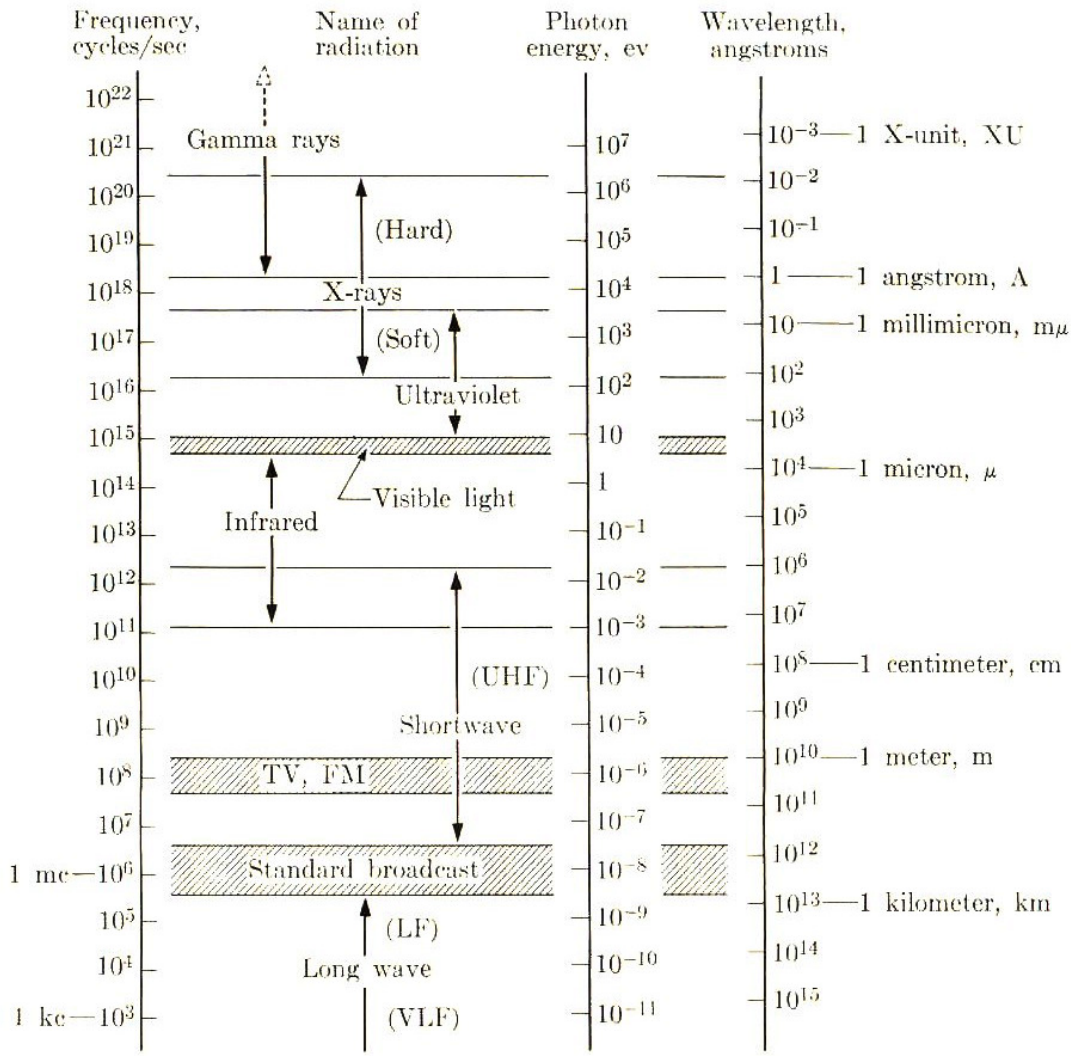
Chapter 33 - Light

Properties of Light

1. The Speed of Light
2. The Propagation of Light
3. Reflection and Refraction
4. Polarization

Electromagnetic Spectrum of Radiation

The visible spectrum runs from about 4000 Å to 8000 Å or 400nm to 800nm.



Electromagnetic Spectrum of Radiation

$$Ultraviolet \Leftarrow\ 400nm \quad \le \quad \lambda \quad \le \quad 700nm \Rightarrow\ Infrared$$

Short wavelength | Long wavelength

Violet | Red

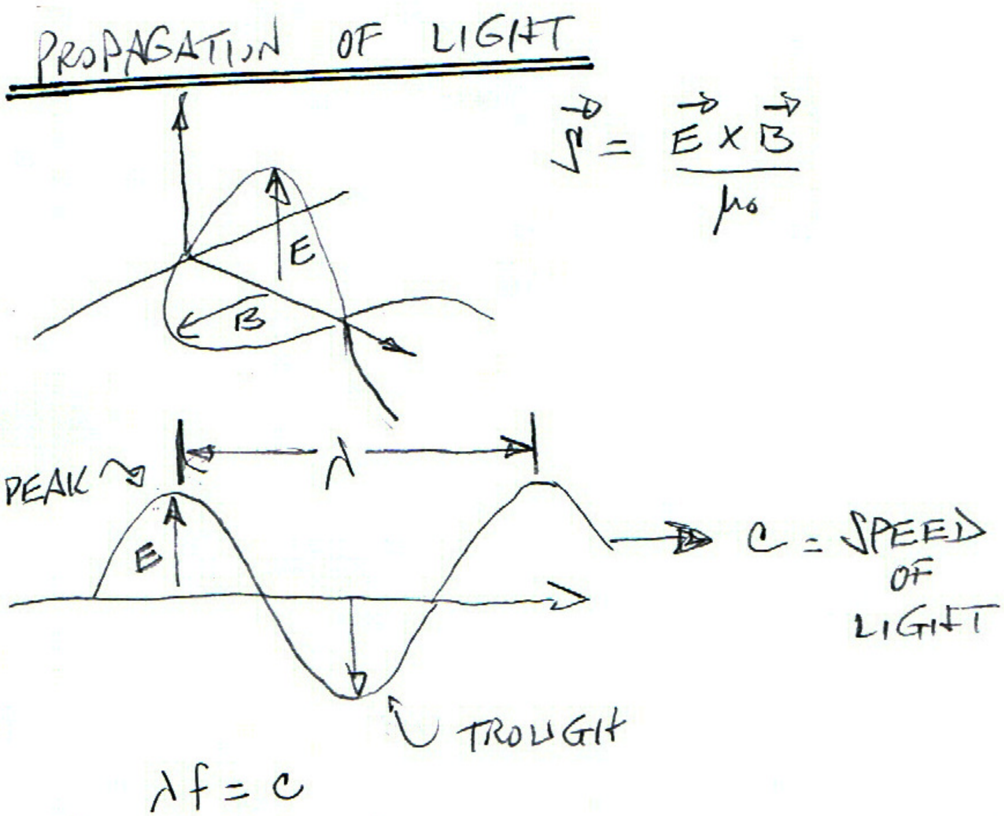
High Energy | Low Energy

$$\lambda f = c \qquad E = hf$$

Planck's constant $h = 6.626 \times 10^{-34}$ Js $= 4.136 \times 10^{-15}$ ev-s

The Propagation of Light

Electromagnetic Waves

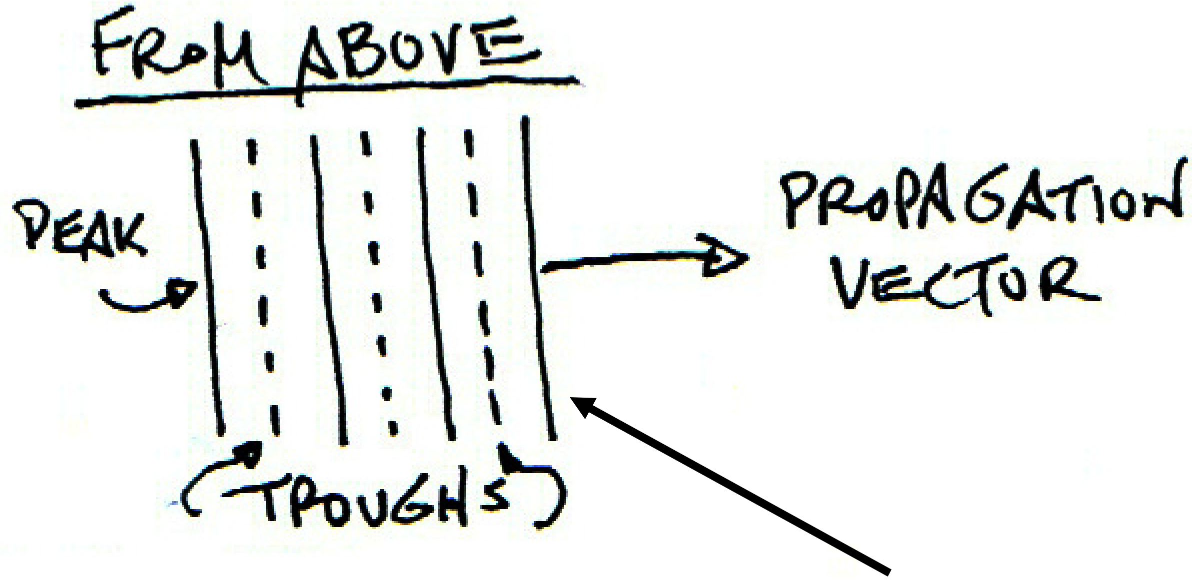


In Optics we treat light (EM radiation) as a wave.

We ignore the B vector and treat the E vector only when it comes to polarization.

The orientation of the E vector can be manipulated.

Propagation Vectors are Light Rays



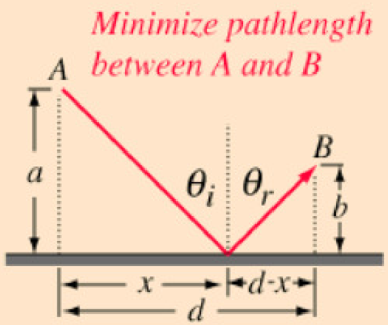
Wave fronts of plane waves

Fermat's Principle

The path taken by light traveling from one point to another is such that the time of travel is a minimum.

Fermat's Principle:Reflection

Fermat's Principle: Light follows the path of least time. The law of reflection can be derived from this principle as follows:



The pathlength L from A to B is

$$L = \sqrt{a^2 + x^2} + \sqrt{b^2 + (d - x)^2}$$

Since the speed is constant, the minimum time path is simply the minimum distance path. This may be found by setting the derivative of L with respect to x equal to zero.

$$\frac{dL}{dx} = \frac{1}{2}\frac{2x}{\sqrt{a^2 + x^2}} + \frac{1}{2}\frac{2(d-x)(-1)}{\sqrt{b^2 + (d-x)^2}} = 0$$

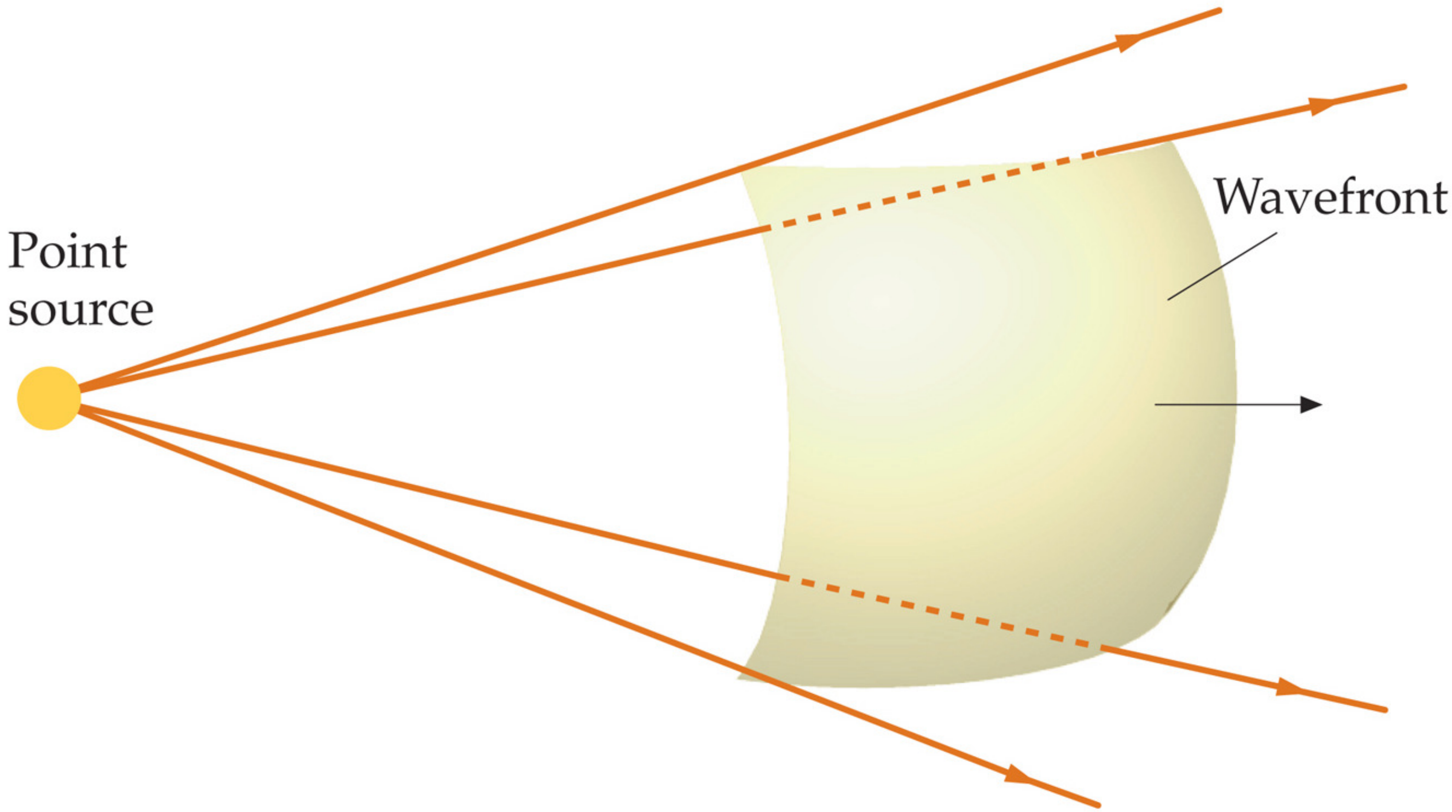
This reduces to $\dfrac{x}{\sqrt{a^2 + x^2}} = \dfrac{(d-x)}{\sqrt{b^2 + (d-x)^2}}$ which is $\sin\theta_i = \sin\theta_r$

This shows that: $\theta_i = \theta_r$ Law of Reflection

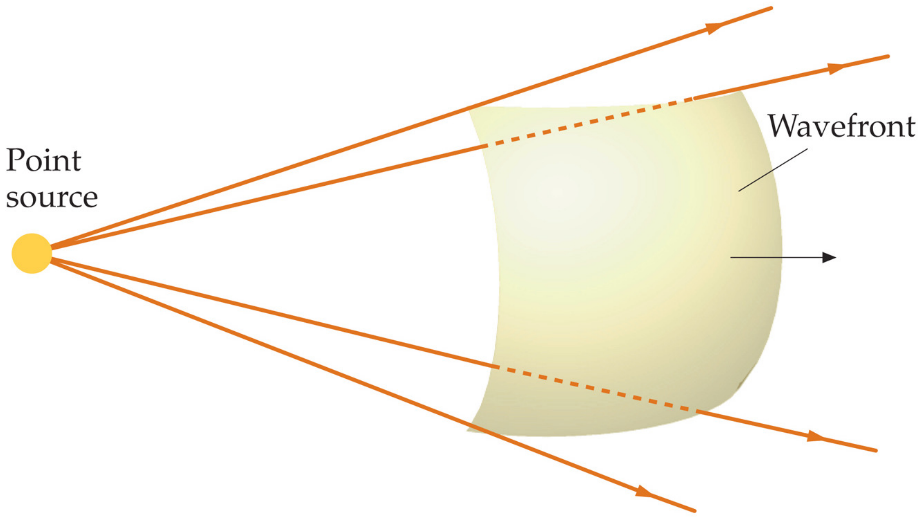
This derivation makes use of the calculus of maximum-minimum determination, the derivative of a square root, and the definitions of the triangle trig functions.

http://hyperphysics.phy-astr.gsu.edu/hbase/phyopt/fermat.html

Spherical Wave Front



Wave Fronts and Rays

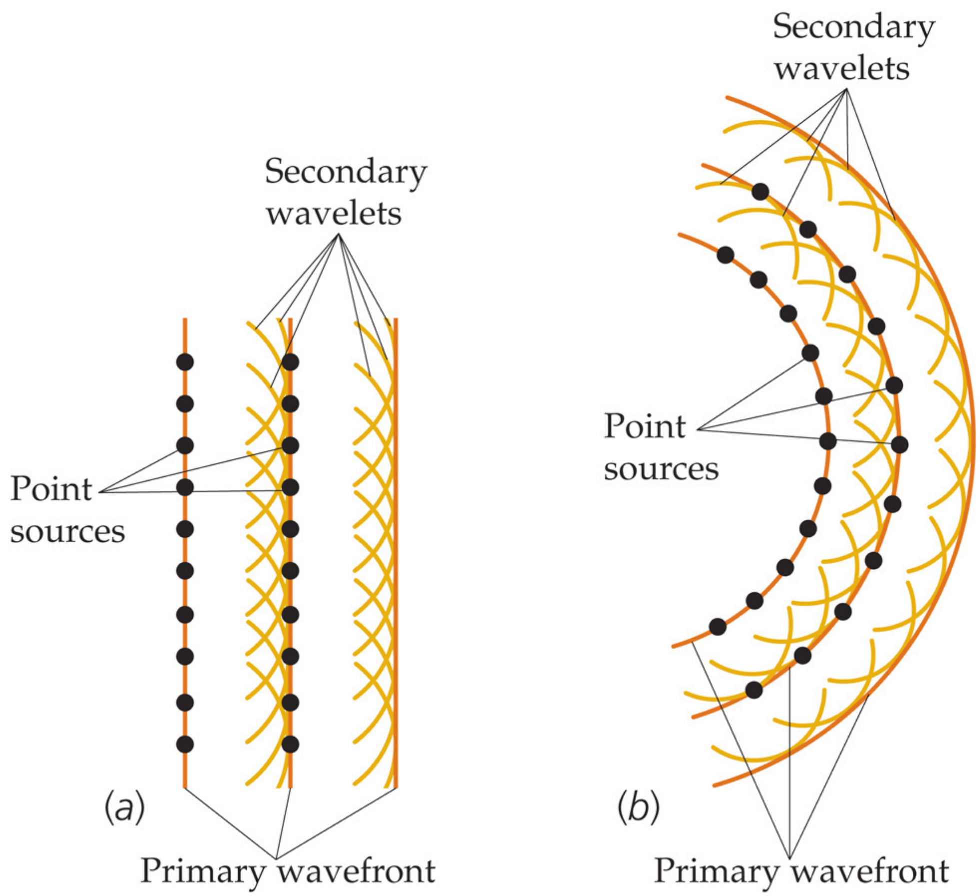


A light wave can be represented by a wave front which is useful for discussing certain aspects of wave propagation.

A vector that is normal to the wave front is called a light ray.

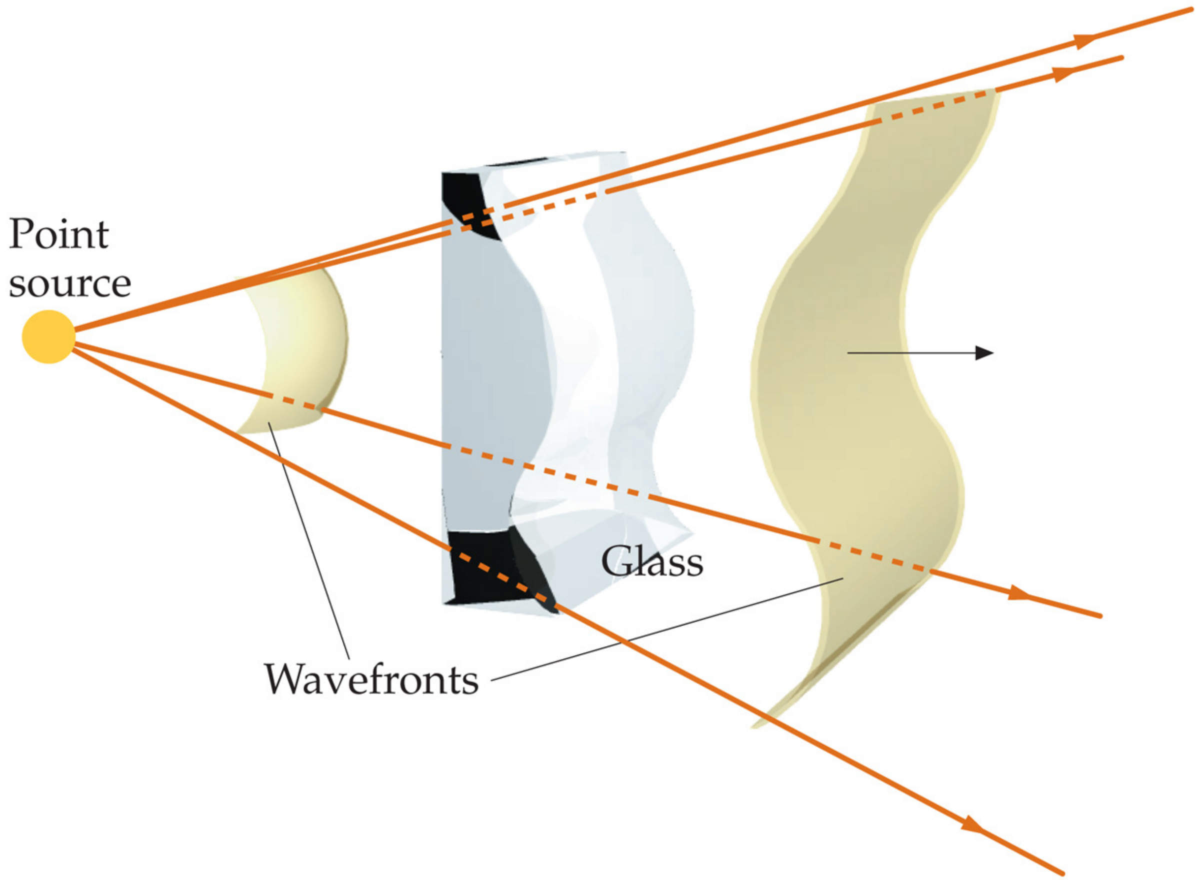
For tracing light through a transparent material the light ray formalism is more useful

Huygens Principle

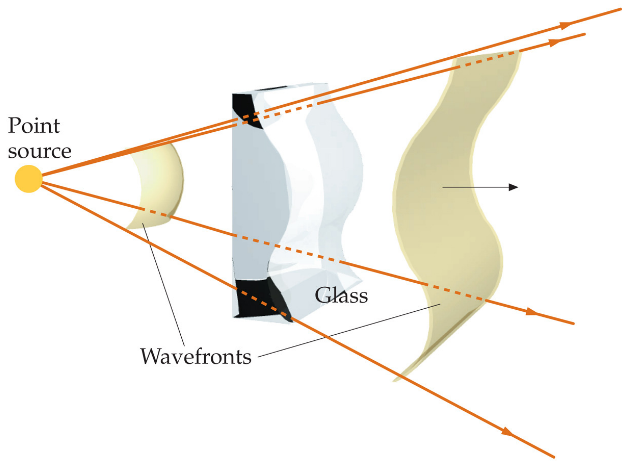


"Each point on a primary wavefront serves as the source of spherical secondary wavelets that advance at the wave speed for the propagating medium. The primary wavefront at some later time is the envelope of these wavelets."

Transformation of the Wave Front



Transformation by Elastic Scattering

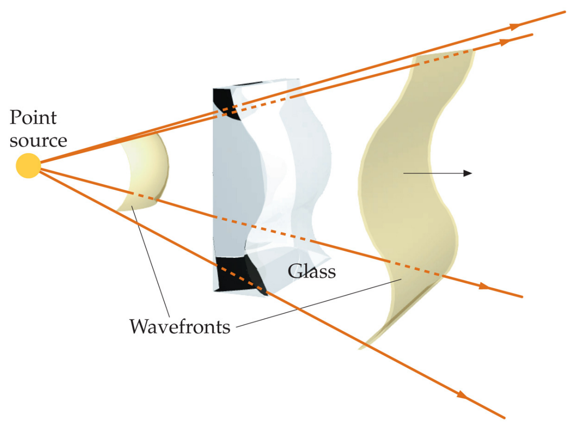


Scattering of electromagnetic radiation (light) is described physically as elastic absorbtion and re-radiation (emission).

The word elastic means that no energy is lost in the scattering process.

This absorbtion and emission process takes time. It makes the light appear to be traveling slower when passing through a transparent material such as glass.

Transformation by Elastic Scattering



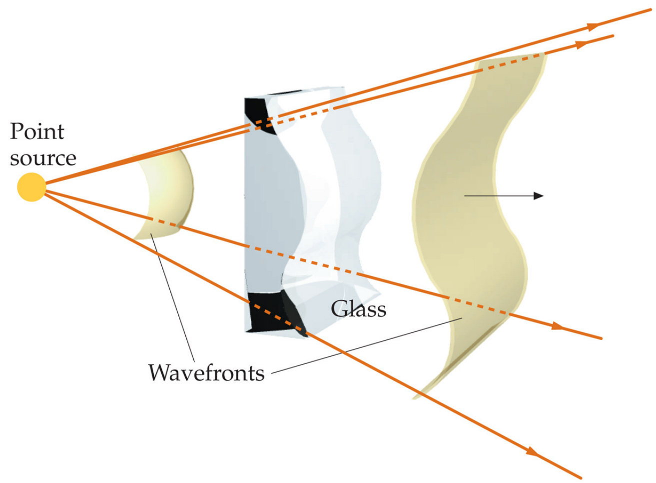
$$\lambda f = c \qquad E = hf$$

In free space the speed of light is a constant. EM radiation travels at the speed of light or it doesn't exist at all. Between the absorption and emission processes the EM wave doesn't exist. Its energy is in the absorbing atom or molecule.

It is convenient to describe the passage of light through a transparent material as traveling slower rather than describing the details of the absorbtion and emission.

Transformation of the Wave Front

$\lambda f = c \qquad E = hf = h\dfrac{c}{\lambda}$



Notice that the portion of the wave front that went through the thickest piece of glass is the farthest behind. This is because the speed of the wave slows down in glass.

Remember this is elastic scattering - energy is conserved. The wavelength and speed must both decrease to maintain constant E.

Planck's constant $h = 6.626\text{x}10^{-34}$ Js $= 4.136\text{x}10^{-15}$ ev-s

Wavelength in a Medium

For all waves $\lambda f = v$

In a medium λ *and v change*

λ' *has a velocity v in the medium*

$$\lambda' f = v$$

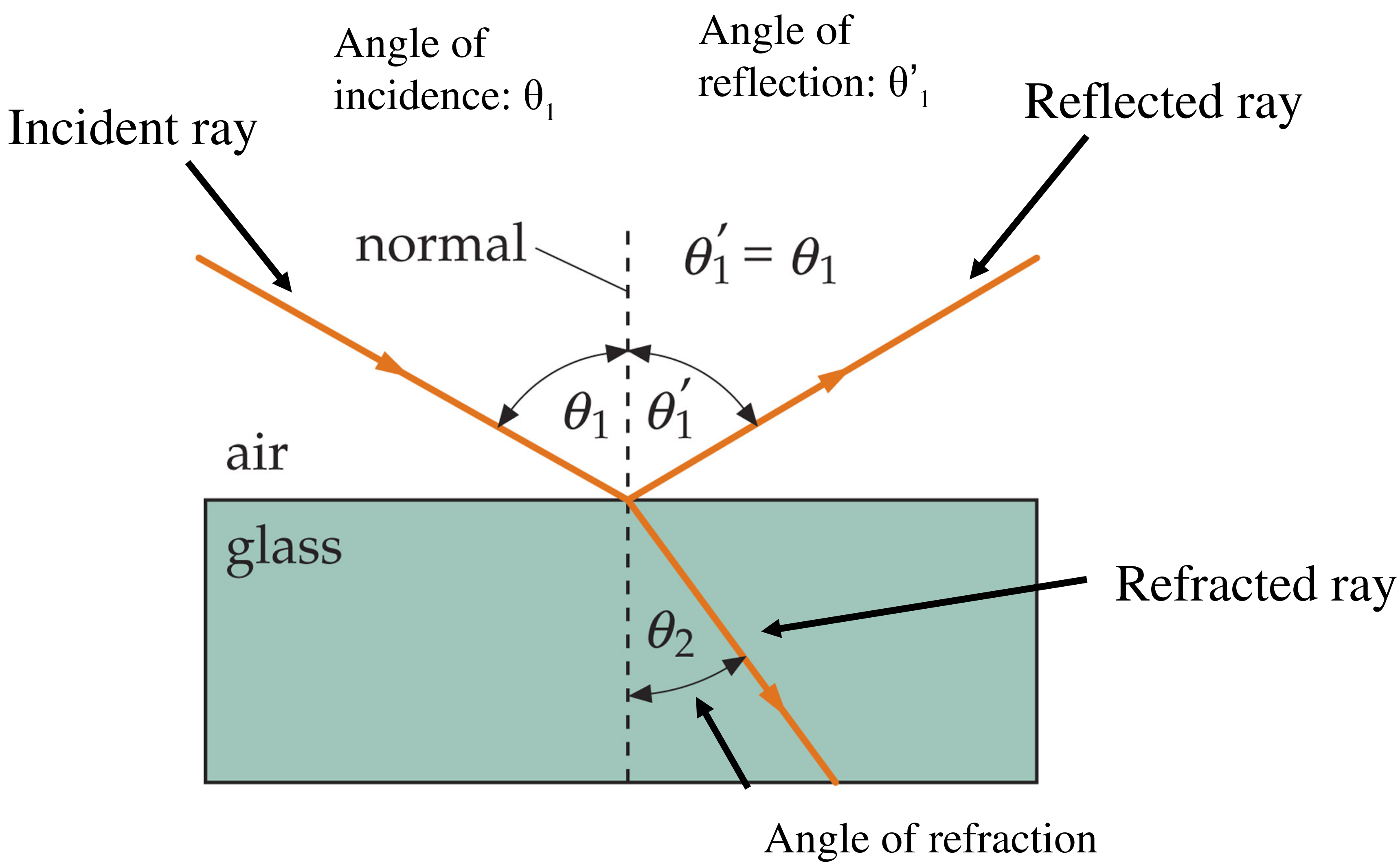
$$\frac{\lambda}{\lambda'} = \frac{c}{v} \;\; or \;\; \lambda' = \frac{\lambda}{c/v} = \frac{\lambda}{n}$$

Since $n > 1 \quad \lambda' < \lambda$

Therefore λ decreases in a transparent material

Reflection and Refraction

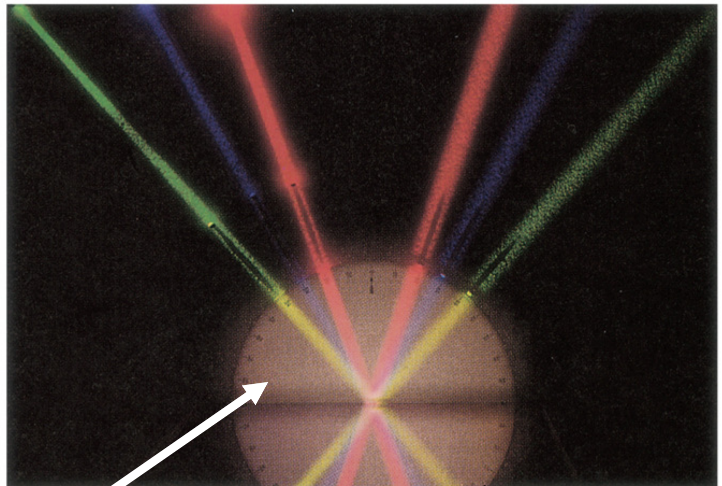
Reflection and Refraction



Reflection and Refraction

Incident waves

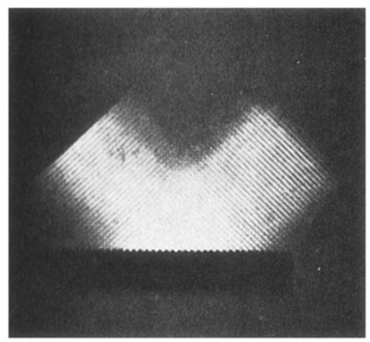
Reflected waves



(a)

Semicircular glass disk

Refracted waves

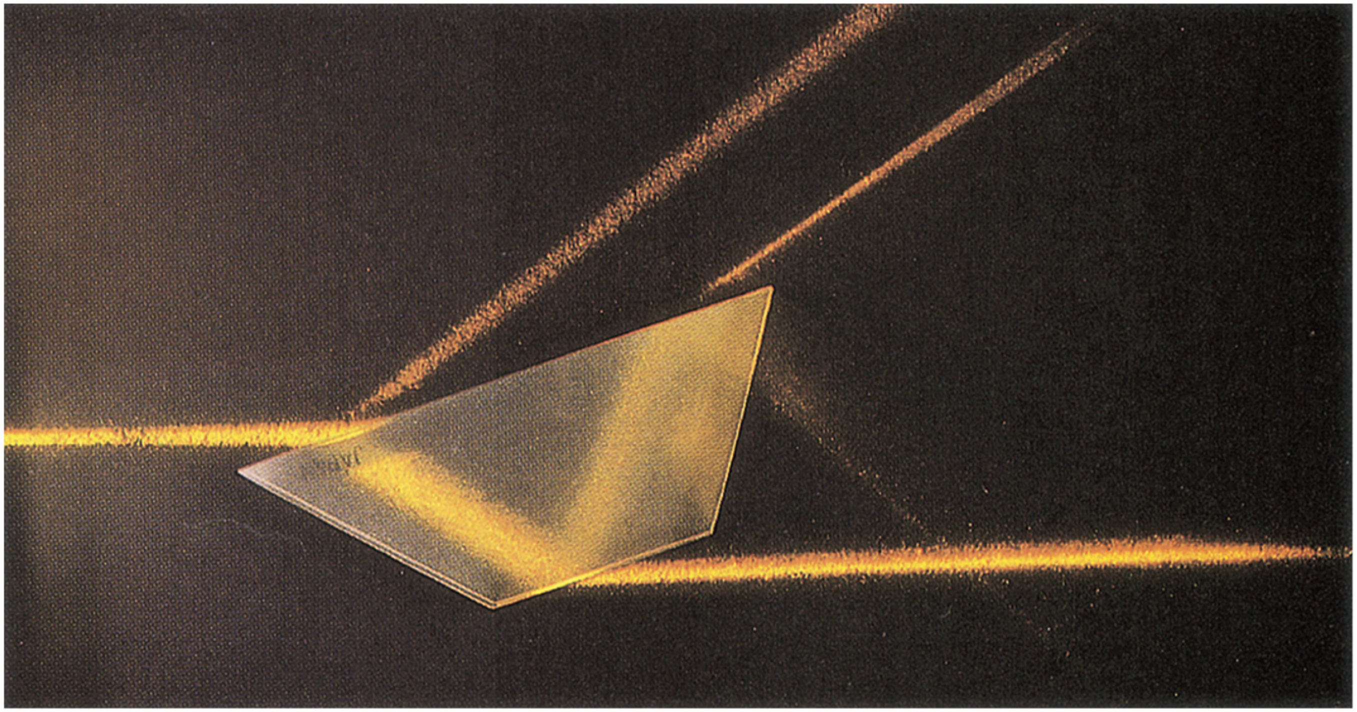


(b)

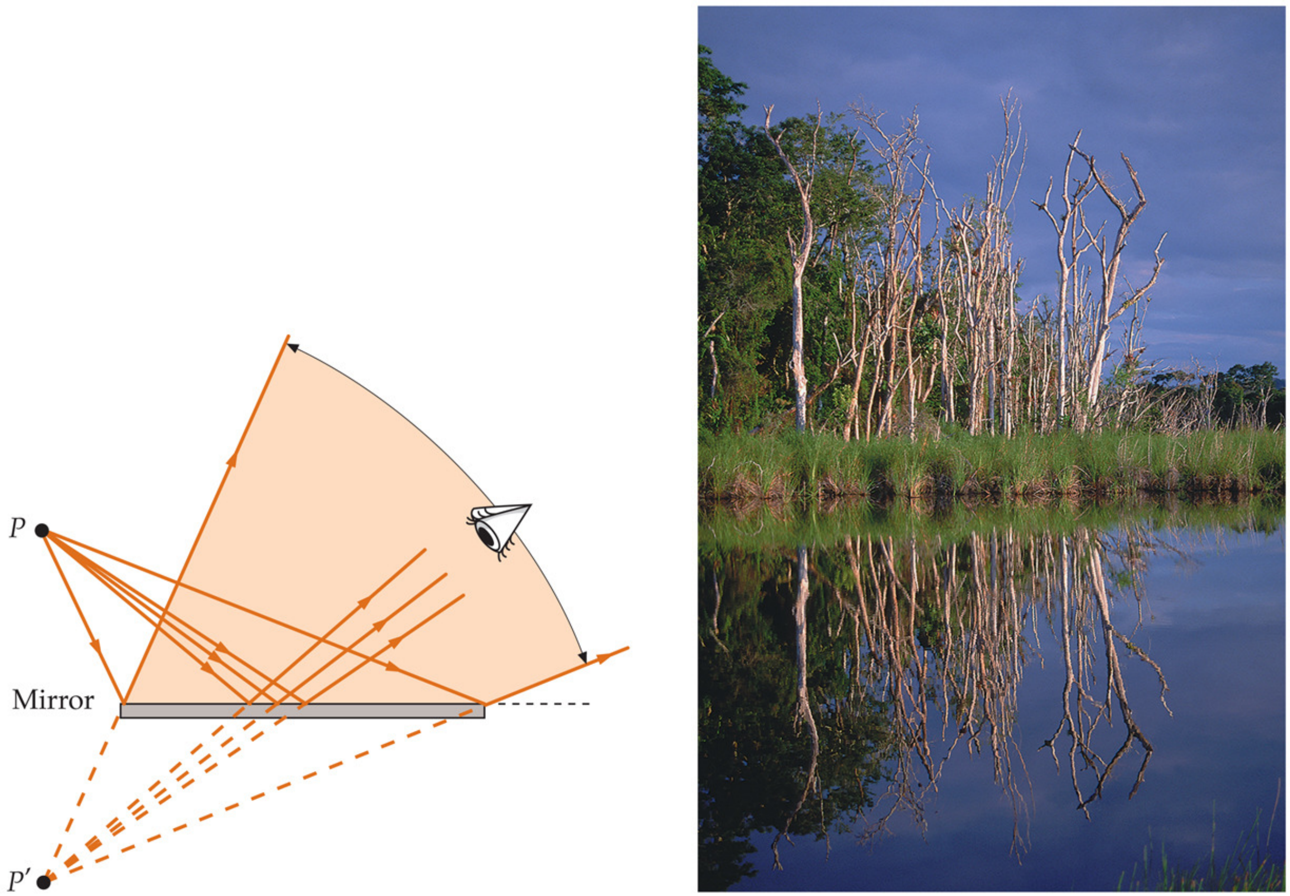
Ultrasonic waves in water reflecting off a steel plate.

Multiple Reflection and Refraction

Incident Light

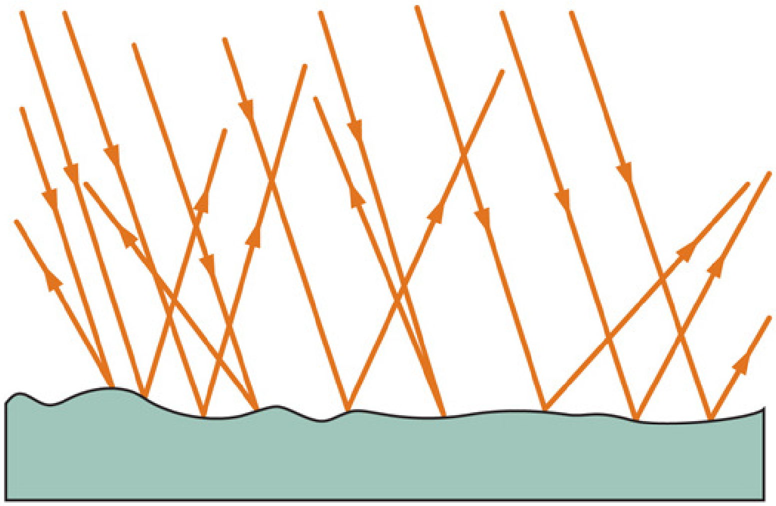


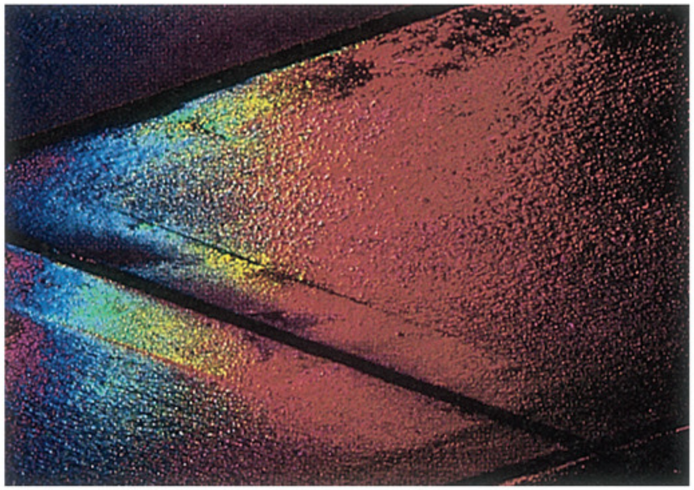
Mirror Reflection



(a) (b)

Reflection From a Rough Surface



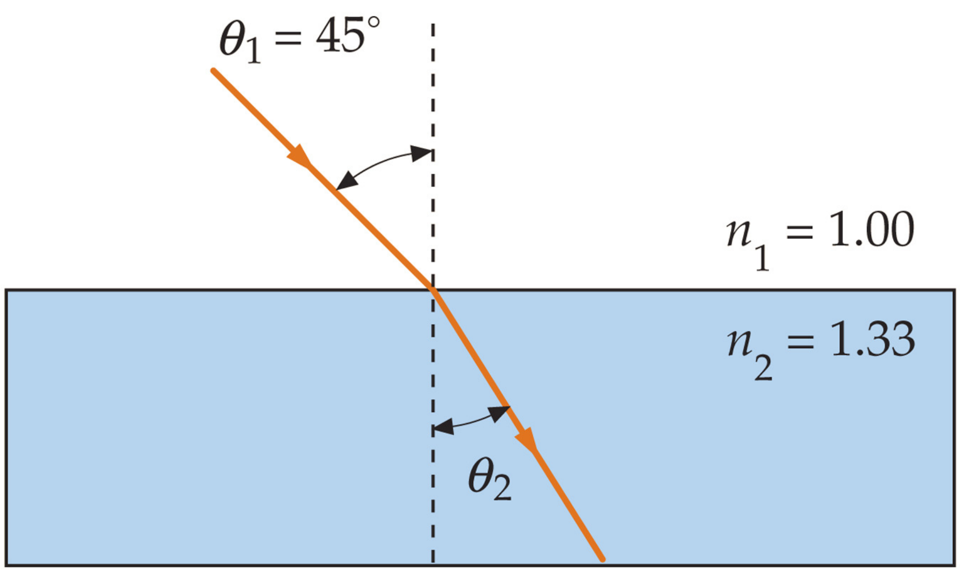


Smooth and rough are relative terms. Variations are large or small relative to the wavelength of the light.

Snell's Law

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

<u>All angles are measured from the surface normal.</u>



$$sin\theta_2 = \frac{n_1}{n_2} sin\theta_1$$

$$\theta_2 = sin^{-1}\left[\frac{n_1}{n_2} sin\theta_1\right]$$

$$\theta_2 = sin^{-1}\left[\frac{1.00}{1.33} sin45^0\right]$$

$$\theta_2 = sin^{-1}\left(0.751\, x\, 0.707\right)$$

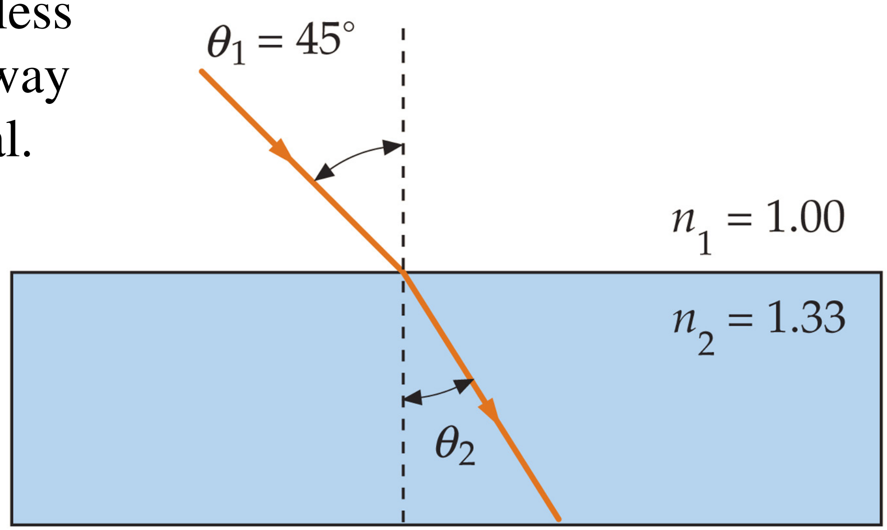
$$\theta_2 = 32.1^0$$

Snell's Law

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

All angles are measured from the surface normal.

More dense to less dense - bend away from the normal.



Less dense to more dense - bend toward the normal.

The reverse pathway of the light beam also satisfies Snell's Law.

Index of Refraction

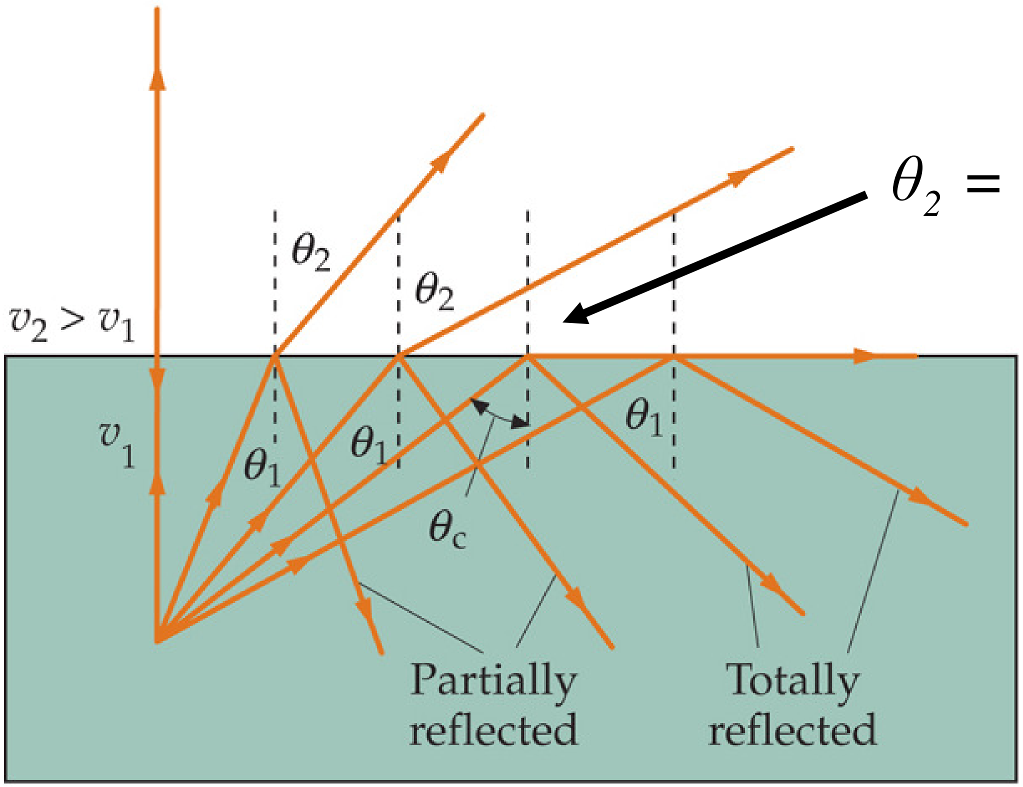
$$f = \frac{c}{\lambda} = \frac{v}{\lambda_n} = constant\ \ frequency$$

$$\lambda_n = \frac{v}{c/\lambda} = \frac{\lambda}{c/v} = \frac{\lambda}{n};\ where\, n = \frac{c}{v}$$

The constant n is the index of refraction and is material and frequency dependent.

Total Internal Reflection

Total internal reflection requires light going from a more dense material to a less dense material.



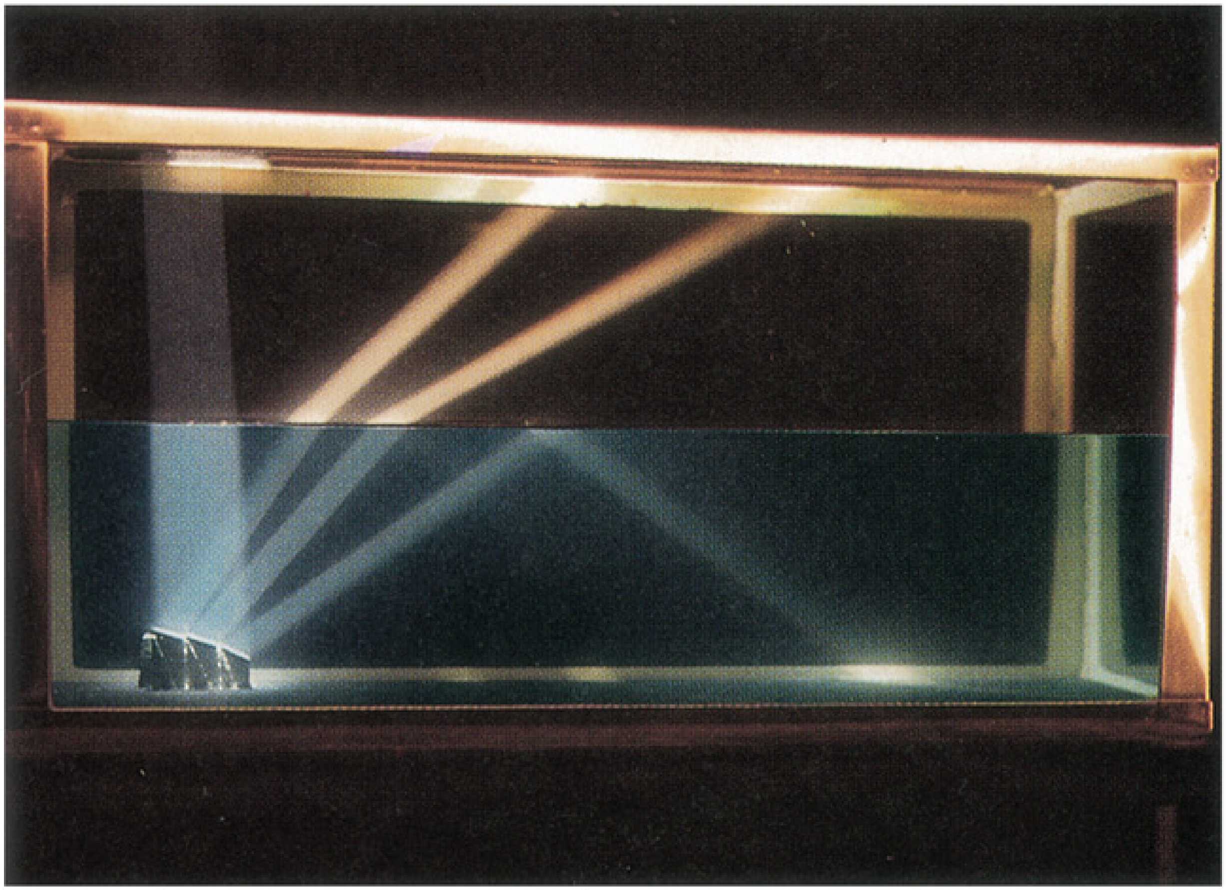
$\theta_2 = 90^0$

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

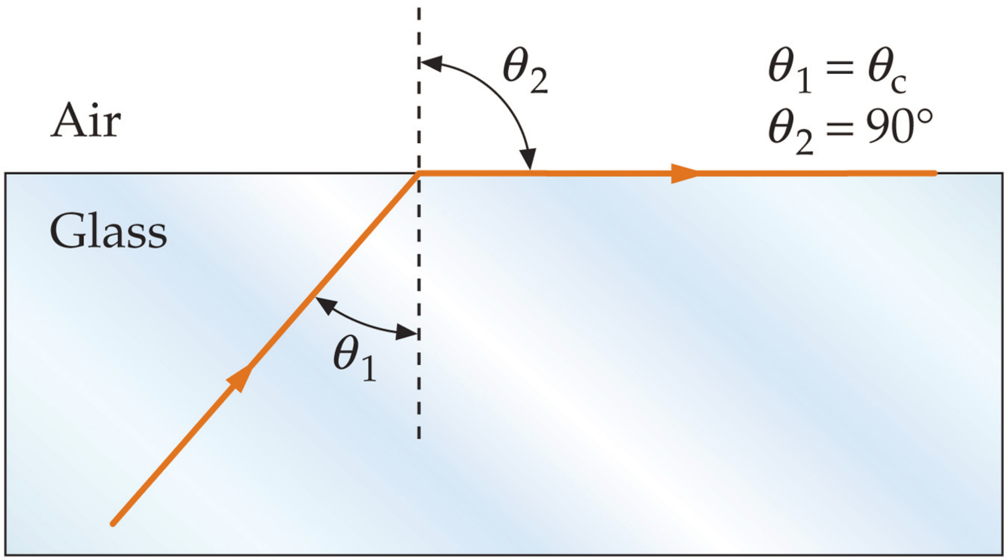
$$\sin\theta_c = \frac{n_2}{n_1}\sin 90^0$$

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

Total Internal Reflection

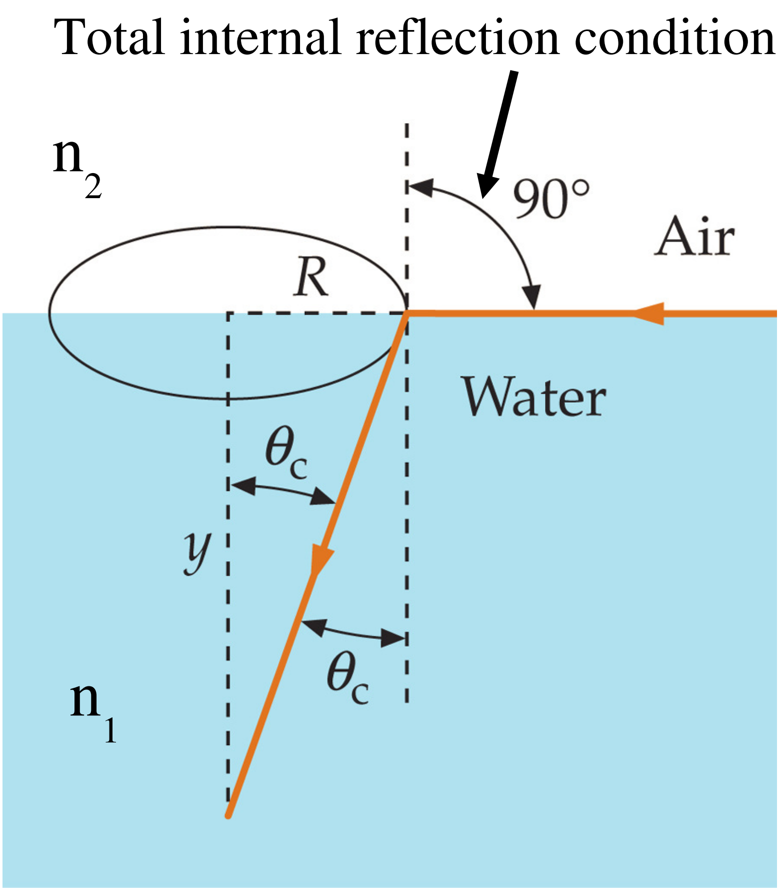


The Geometry of Internal Reflection



How do you get the light source inside the glass?

Typical Internal Reflection Problem



R = 2.0m

Two types of questions:

(1) How big is the circle?

(2) How deep are you?

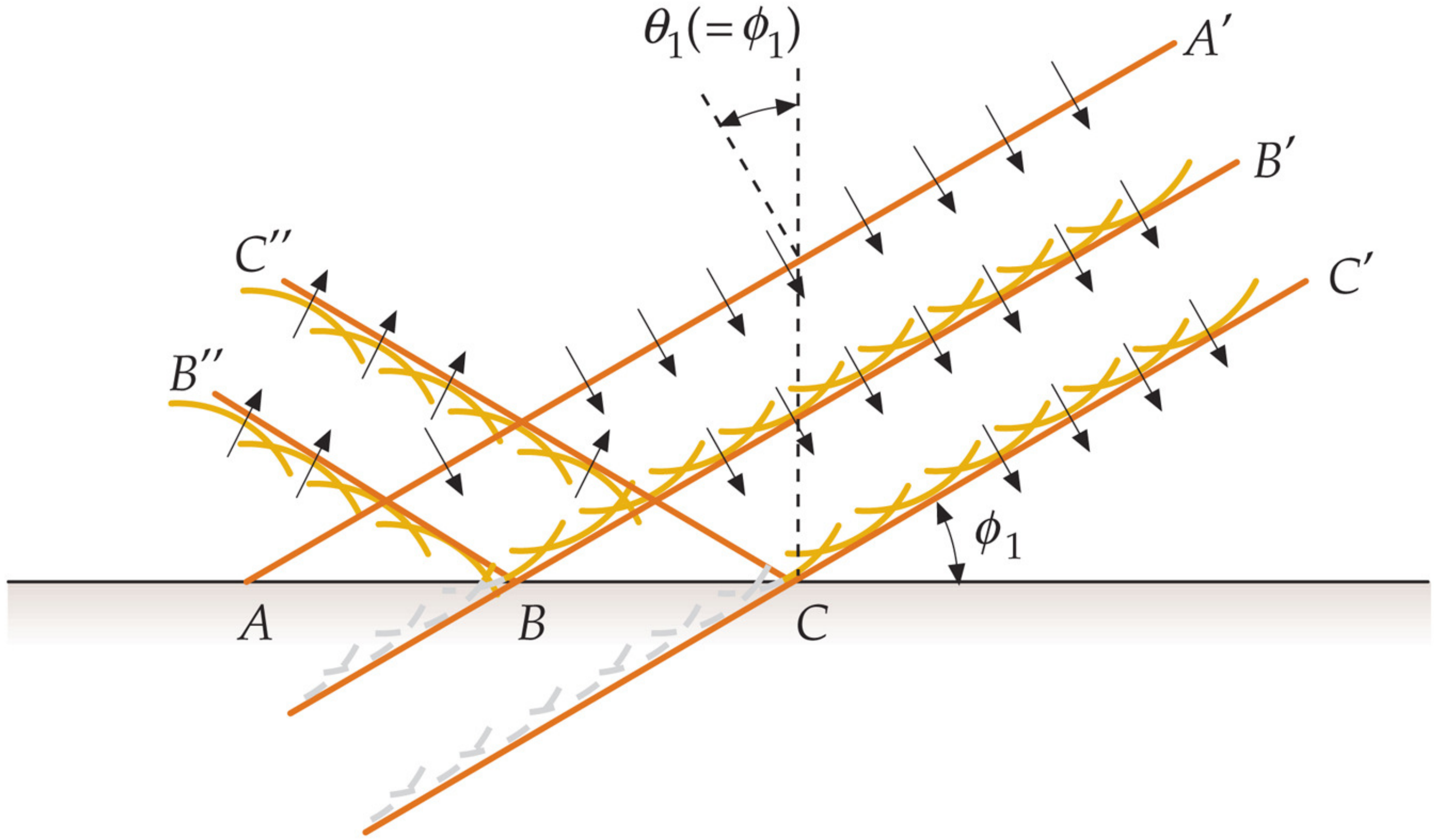
$$tan\theta_c = \frac{R}{y}; \quad sin\theta_c = \frac{n_2}{n_1}$$

$n_2 = 1.00; \; n_1 = 1.33$

$$\theta_c = sin^{-1}\left[\frac{1.00}{1.33}\right] = 48.8^0$$

$$y = \frac{R}{tan\theta_c} = \frac{2.00}{tan(48.8)} = 1.75m$$

Reflection via Wave Front Generation



Special Case - Normal Incidence

I_0 = Incident intensity

I = Reflected intensity

$$I = \left[\frac{n_1 - n_2}{n_1 + n_2}\right]^2 I_0$$

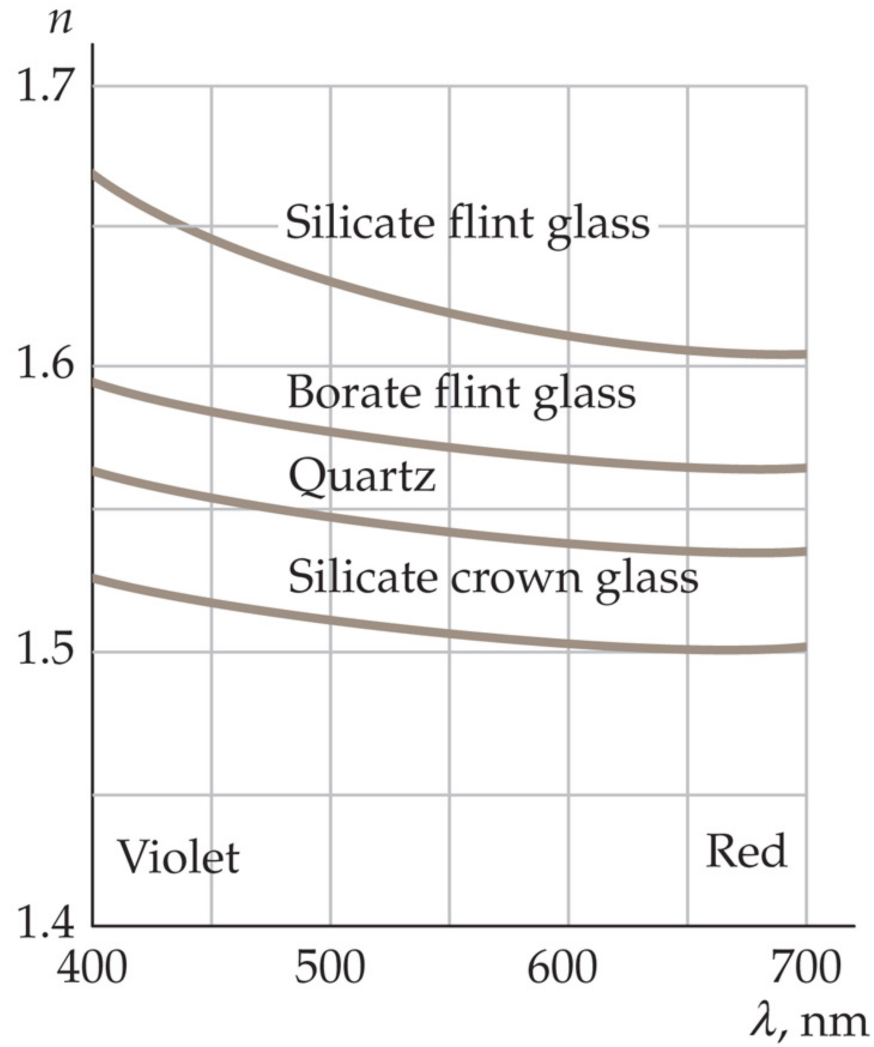
For a typical case $n_1 = 1.0$, $n_2 = 1.5$

$$I = \frac{I_0}{25}$$

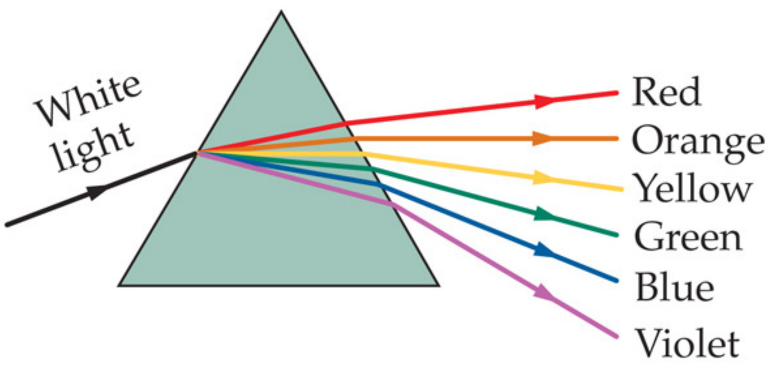
Reflected intensity ~ 4% Transmitted intensity ~ 96%

Index of Refraction versus Frequency

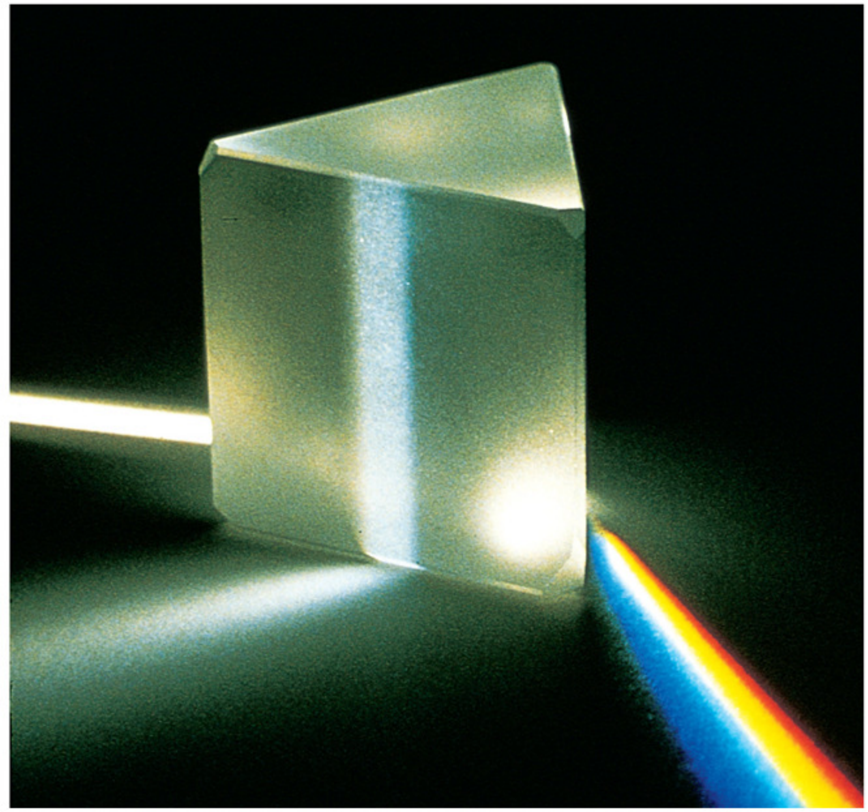
The dependence of the index of refraction with frequency is referred to as dispersion



Dispersion of Light



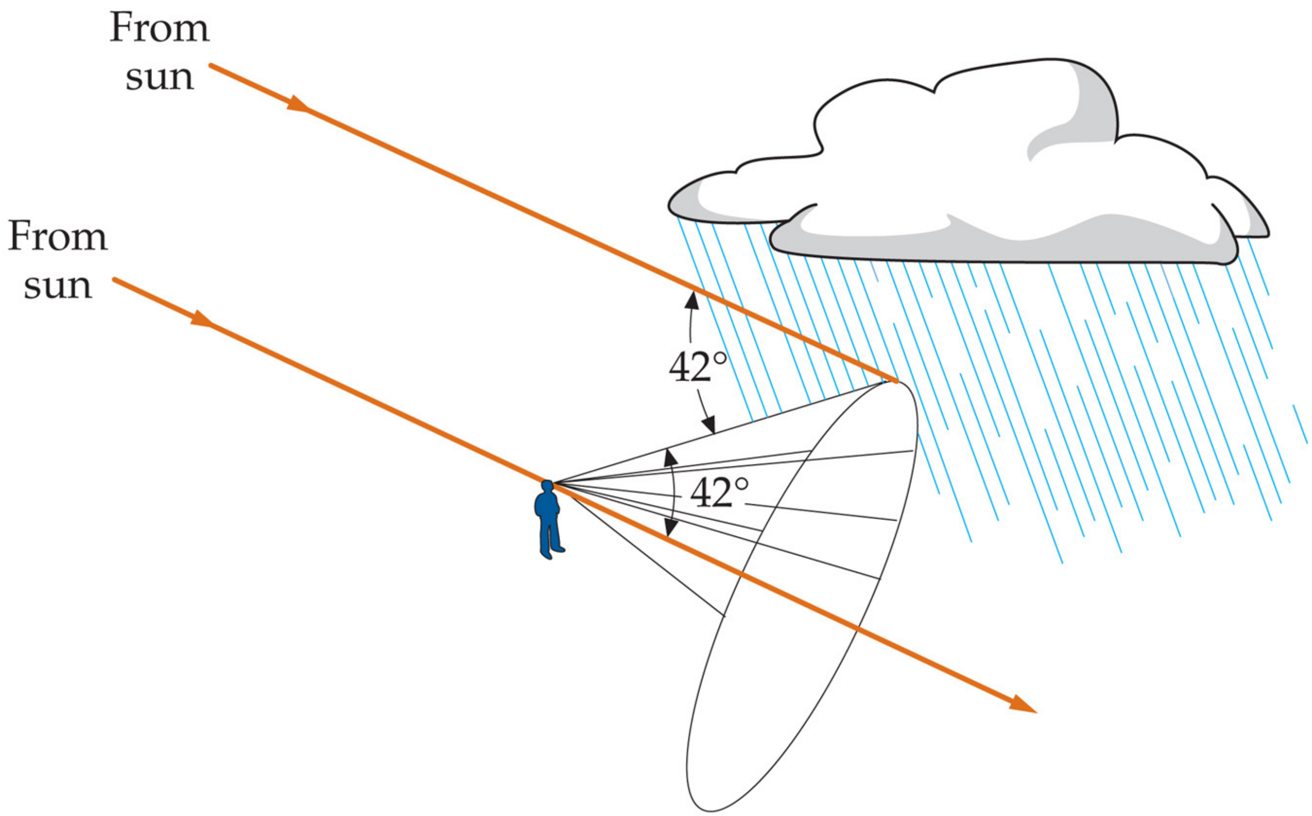
$$n_1 sin\theta_1 = n_2 sin\theta_2$$



By measuring the prism and deflection angles, a very precise determination of the index of refraction to 6 decimals places.

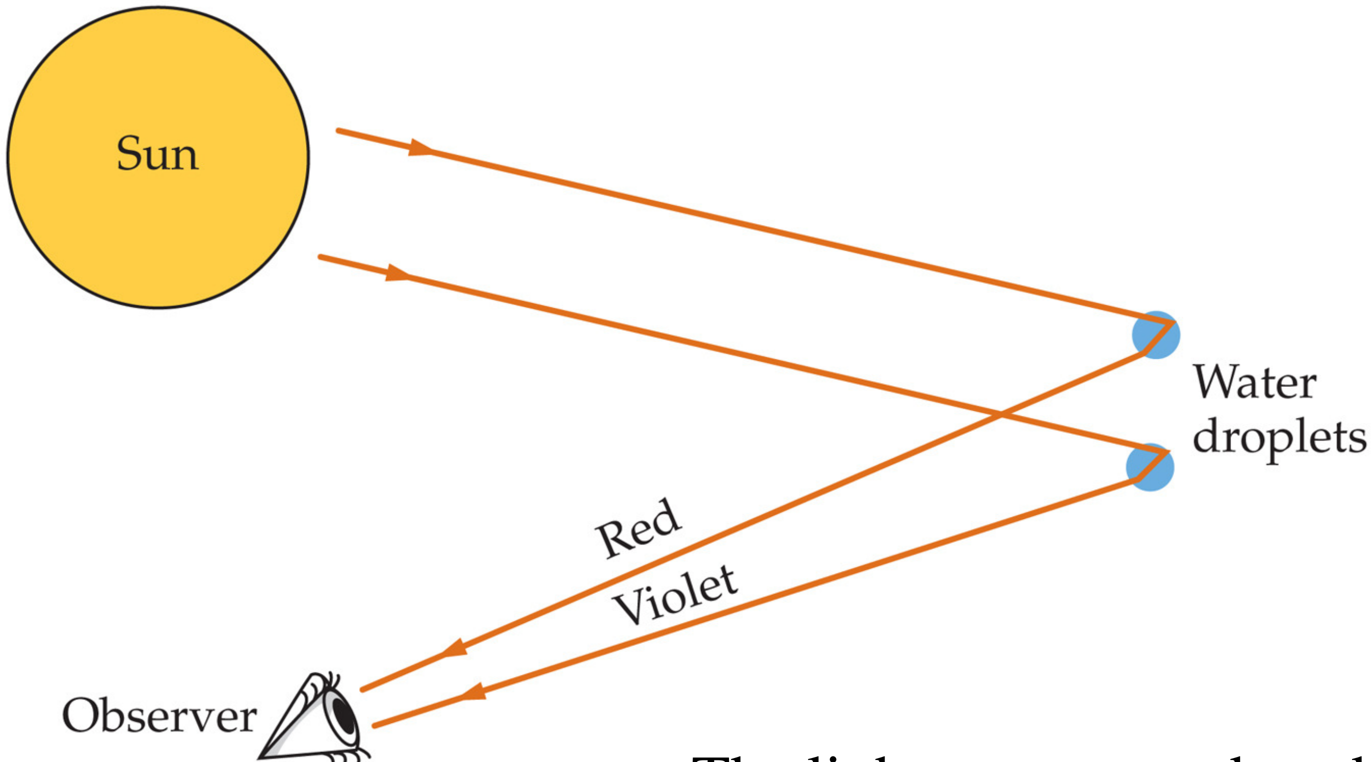
Rainbow Formation

Viewing the Primary Rainbow



A rainbow is the result of light scattering from many water droplets viewed from a particular angle.

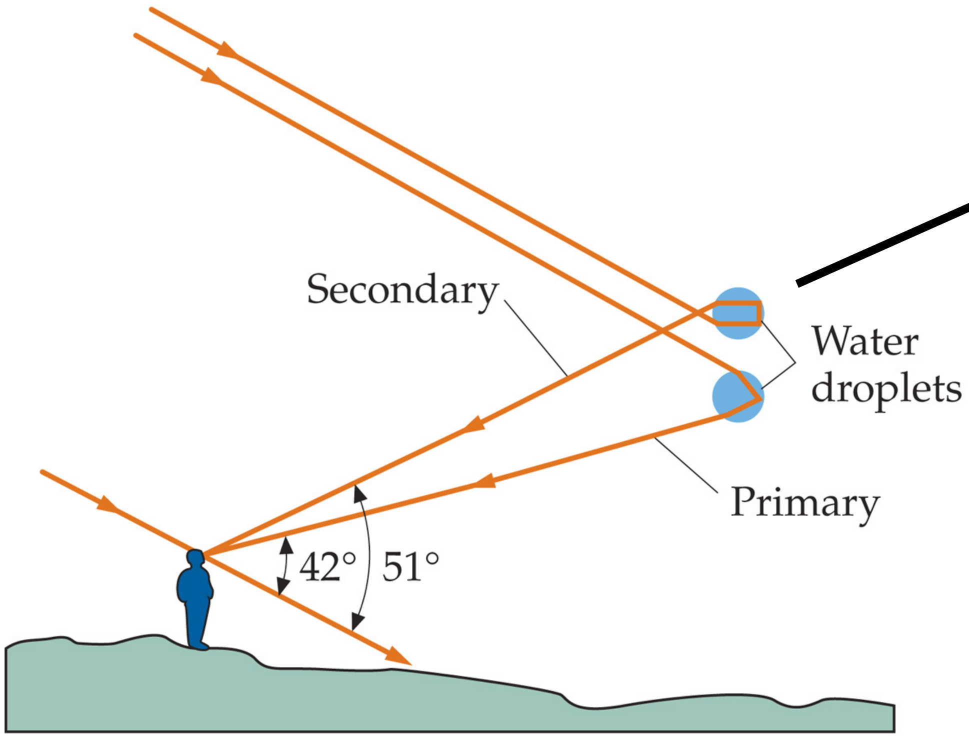
Viewing the Primary Rainbow

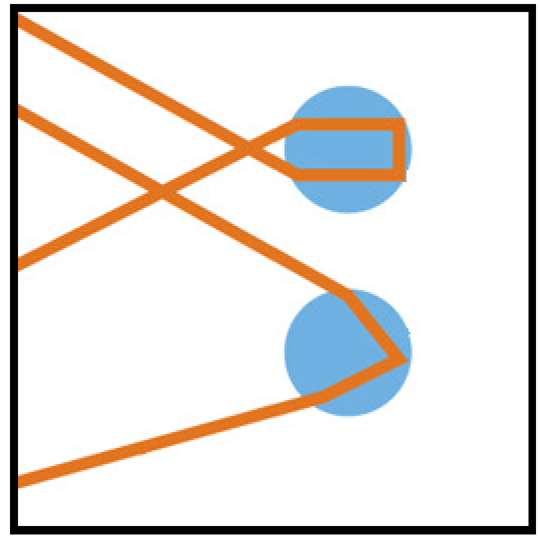


The light source needs to be behind the observer.

A Rainbow is the Result of Internal Scattering of Light within Water Drops

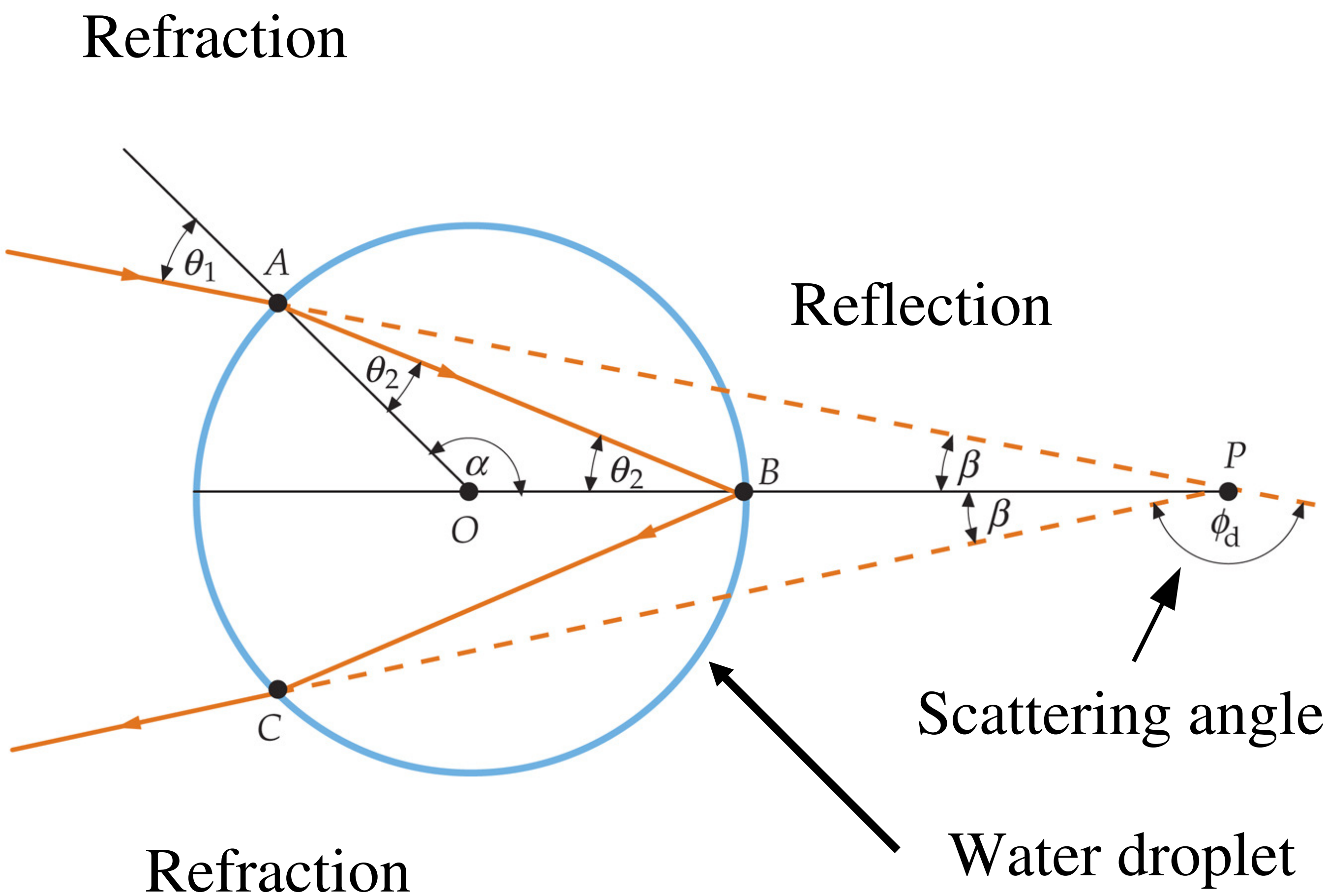
Secondary - Double Scattering





Primary - Single Scattering

Primary Rainbow Geometry

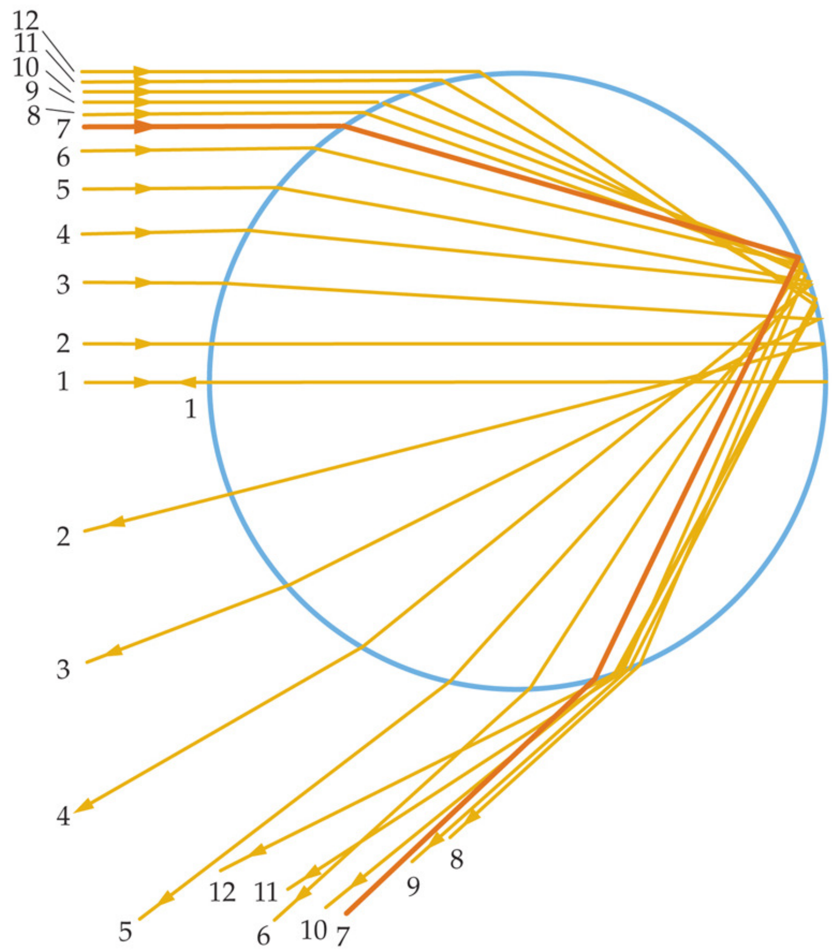


Descartes's Construction of Parallel Rays Entering a Spherical Water Drop

Rays exit at increasing angles up until ray #7.

This maximum angle is about 42^0.

The concentration of the exiting rays around this maximum angle gives rise to the rainbow effect.



From Atmospheric Optics

http://www.atoptics.co.uk/rainbows/primary.htm

Polarization

Optical Scattering

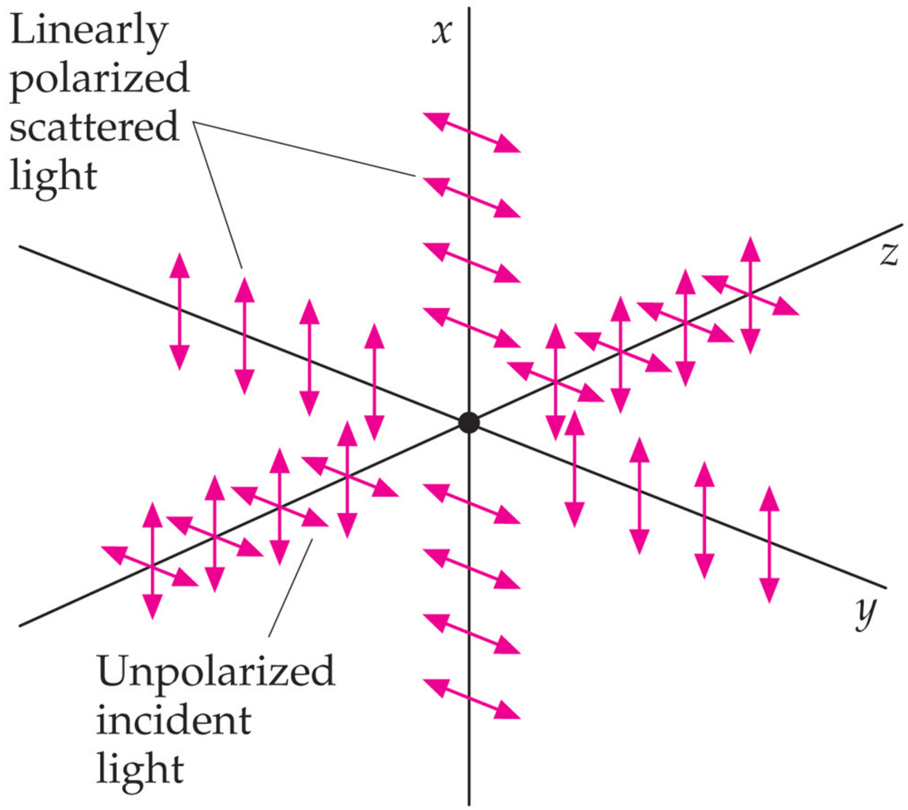
Scattering of electromagnetic radiation (light) is described physically as elastic absorbtion and reradiation (emission).

The elastic description means that no energy is lost in the scattering process.

The process can be visualized be treating the scattering atoms as little dipole antennas. These little antennas have maximum radiation in the direction perpendicular to the antenna and no radiation along the axis of the antenna..

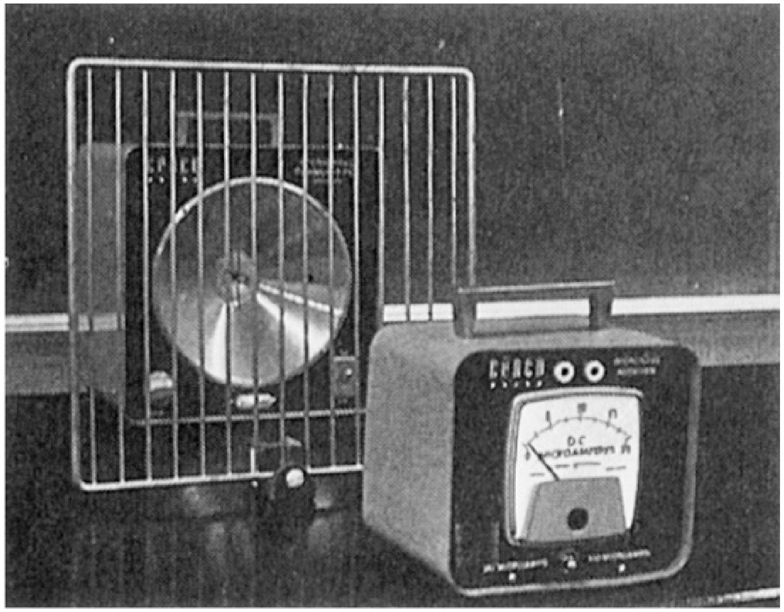
Polarization by Scattering

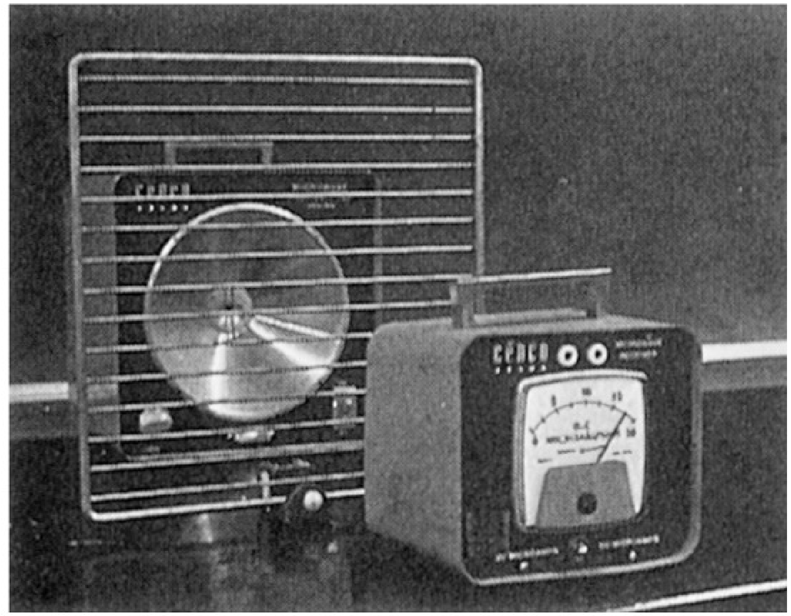
Incident light polarized along the ***x-direction*** cannot produce radiation along the ***x-direction***.



Incident light polarized along the ***y-direction*** cannot produce radiation along the ***y-direction***.

Microwave Polarization Example





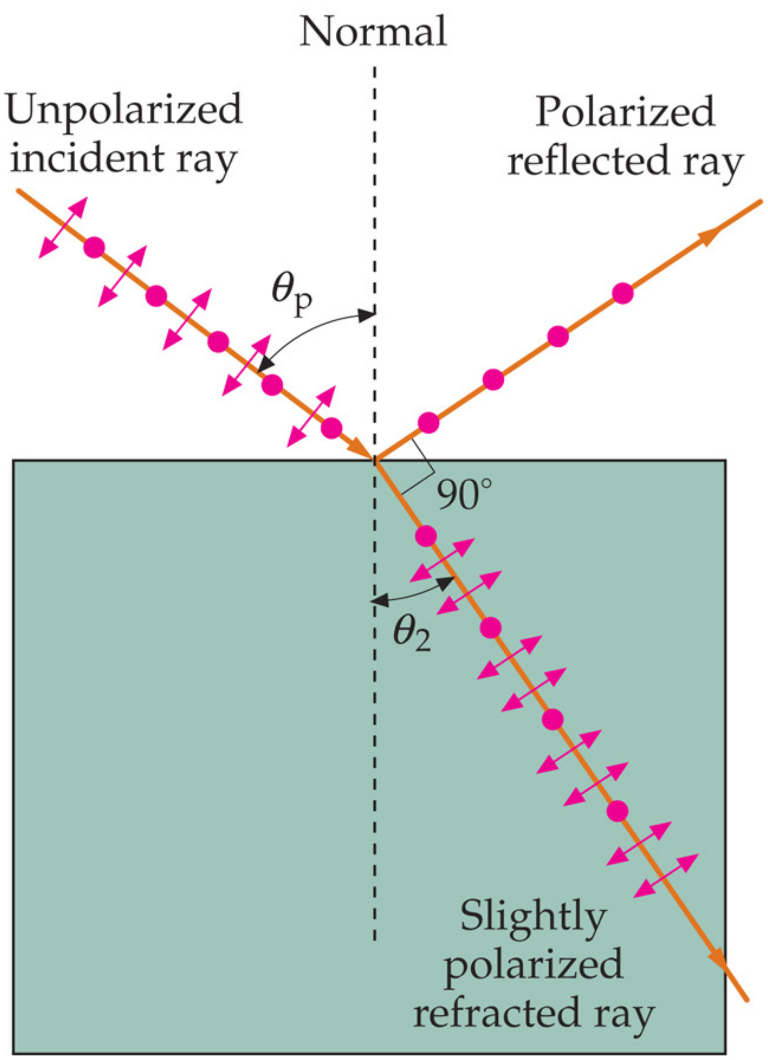
The electric field vector of the microwave radition is oriented in the vertical direction. The wires in the grating on the left are oriented parallel to the electric vector and ***absorb energy*** and hence the microammeter gives a low reading.

The grating wires on the right are perpendicular to the microwave electric vectors. Therefore they ***do not absorb any energy*** and hence the high reading on the microammeter.

Polarization by Scattering

Ordinary light incident from the left

At the polarizing angle, known as Brewster's angle, the angle between the reflected ray and the refracted ray is 90^0



Polarization by Scattering

Plane polarized light incident from the left

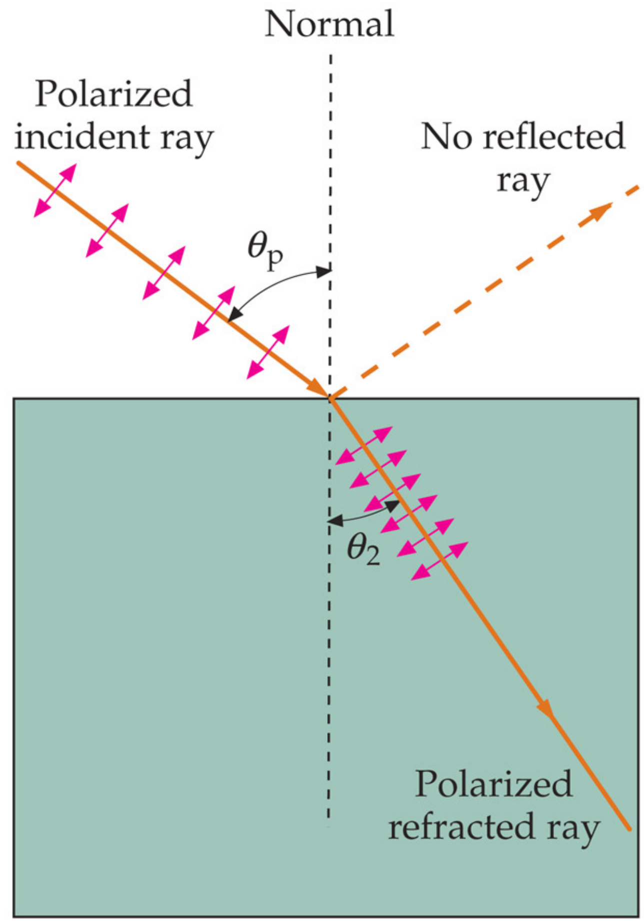
$$n_1 sin\theta_p = n_2 sin\theta_2$$

$$\theta_2 = 90^0 - \theta_p$$

$$n_1 sin\theta_p = n_2 sin\left(90^0 - \theta_p\right)$$

$$n_1 sin\theta_p = n_2 cos\theta_p$$

$$tan\theta_p = \frac{n_2}{n_1}$$



The separation of the electric vectors indicate the wavelength. The vectors are closer inside the glass because the wavelength is shorter in the glass.

Polarization by Scattering

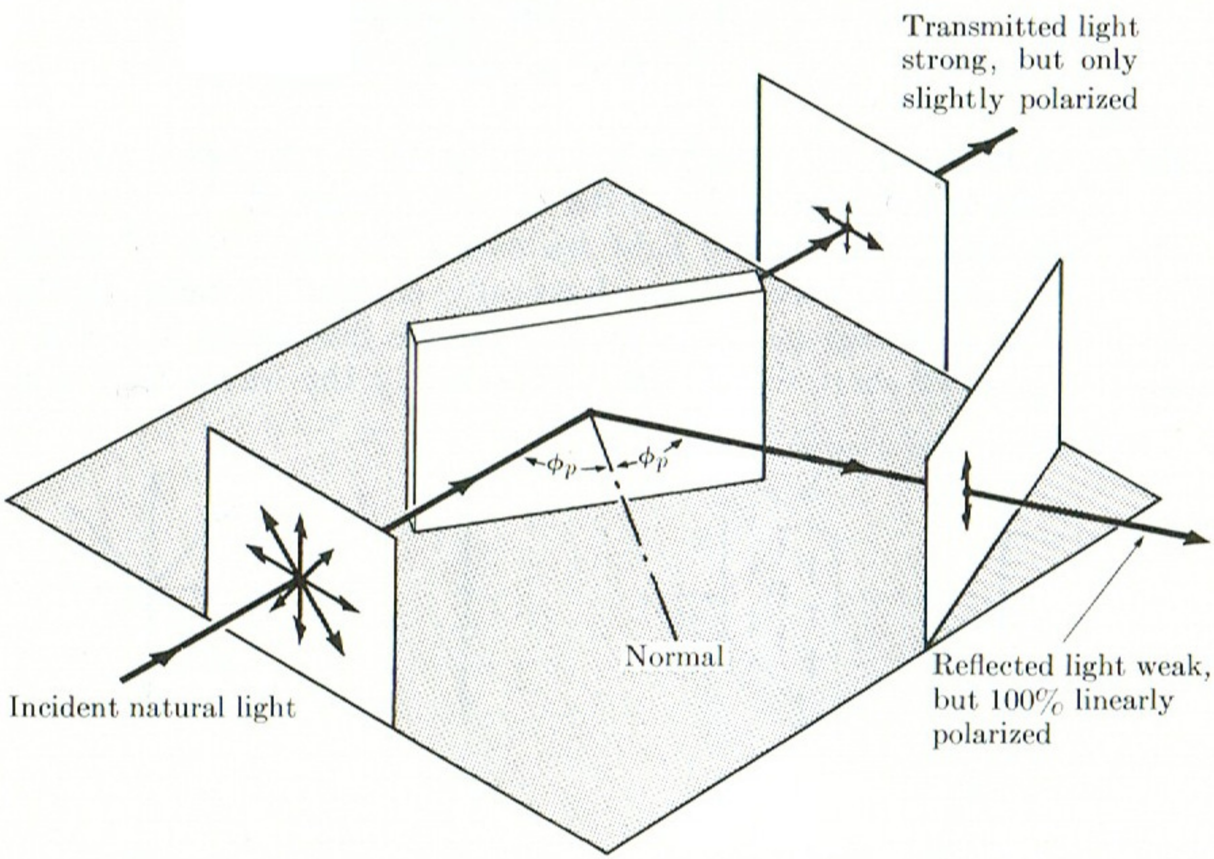


FIG. 36–3. When light is incident at the polarizing angle, the reflected light is linearly polarized.

Polarization by Scattering

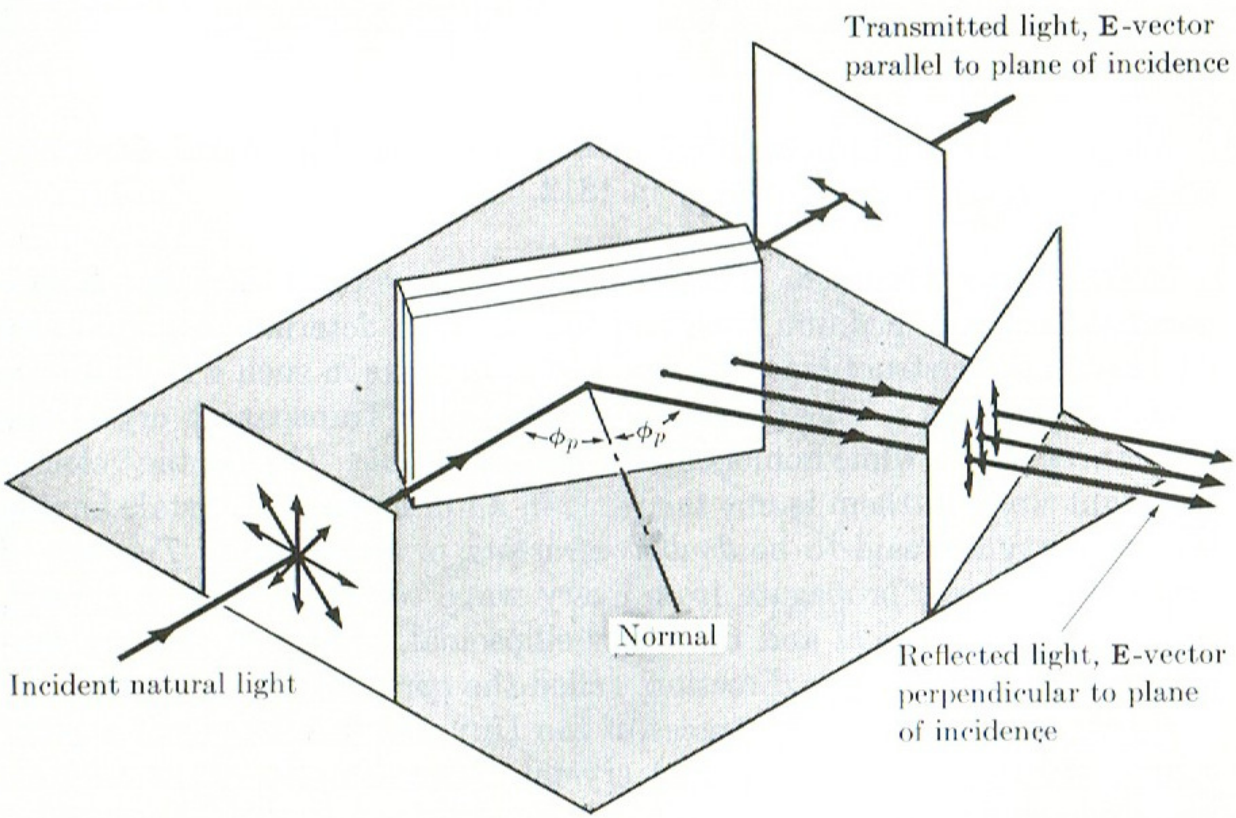
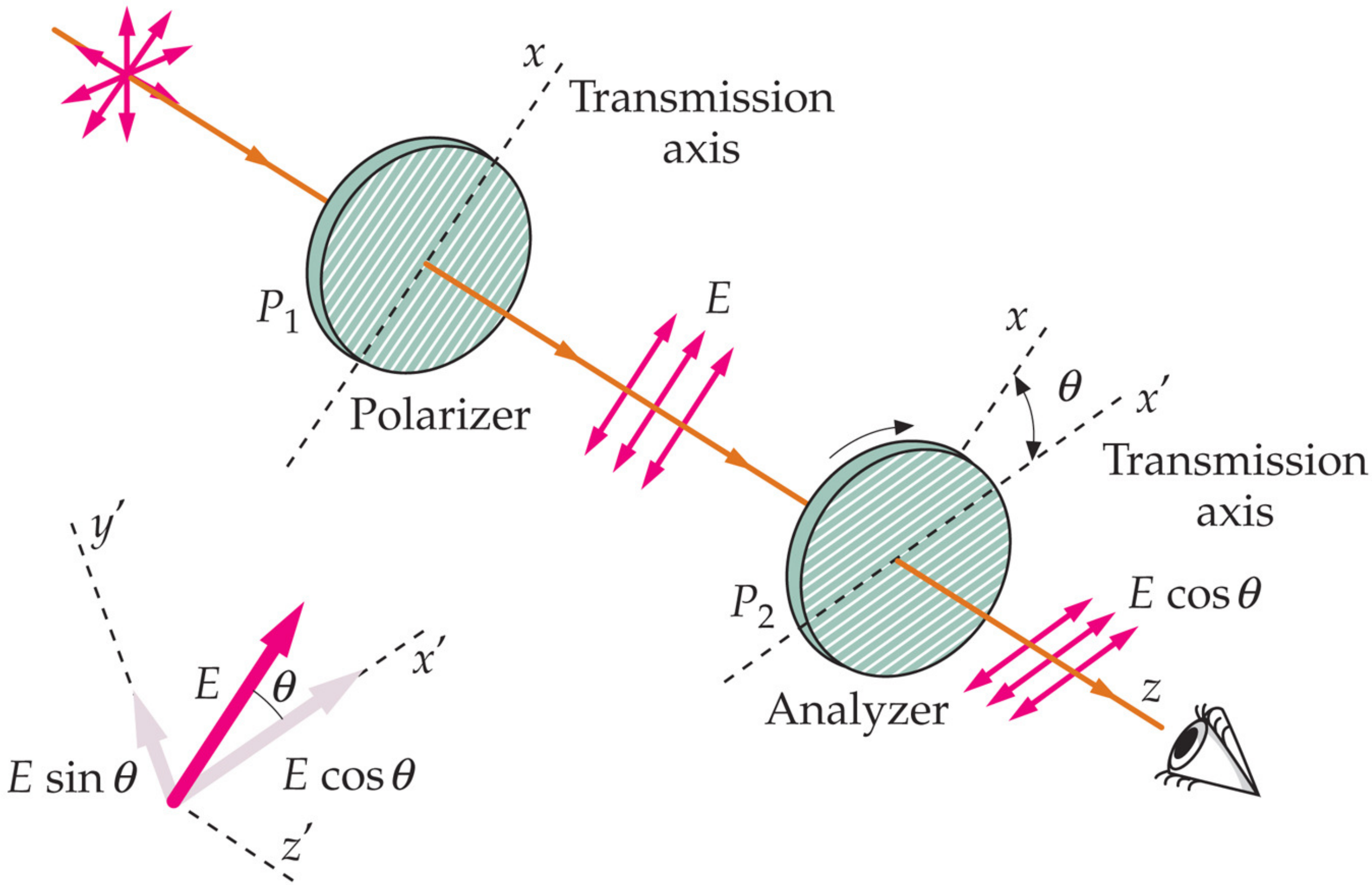


FIG. 36–5. Separation of natural light into two beams of linearly polarized light by reflection from a pile of plates.

Crossed Polarizers



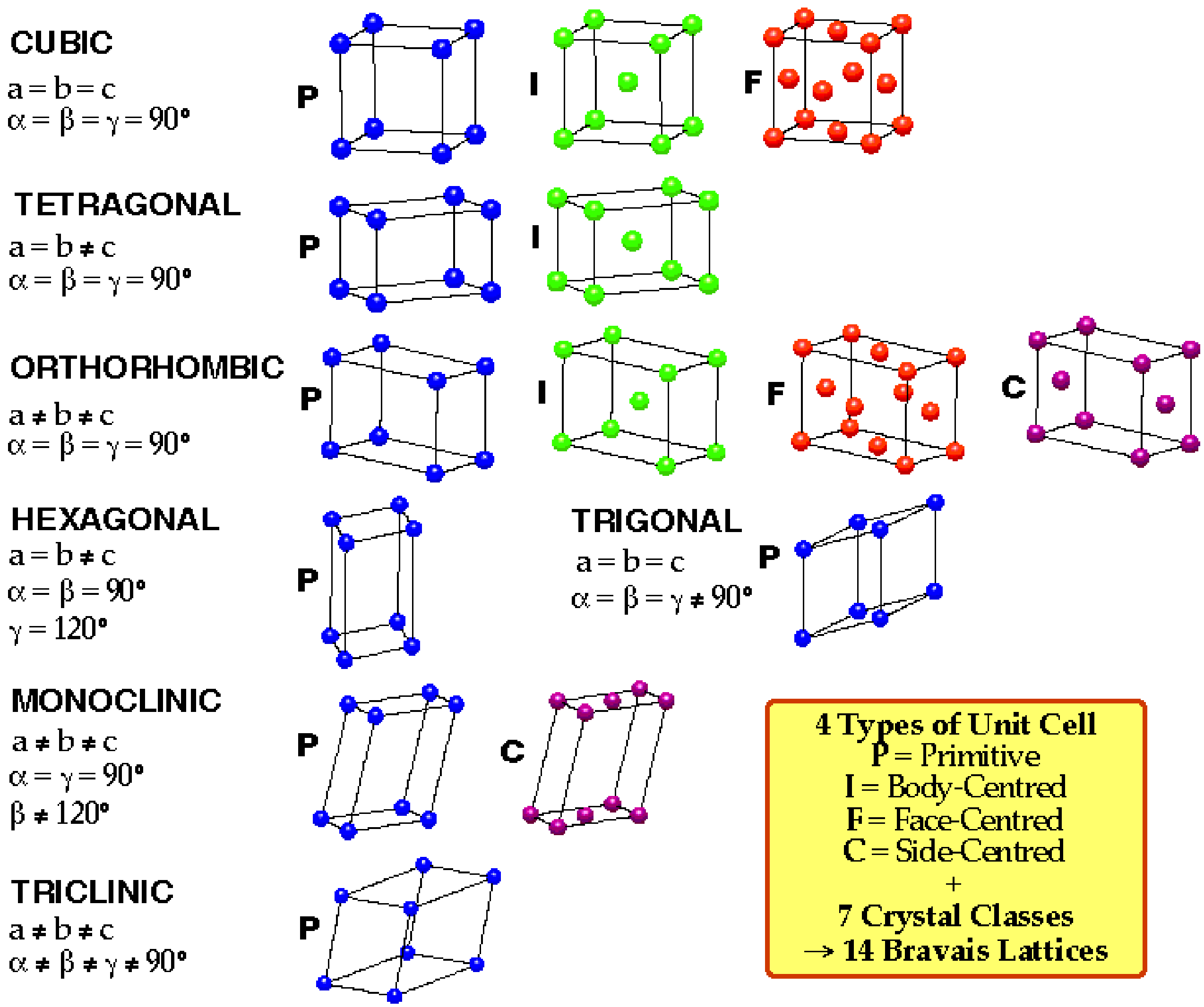
Birefringence

Crystals vs Glass

Glass is described as an amorphous, homogenous and isotropic material

- Amorphous = It has no preferred directions such as found in a crystal.
- Homogenous = Every part of the material is exactly like every other part of the material.
- Isotropic = All directions in the material are the same.

Crystal Structure



Crystals vs Glass

Crystals are defined by their symmetry under rotation.

A cubic crystal such as NaCl is not amorphous but it can still be described as isotropic because its properties are the same in all three directions.

If a crystal is described by two different indices of refraction then we say the crystal exhibits axial symmetry. This symmetry axis is referred to as the *optic axis*

- Ordinary ray - electric vector perpendicular to optic axis.
- Extraordinary ray – electric vector is parallel to the optic axis.

Crystal Symmetries

The Index of Refraction Ellipsoid

1. Type I: These include Si, GaAs and CdTe. They have <u>*cubic*</u> symmetry; 3 equivalent directions; $n_1 = n_2 = n_3$; the ellipsoid is a sphere; the material is <u>*isotropic*</u>.

2. Type II: These include calcium carbonate, quartz, LiNb, calcium sulfide. They have <u>*trigonal, tetragonal or hexagonal*</u> structure. There is one axis of symmetry, which is one of the principal axes. Thus, $n_1 = n_2 \neq n_3$. The ellipsoid is an ellipse with one axis along the 3-direction, rotated around the 3-axis. That is, the ellipsoid exhibits the same symmetry as the crystal. Such crystals are called <u>*uniaxial*</u>.

3. Type III: These crystals have two axes of symmetry $n_1 \neq n_2 \neq n_3$ and so are called <u>*biaxial*</u>. The structure is <u>*orthorhombic, monoclinic or triclinic*</u>. All three principal axes of the ellipsoid are different.

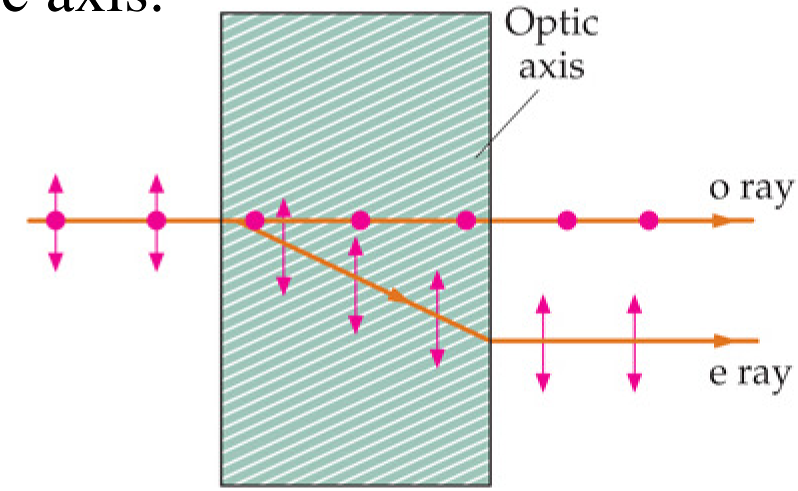
Uniaxial Crystal

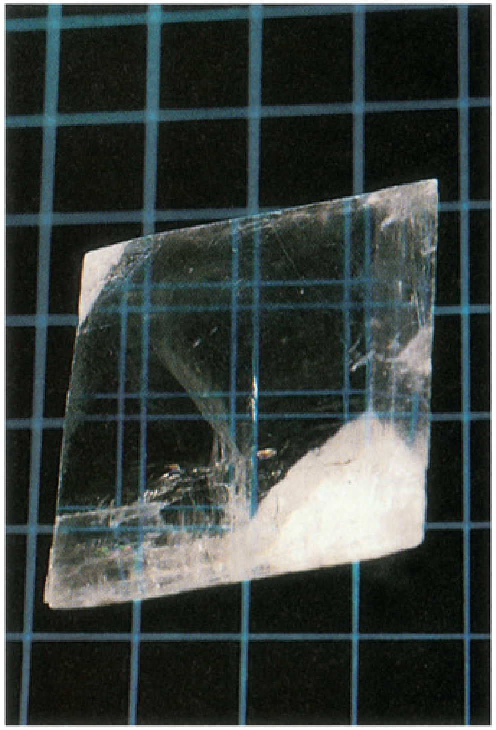
- An uniaxial crystal is isotropic within the plane orthogonal to the optical axis of the crystal. This demonstrates that the optic axis a symmetry axis of the crystal under rotations.

- The refractive index of the ordinary ray (electric vector perpendicular to optic axis) is constant for any direction in the crystal.
- The refractive index of the extraordinary ray (electric vector parallel to the optic axis) is variable and depends on the direction.
- Non-crystalline materials have no double refraction and thus, no optic axis.

Polarization By Birefringence

Light propagation in the material is at an arbitrary angle relative to the optic axis.





The ordinary ray has its electric vector perpendicular to the optic axis. The extraordinary ray's electric vector makes an angle with the optic axis.

Birefringence

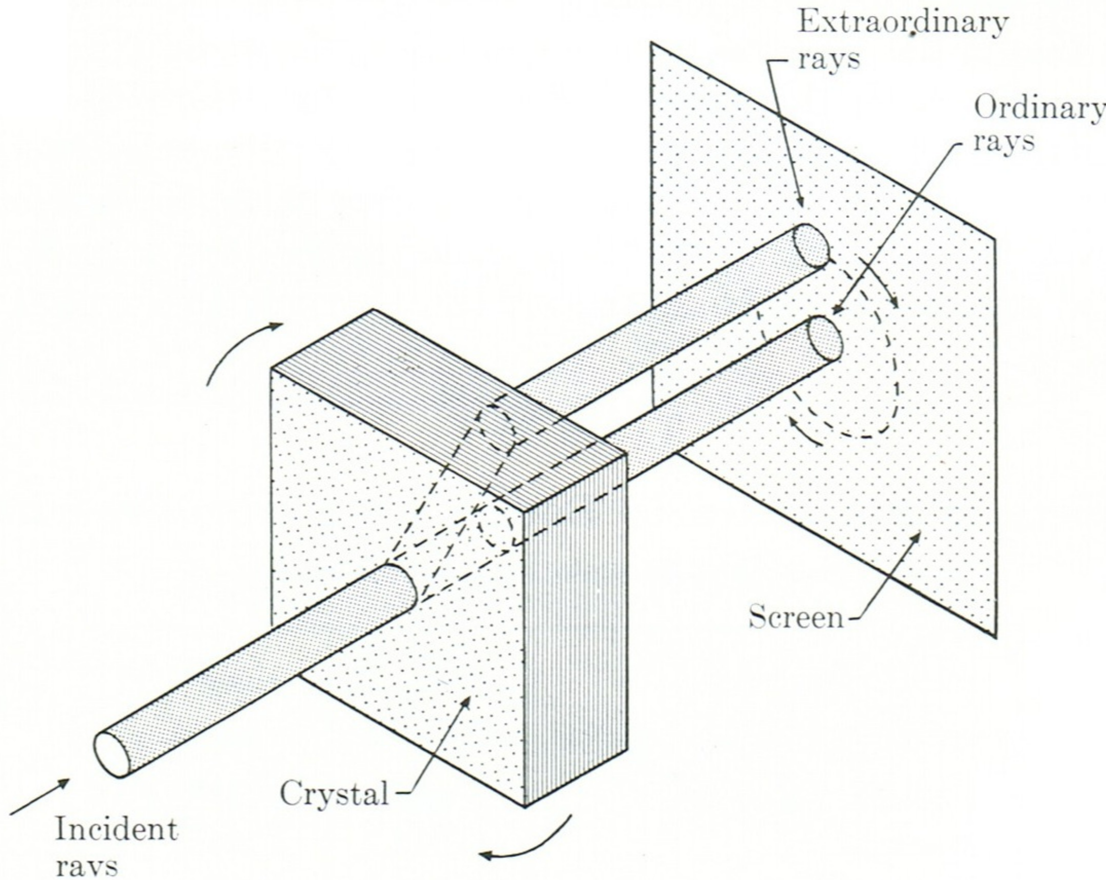
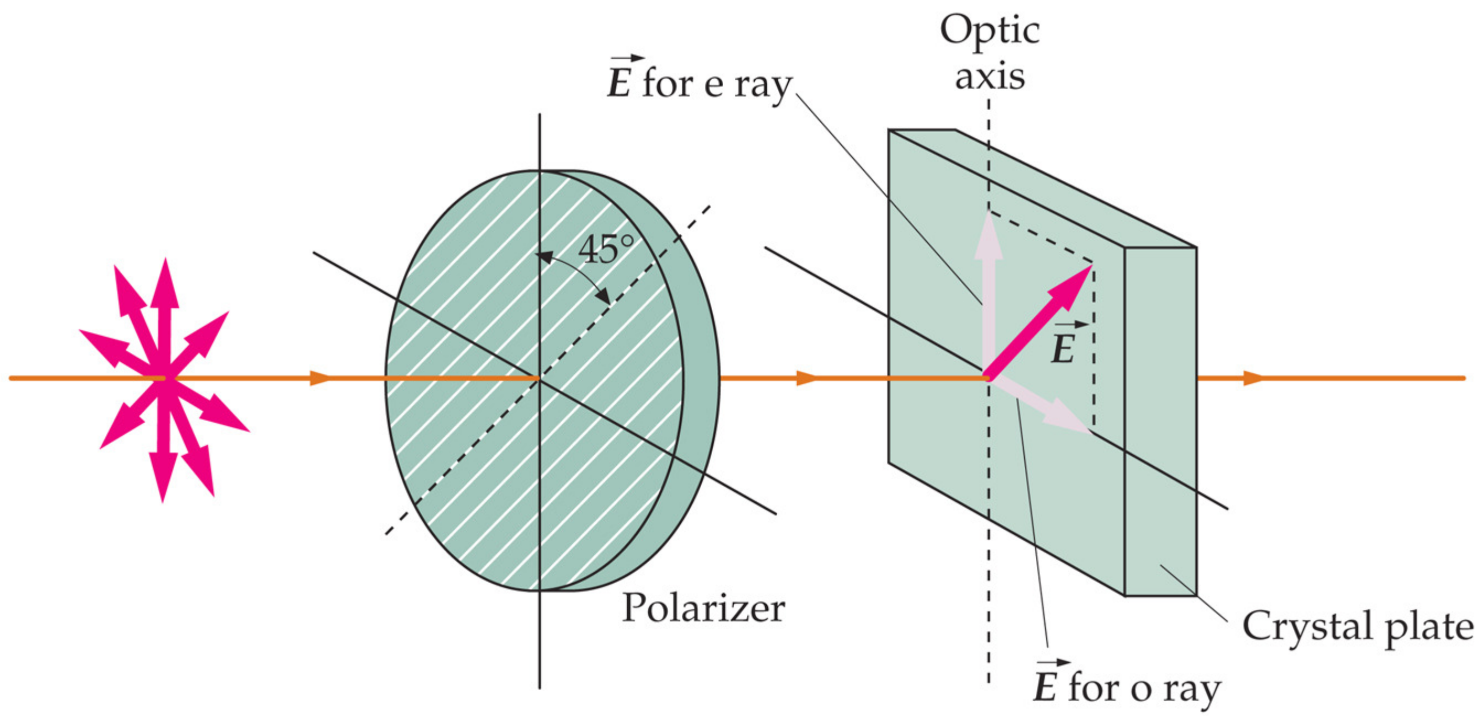


Fig. 36–7. A narrow beam of natural light can be split into two beams by a doubly refracting crystal.

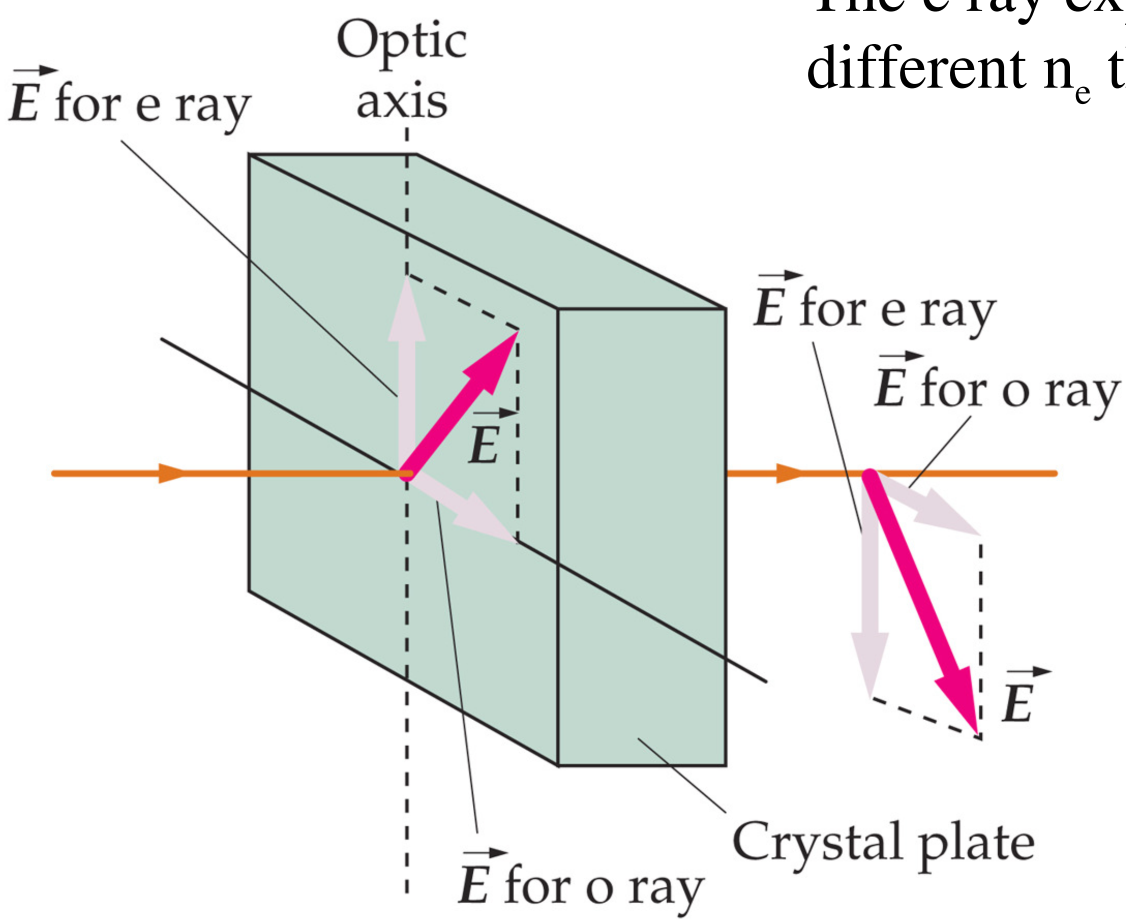
Optic Axis



Prepares the light with the desired polarization

The next slide shows the light exiting the Crystal plate.

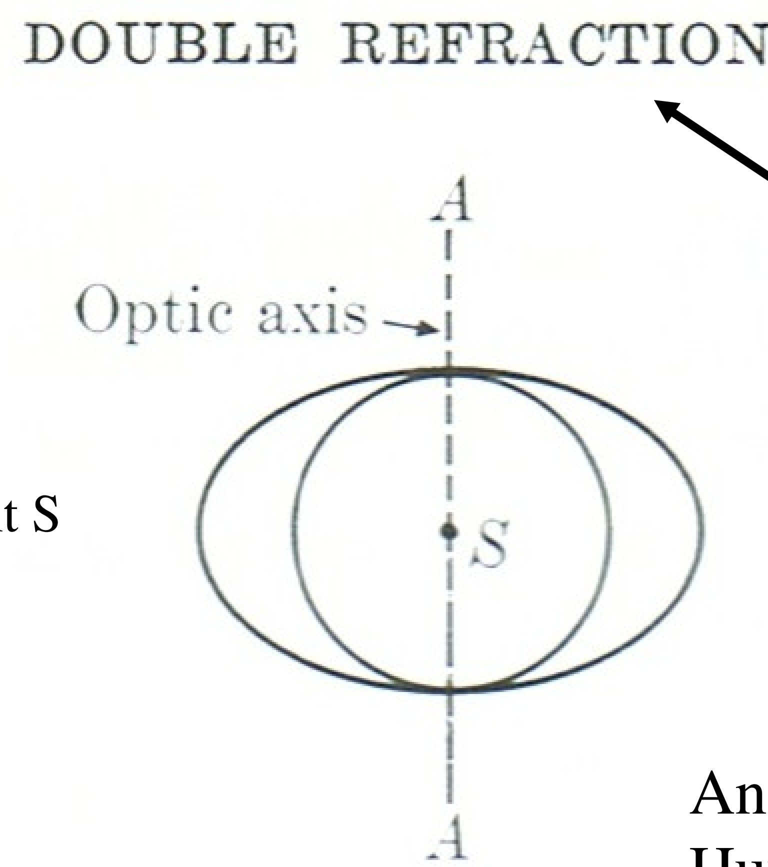
Ordinary and Extraordinary Light Rays



The e ray experiences a different n_e than the o ray n_o

The e ray will get out of phase with the o ray. In effect the optic material acts to rotate the direction of the electric field vector.

Birefringence

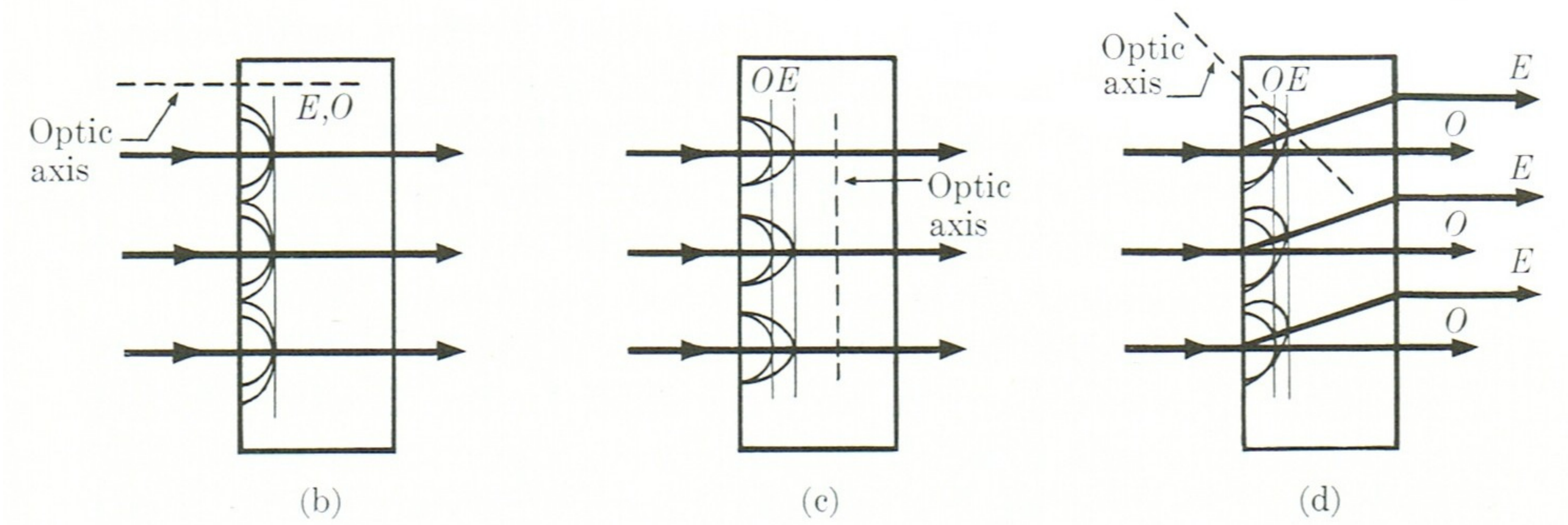


Old name

Spherical and ellipsoidal waves diverge from point S in a birefringent crystal

An example of Huygen's wavelets.

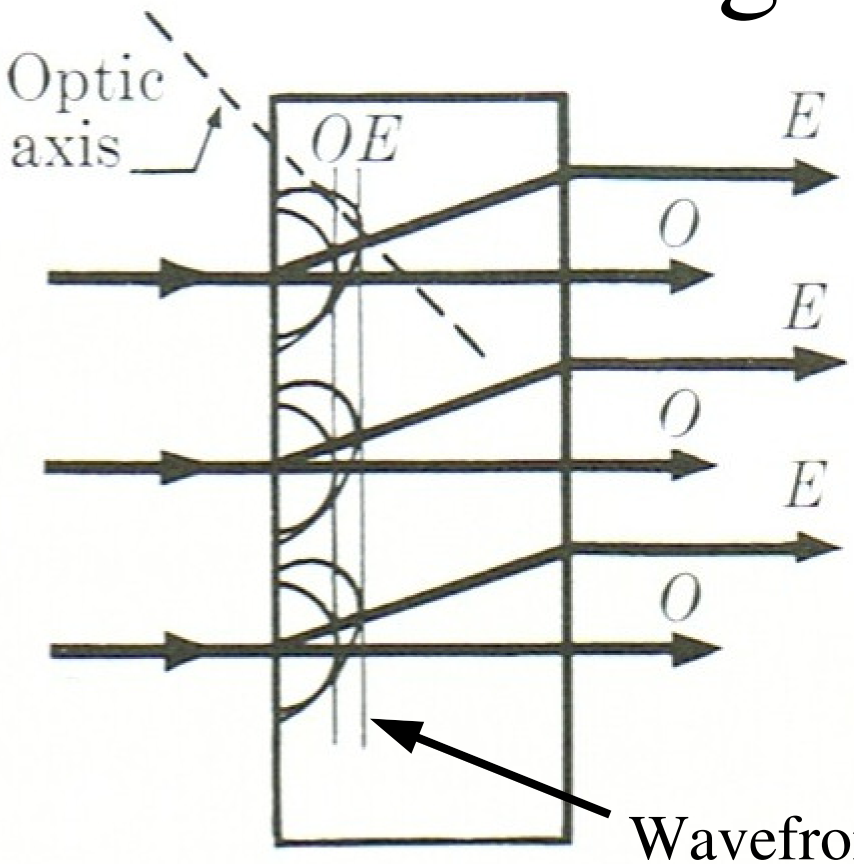
Birefringence



(b) Light traveling in the direction of the optic axis, (c) perpendicular to the optic axis, and (d) at an arbitrary angle to the optic axis.

In case (c) there is no separation or shifting of the two polarization states but they are traveling at different speeds inside the material.

Birefringence



(d)

The optic axis determines the orientation of the propagation ellipsoid.

Wavefront for the two rays.

Ordinary and Extraordinary Light Rays

Rays separated for ease of viewing

Polarization perpendicular to the plane of O.A.

Polarization in the plane of O.A.

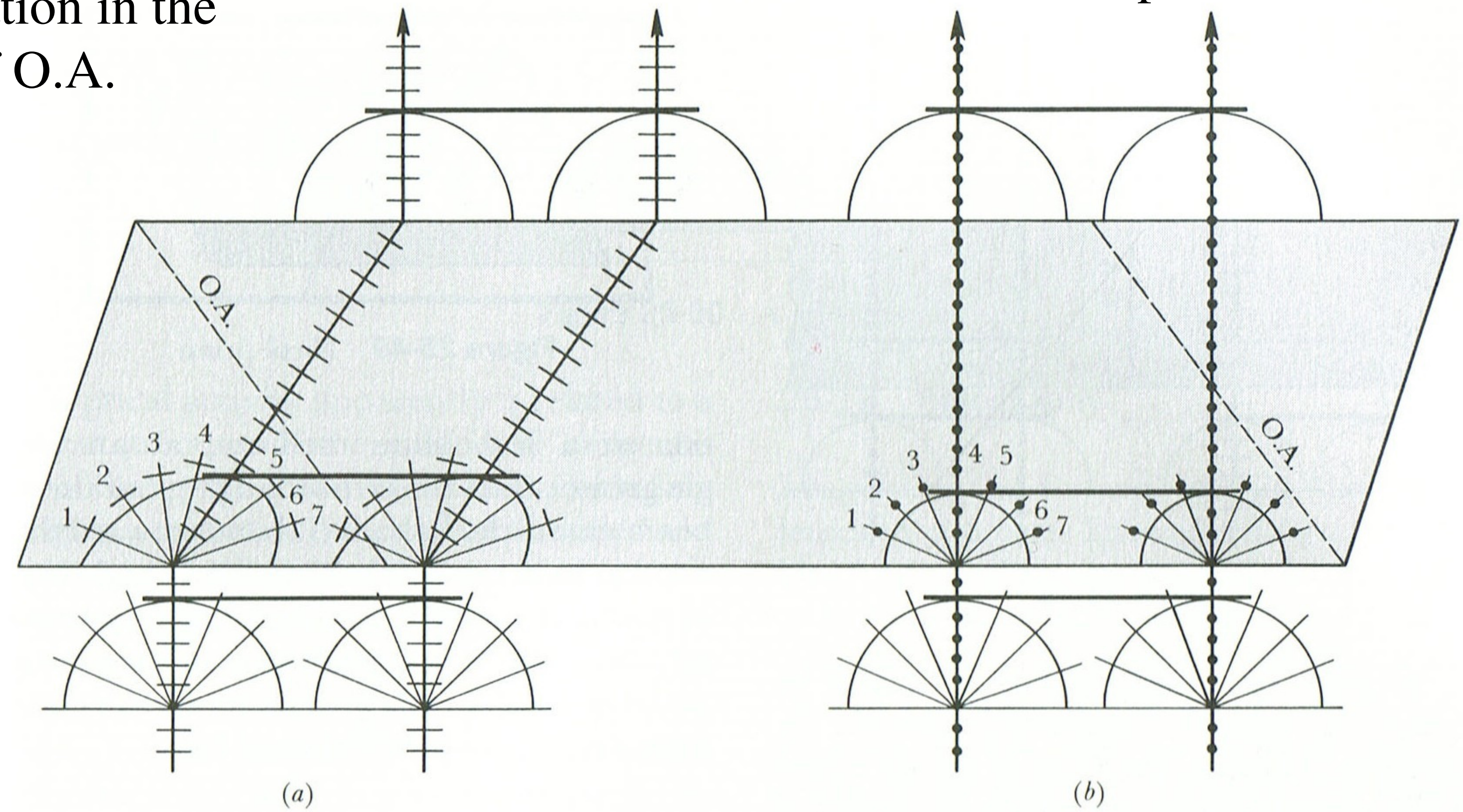
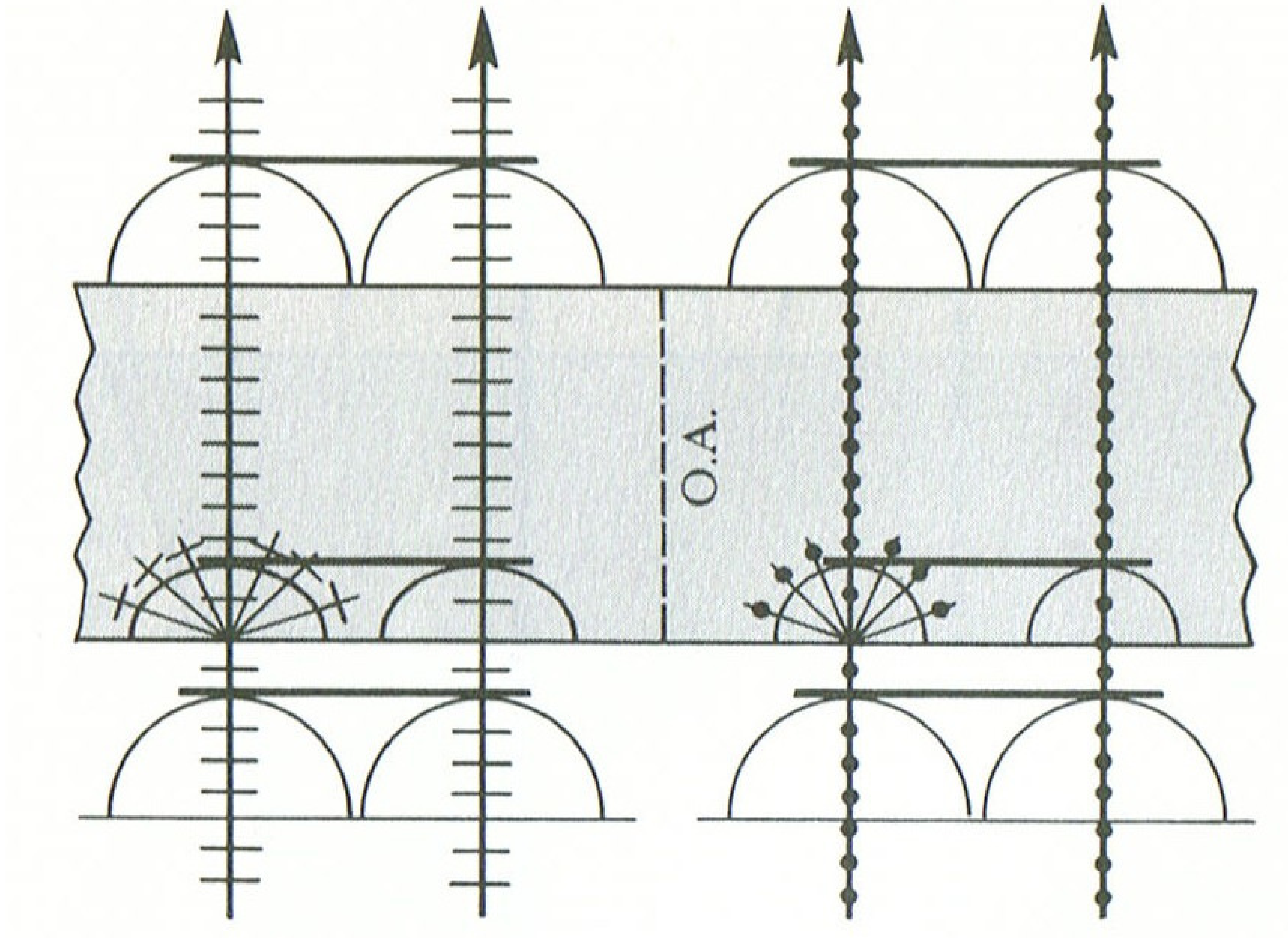


Figure 25-47 Wave fronts in calcite. (*a*) Extraordinary beam; (*b*) ordinary beam.

Ordinary and Extraordinary Light Rays

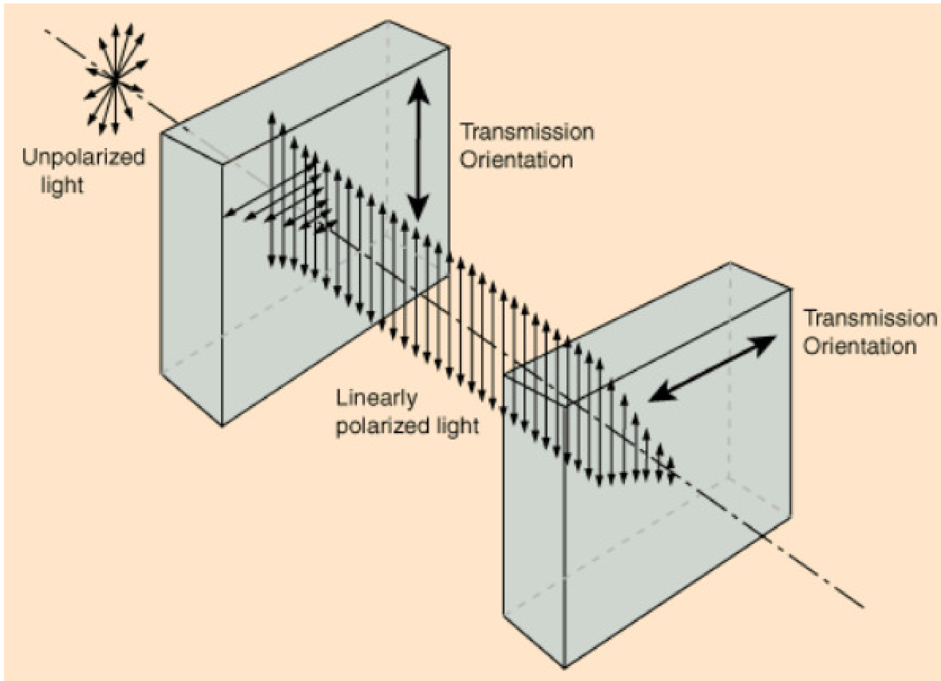
Rays separated for ease of viewing



Crossed Polarizing Sheets

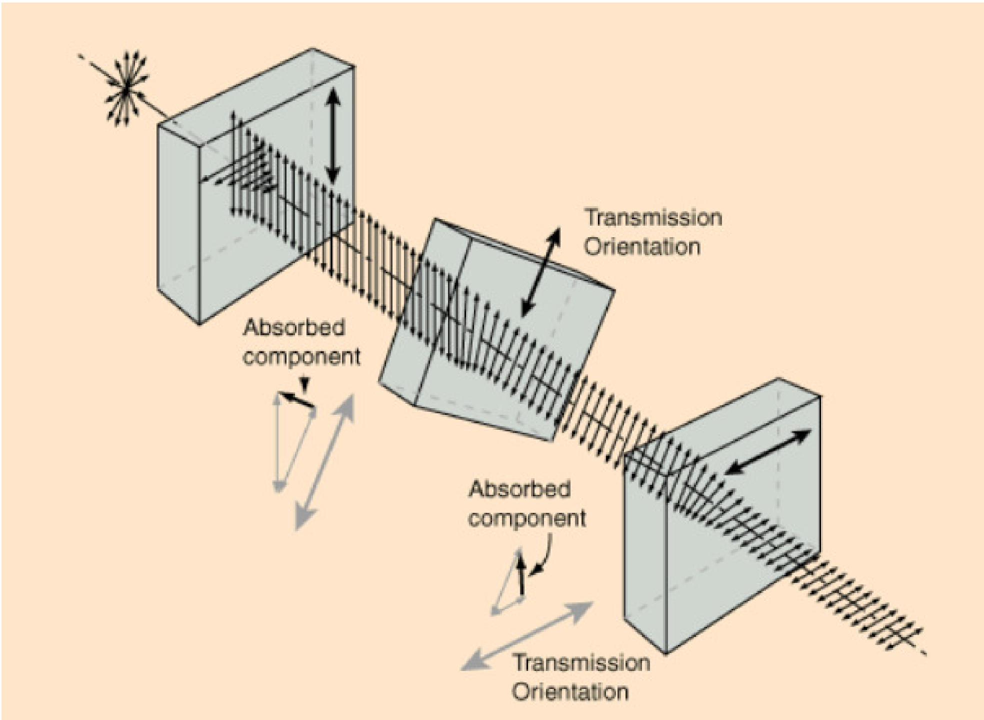
Crossed Polarizing Sheets for Analysis

A polarizing sheet transmits light polarized parallel to the optic axis.



The first sheet prepares the polarization in the vertical direction. The second sheet only allows light through that is polarized in the horizontal direction. As a result no light is transmitted.

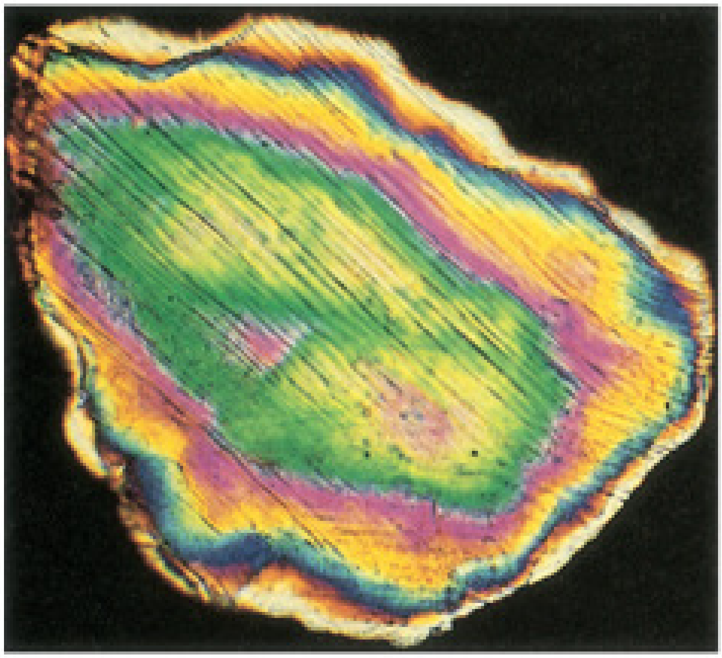
Crossed Polarizing Sheets for Analysis



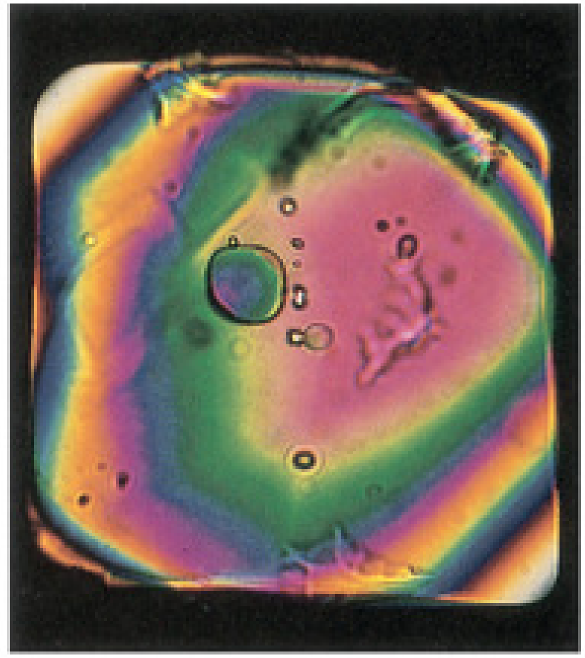
We are interested in the physical properties and phenomena taking place in the object between the polarizers.

An object placed between the crossed polarizers can affect the light passing through it. By changing the plane of the polarization some of the light will now be transmitted through the final sheet.

Shocked and Unshocked Quartz Crystals



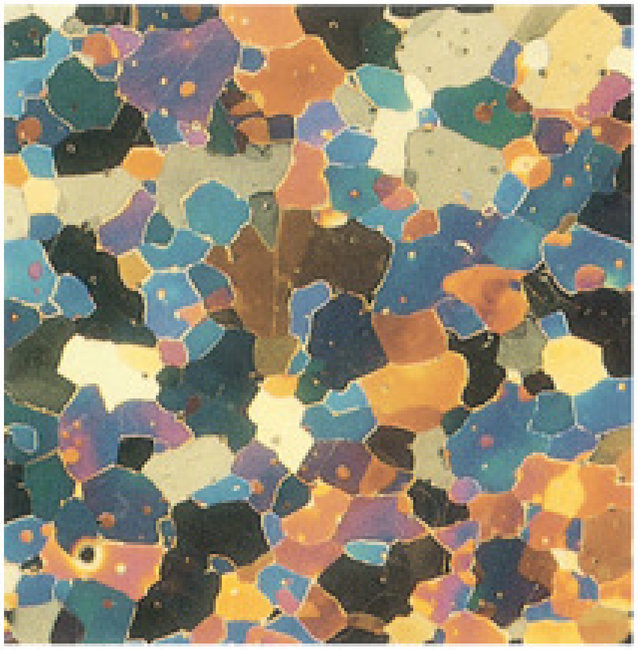
(a)
Quartz crystal grain from meteorite site



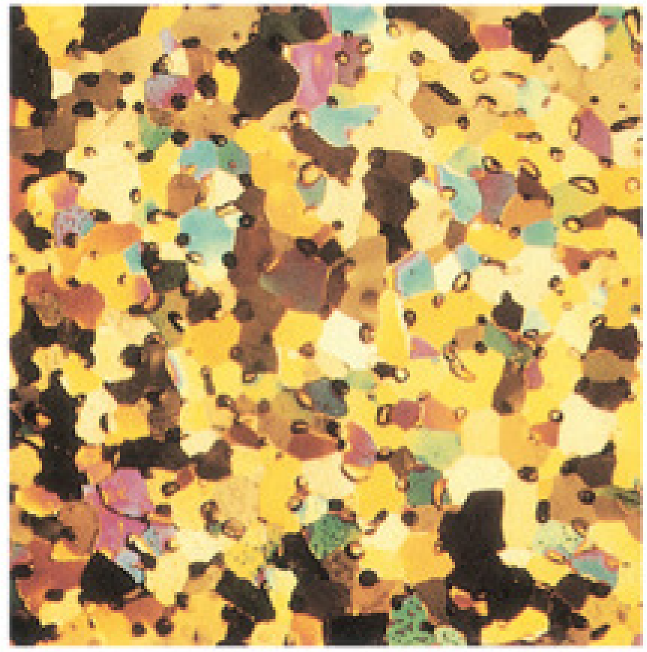
(b)
Quartz crystal grain from volcanic rocks

The shock of the impact is evident in the parallel lines in the crystal on the left. The crystal on the right exhibits no such shocked features.

CO_2 Trapped in Antarctic Ice Cores



(c)
194 m deep - 1600 years old

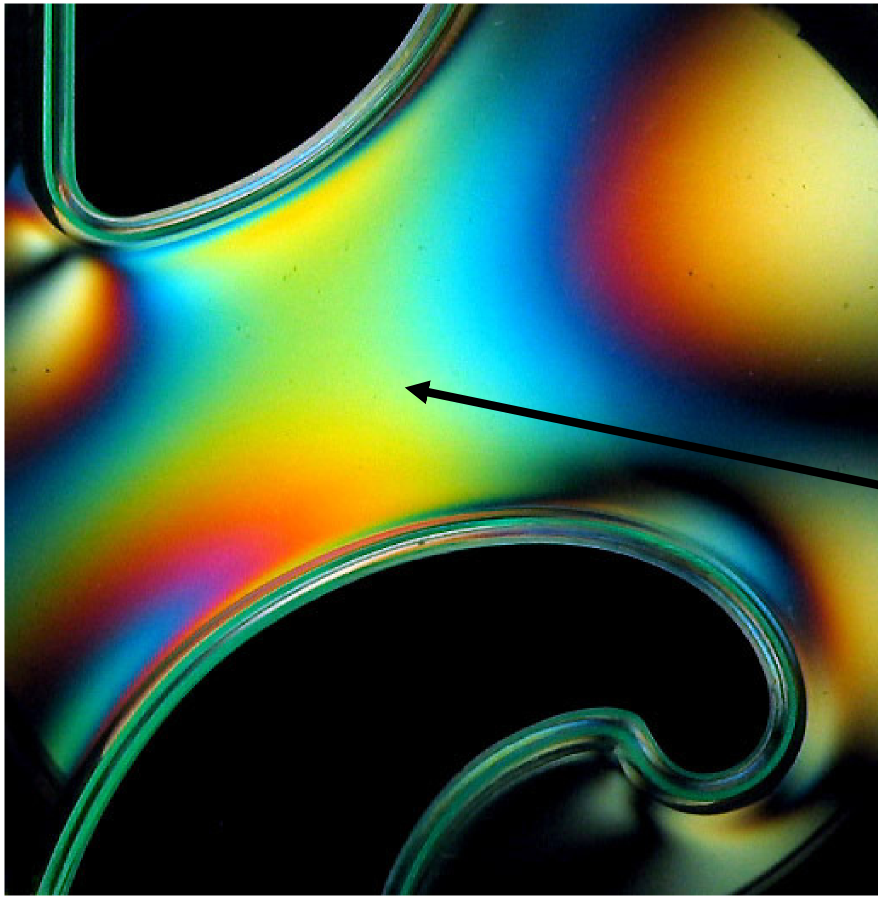


(d)
56 m deep - 450 years old

The trapped CO_2 in the thin slices of ice core appear as amber colored bubbles.

Stressed Plastic

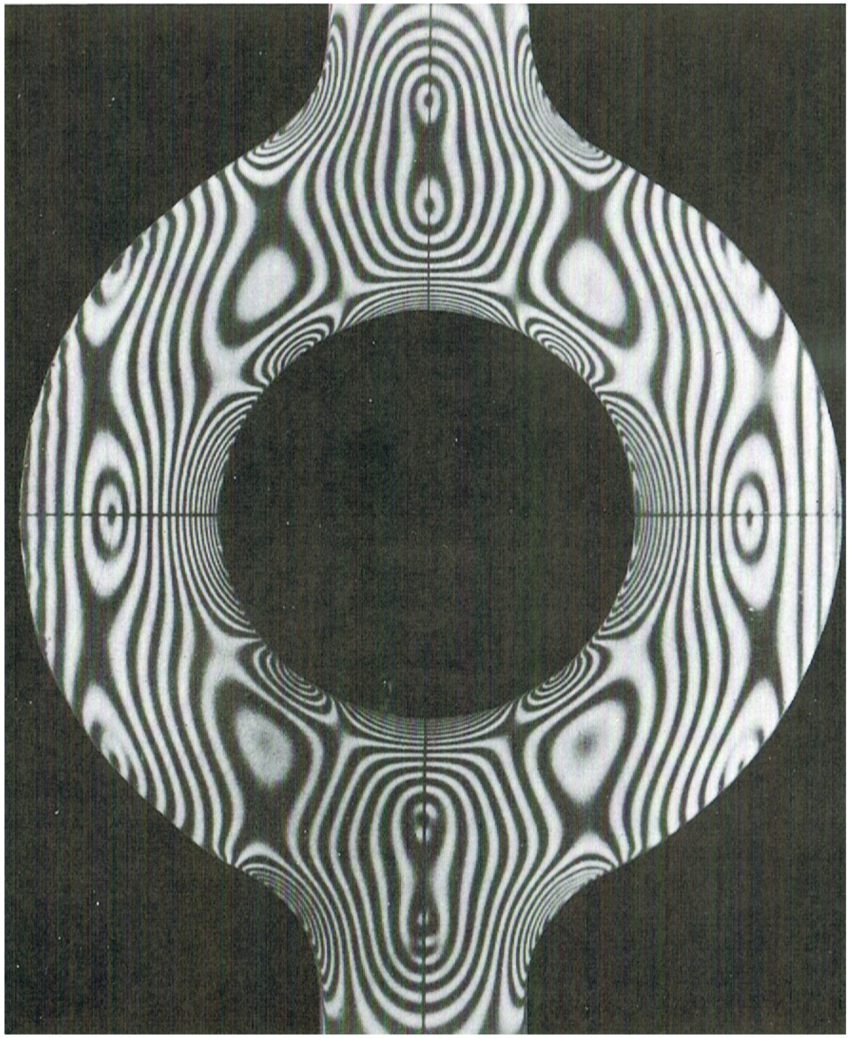
Increased stress at point of tight curves.



Uniform color of light at points of low stress.

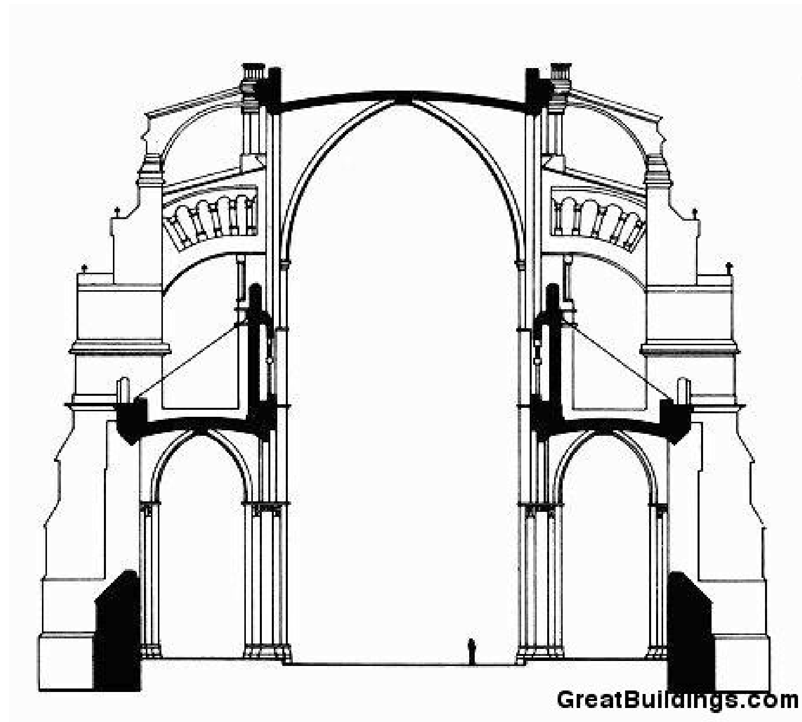
A portion of a stressed French Curve between crossed polarizers.

Stressed Plastic



Chartres Cathedral

Chartres France



Chartres Cathedral thru Crossed Polarizers