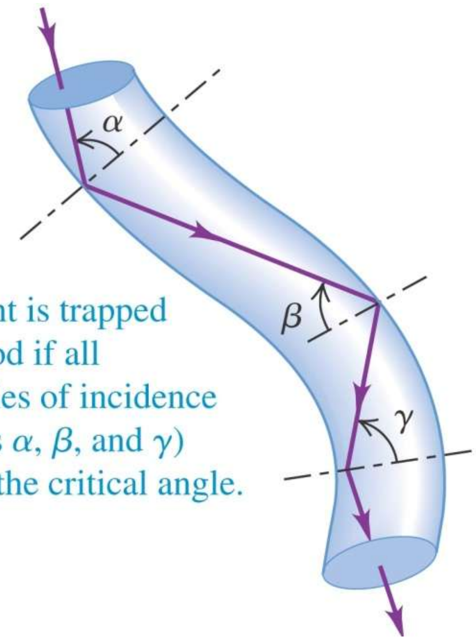
(a) Total internal reflection in a Porro prism



If the incident beam is oriented as shown, total internal reflection occurs on the 45° faces (because, for a glass–air interface, $\theta_{crit} = 41.1°$).

(b) Binoculars use Porro prism reflect the light to each eyepiec



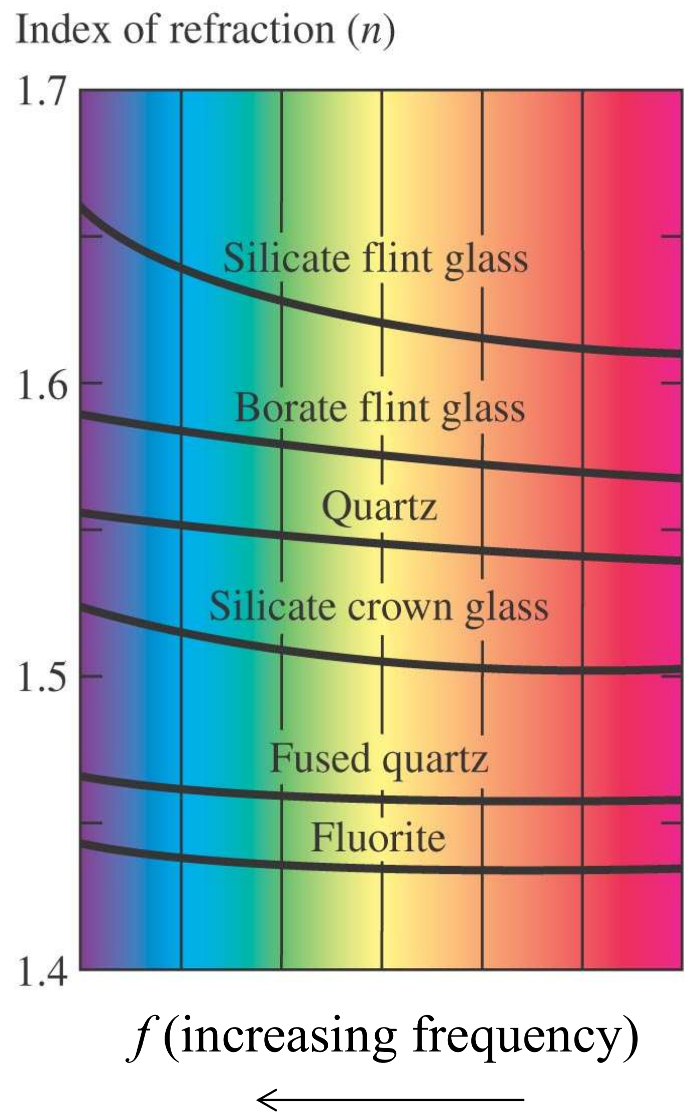


The light is trapped in the rod if all the angles of incidence (such as α, β, and γ) exceed the critical angle.

$D_{light\ pipe}$ $D_{natural\ rock}$

Dispersion

- The index of refraction *n* is usually a property of the medium but equally important, it also *varies* with the *frequency f* of light → **dispersion**.
- *n* typically increases with increasing *f*.



Physical Observable Consequence of Dispersion

- The Visible Spectrum of White Light

According to Snell's Law, angle of refraction depends on *n*,

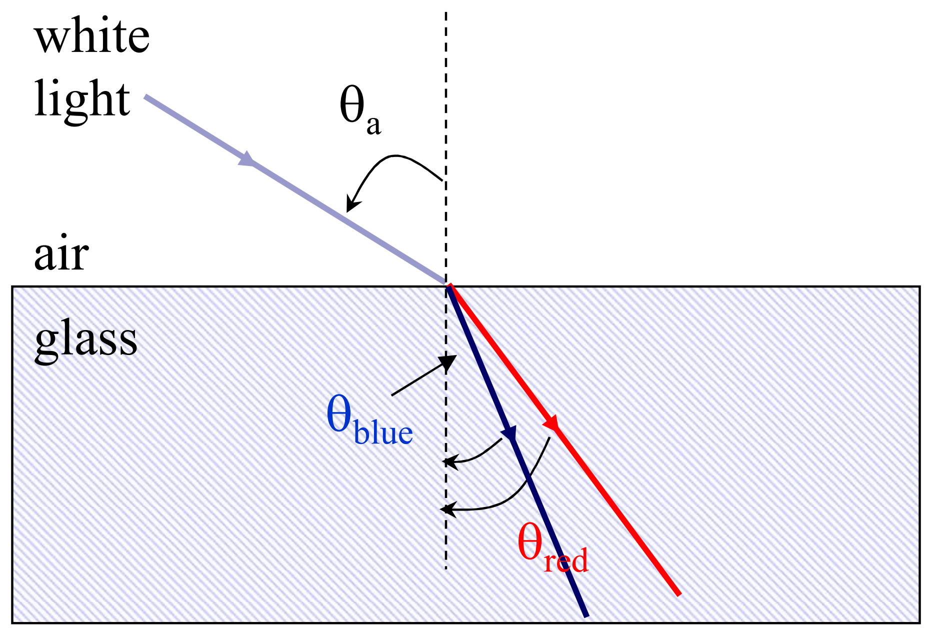
$$n \downarrow \;\Longrightarrow\; \text{angle of refraction} \uparrow$$

$$\sin\theta_a = n\sin\theta_{blue} \quad \text{and} \quad n\sin\theta_{red}$$

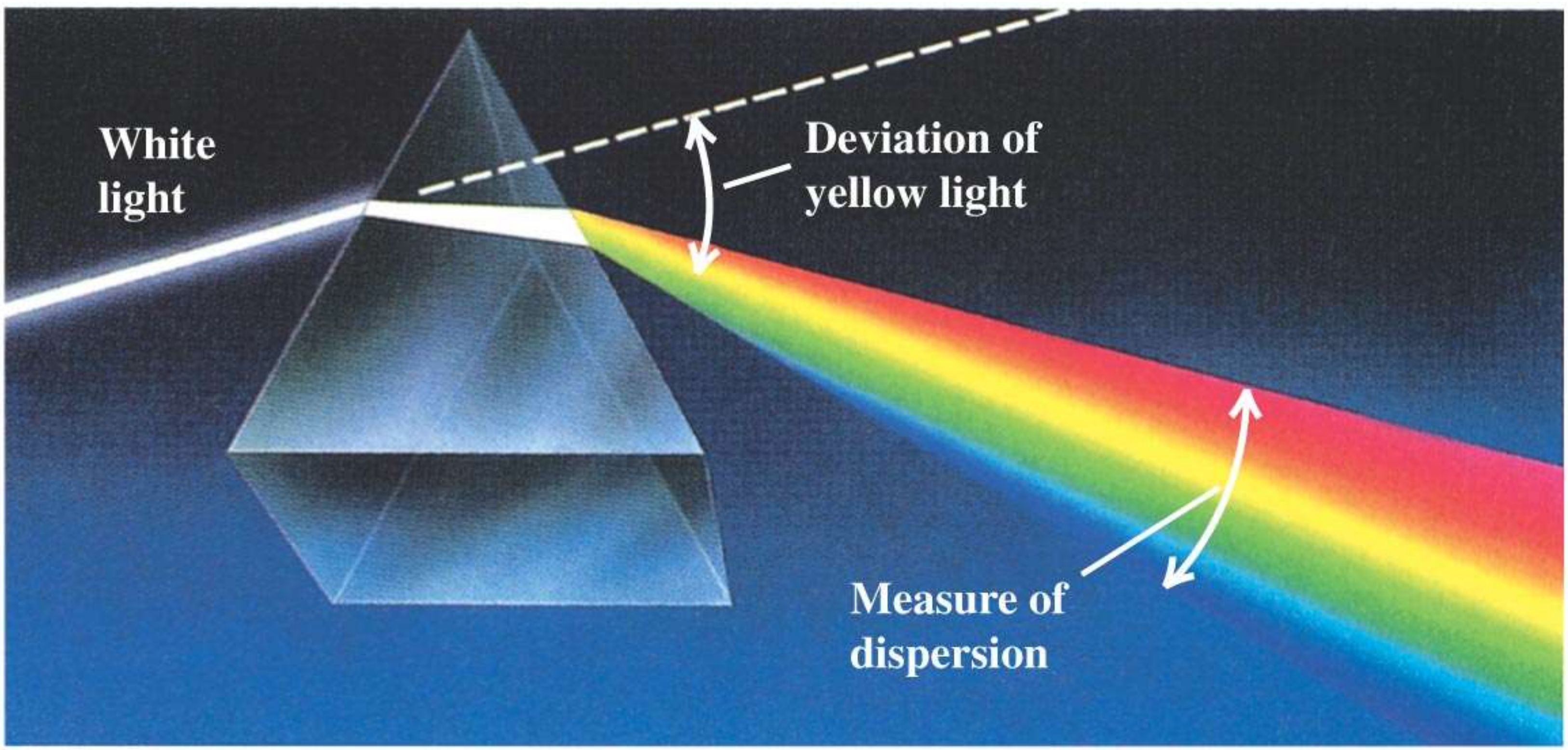
fixed incident direction of white light

$$n > n$$

$$\theta_{blue} < \theta_{red}$$



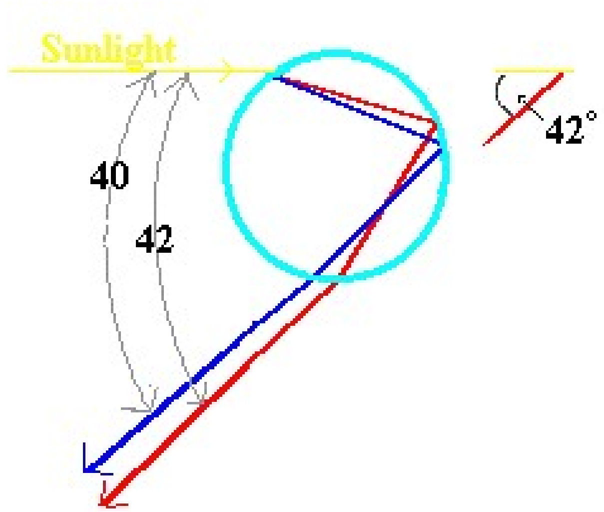
Dispersion by a Prism



D_{prism}

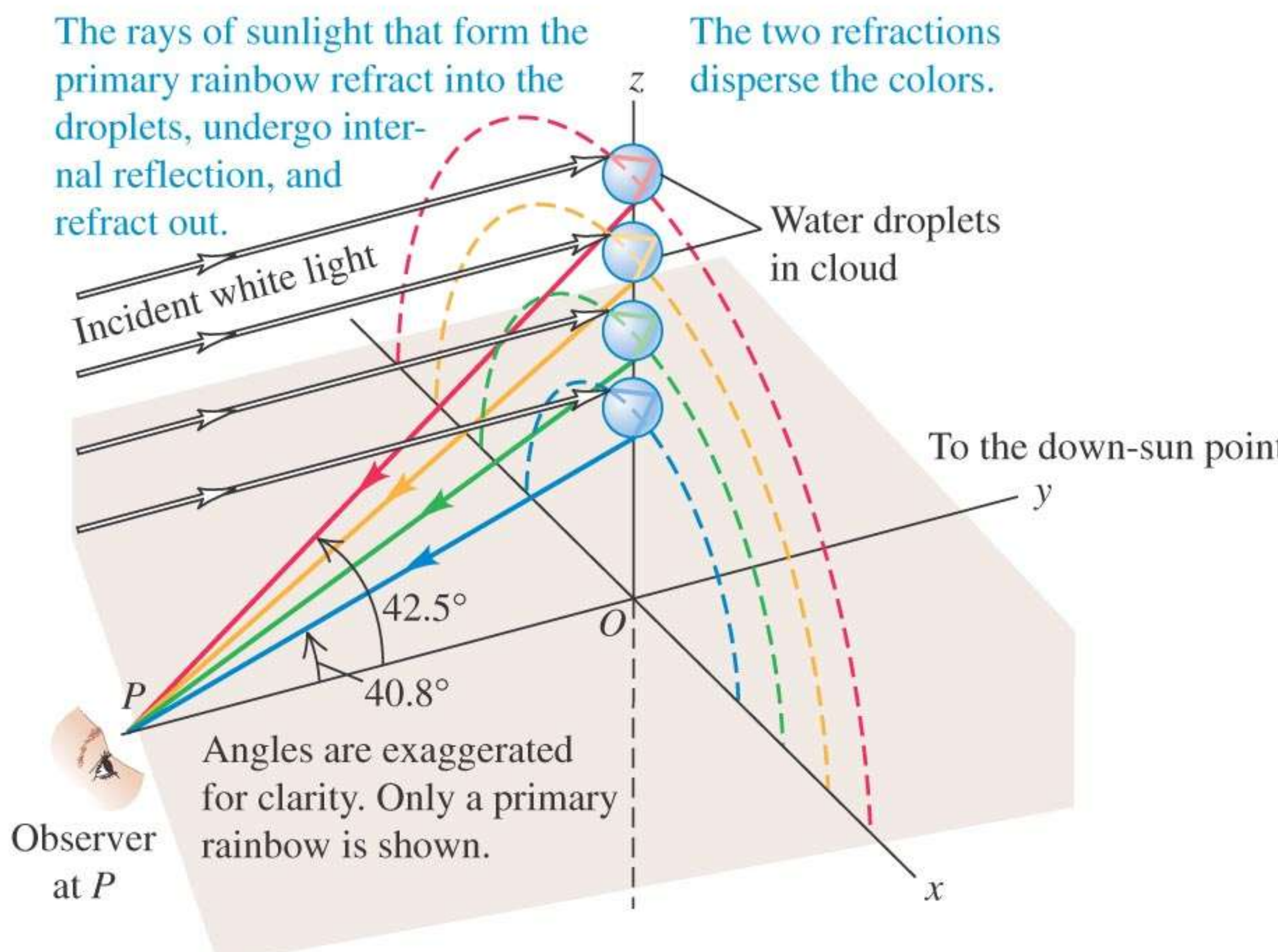
Dispersion in a Rainbow

From a Single Drop



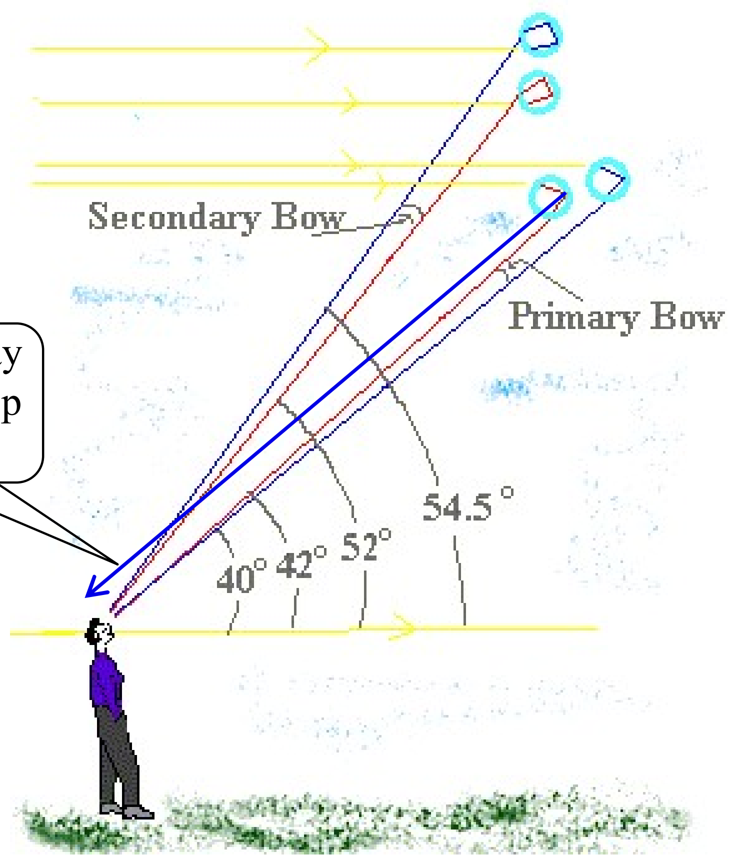
- Red comes out at 42°
  Blue comes out at 40°

Forming a rainbow. The sun in this illustration is directly behind the observer at P.



Dispersion in a Rainbow

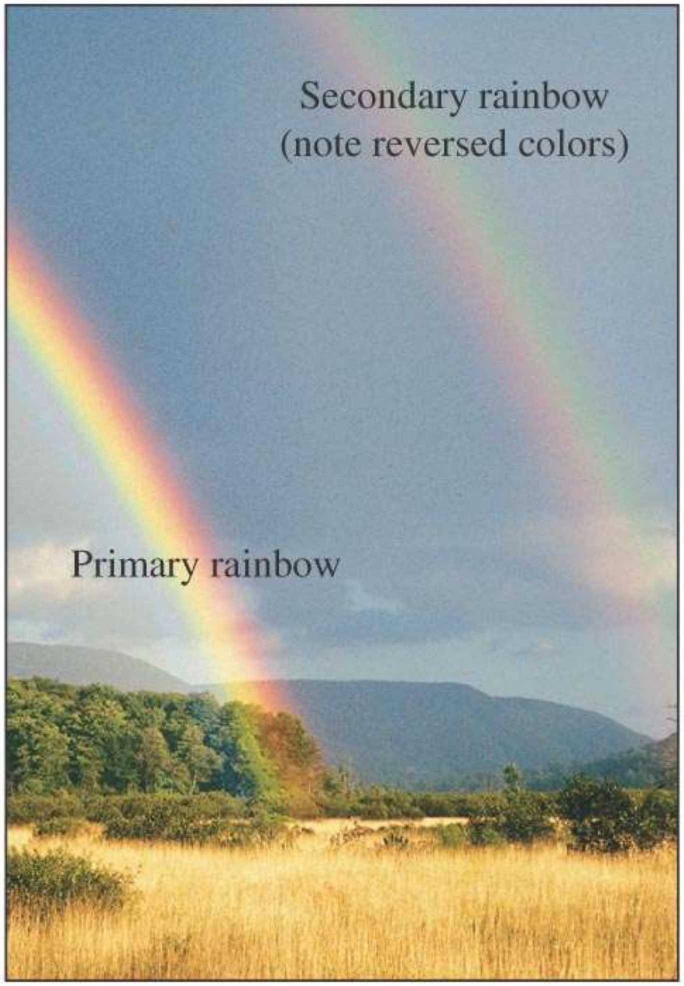
Double Rainbow from Multiple Droplets



Note: blue ray from this drop misses eye

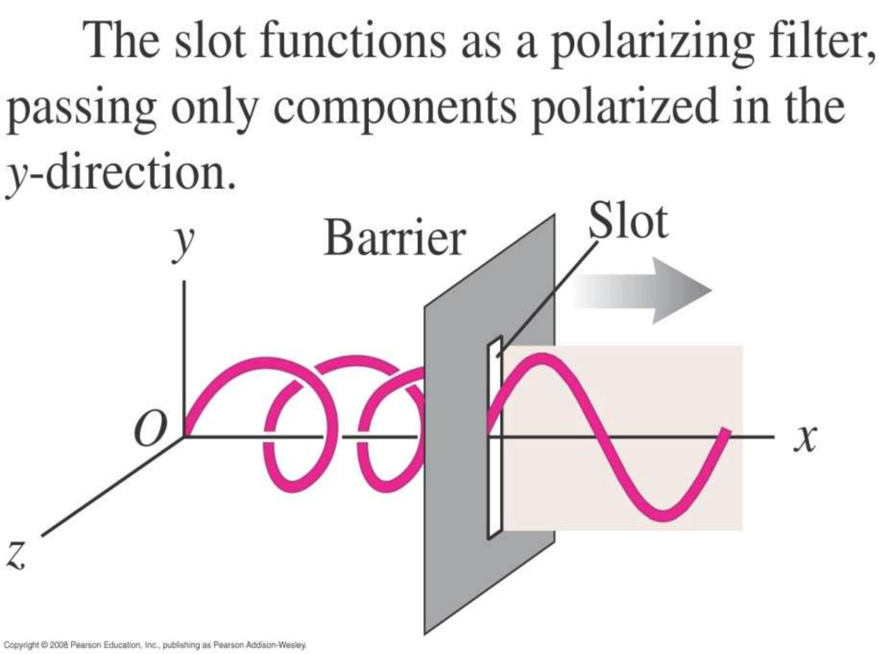
Gifs taken from http://eo.ucar.edu/rainbows/

A double rainbow

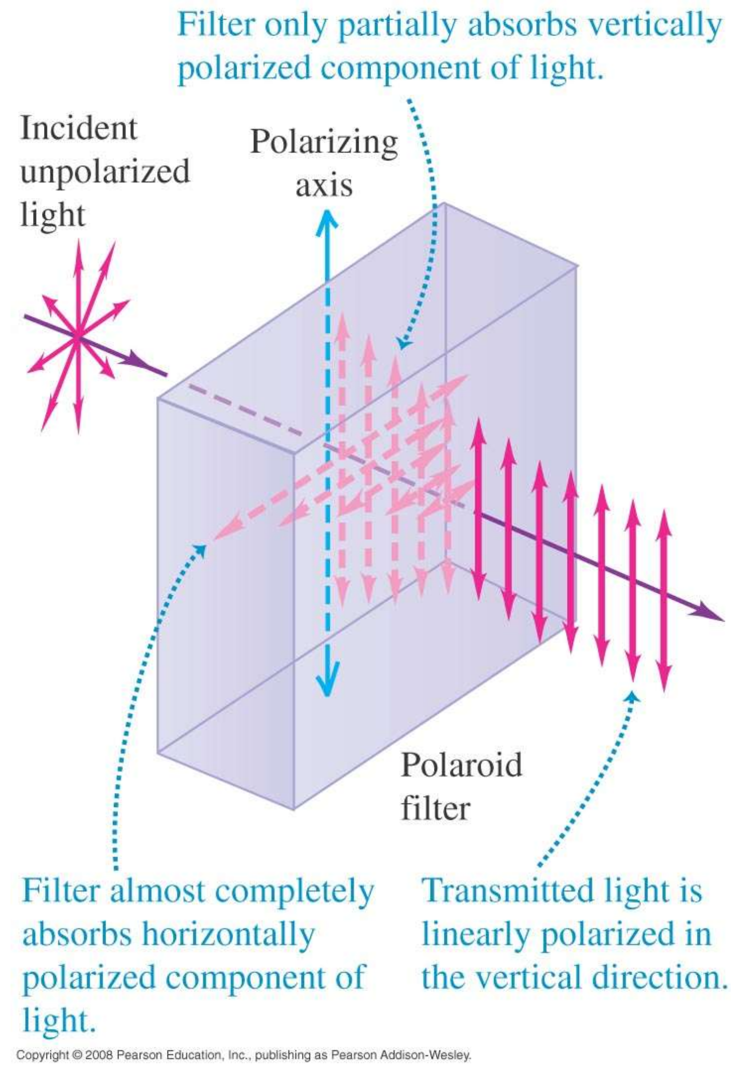


Polarization by Filters

A *non*-linearly polarized wave on a string can be polarized by a slot barrier.



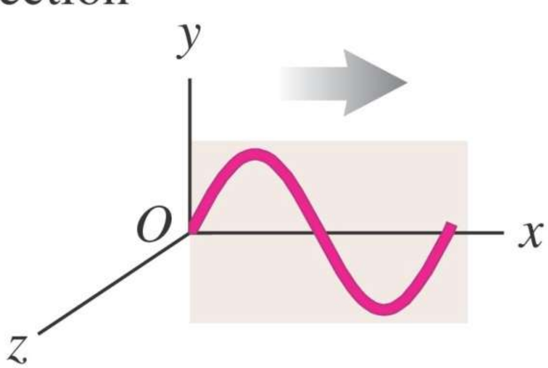
Polaroid Filter for an EM Wave



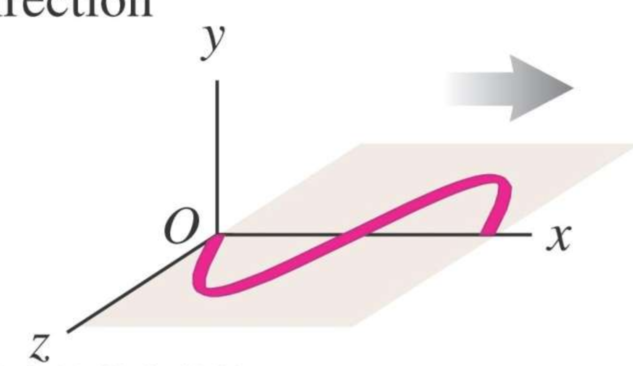
Polarization

For a transverse wave on a string, the direction of the wave's *displacement* gives the **polarization** of the wave.

(a) Transverse wave linearly polarized in the y-direction



(b) Transverse wave linearly polarized in the z-direction

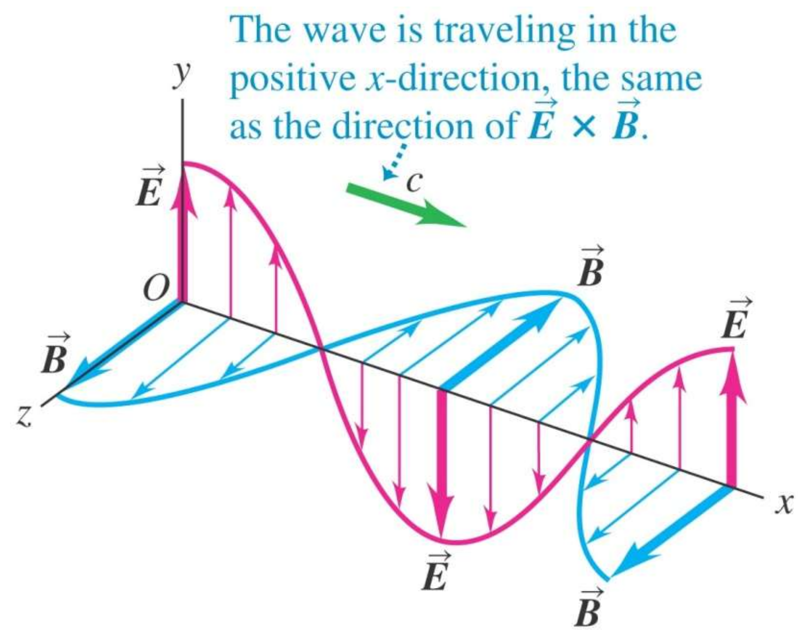


A Linearly Polarized EM Wave

For an electromagnetic wave, the direction of the *electric* field vector $\vec{\mathbf{E}}(x,t)$ gives the **polarization** of the wave.

An transverse electromagnetic wave with polarization in the y-direction:

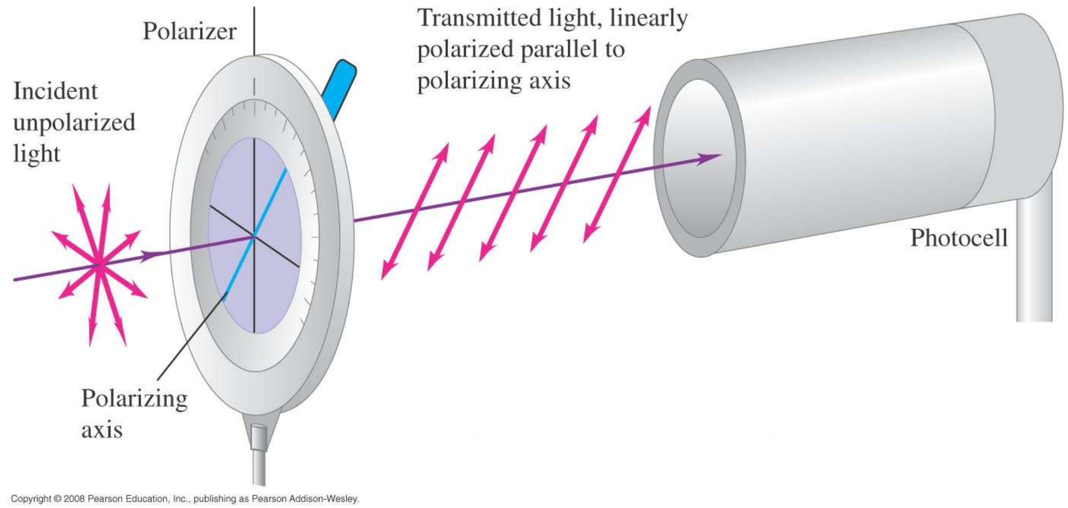
$$\begin{cases} \vec{\mathbf{E}}(x,t) = E_{\max}\cos(kx-\omega t)\,\hat{\mathbf{j}} \\ \vec{\mathbf{B}}(x,t) = B_{\max}\cos(kx-\omega t)\,\hat{\mathbf{k}} \end{cases}$$



A polarized wave in a well defined direction is called a *linearly polarized* wave.

The Action of a Polarizing Filter

Unpolarized incident light will be linearly polarized parallel to the polarizing axis after transmission.



We can analyze the intensity of the transmitted light passing thru the *second* polarizer (an analyzer):

Only $E_{||}$ will be transmitted,

$$E_{trans} = E_{||} = E\cos\phi$$