

Geometric Optics

If a beam of light is narrow and has short wavelength in comparison to the dimension of any obstacle or aperture in its path, then this beam may be treated as a straight-line ray of light and its wave properties for the moment ignored.

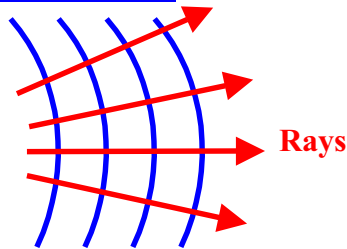
In this approximation, light rays are traced through each optics element in the system responding in a mathematically well-prescribed way at each interaction point.

Reflection

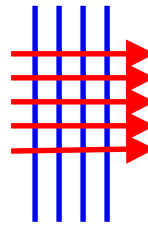
Reflection from a surface depends on the quality of the surface and how much light is absorbed during the process.

A wave front corresponds to the line, sphere or shape formed by connecting the in-time crests in a propagating wave. Rays are vectors perpendicular to wave fronts indicating the direction of propagation.

Wave Fronts

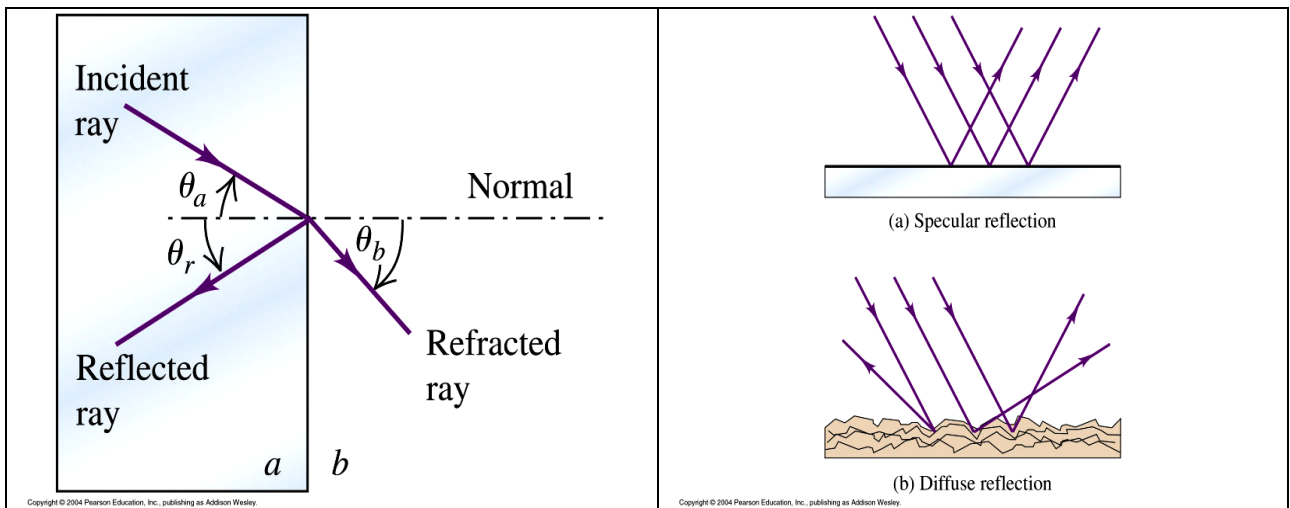


Plane Waves



At sufficiently large distances from a source or by considering a small portion of a spherical wave front, propagating waves may be approximated as plane waves.

The Law of Reflection is: the angle of reflection = the angle of incidence $\theta_a = \theta_r$



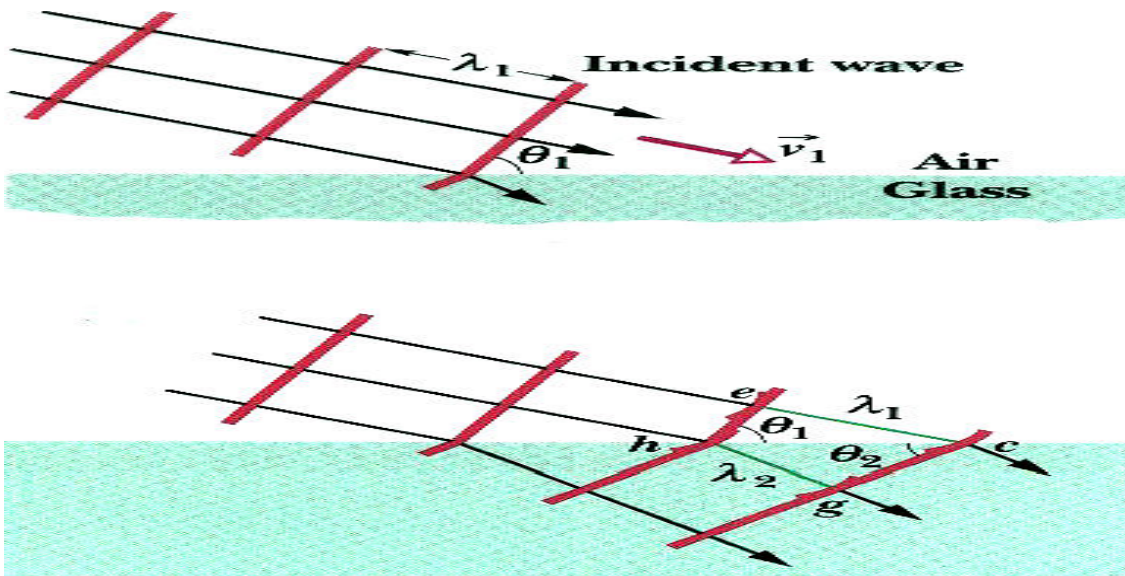
Refraction and Snell's Law

The speed of light in a **vacuum** is $c = 2.99792458 \times 10^8 \text{ m/s}$. If the medium changes, then so does the speed of light in that medium. The medium index of refraction

determines the speed of light within the medium according to:

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

Fermat's principle states light will travel the path that minimizes transit time within any medium. A bending or refraction is therefore seen as light leaves one medium passing into a second of differing index of refraction.



The time to traverse $\overline{ec}$ in n_1 equals the time to traverse $\overline{hg}$ in n_2 .

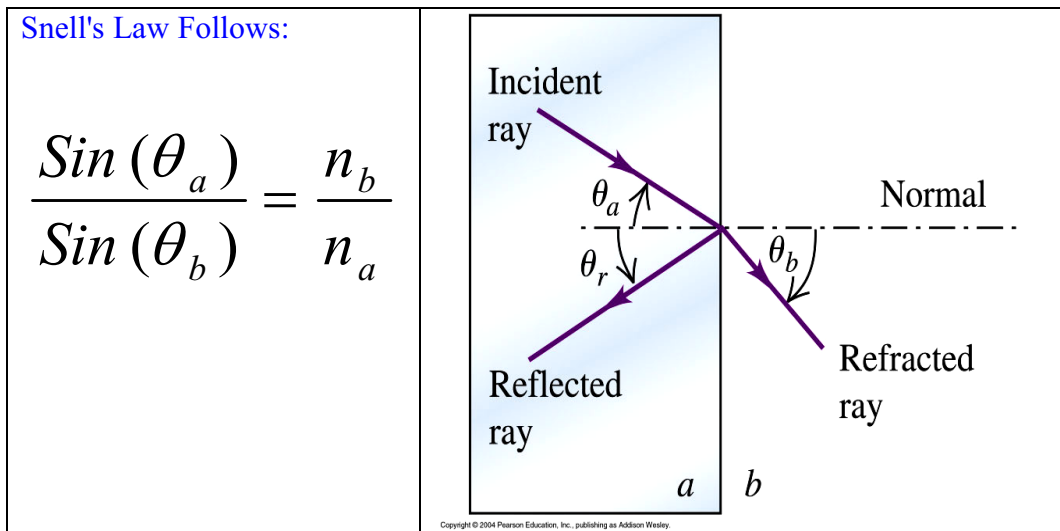
$$\frac{\lambda_1}{v_1} = \frac{\lambda_2}{v_2} \quad \rightarrow \quad \lambda_2 = \frac{v_2}{v_1} \lambda_1 = \frac{n_1}{n_2} \lambda_1$$

Note that although $\lambda_2 = \frac{n_1}{n_2} \lambda_1$, which depends on the medium, the wave frequency is unchanged in the process.

$$f_2 = \frac{v_2}{\lambda_2} = \frac{v_2 n_2}{n_1 \lambda_1} = \frac{v_2 \cancel{c/v_2}}{n_1 \lambda_1} = \frac{c}{n_1 \lambda_1} = \frac{v_1}{\lambda_1} = f_1$$

From triangles **hce** and **hcg**:

$$\sin(\theta_1) = \frac{\lambda_1}{hc} \quad \& \quad \sin(\theta_2) = \frac{\lambda_2}{hc}$$



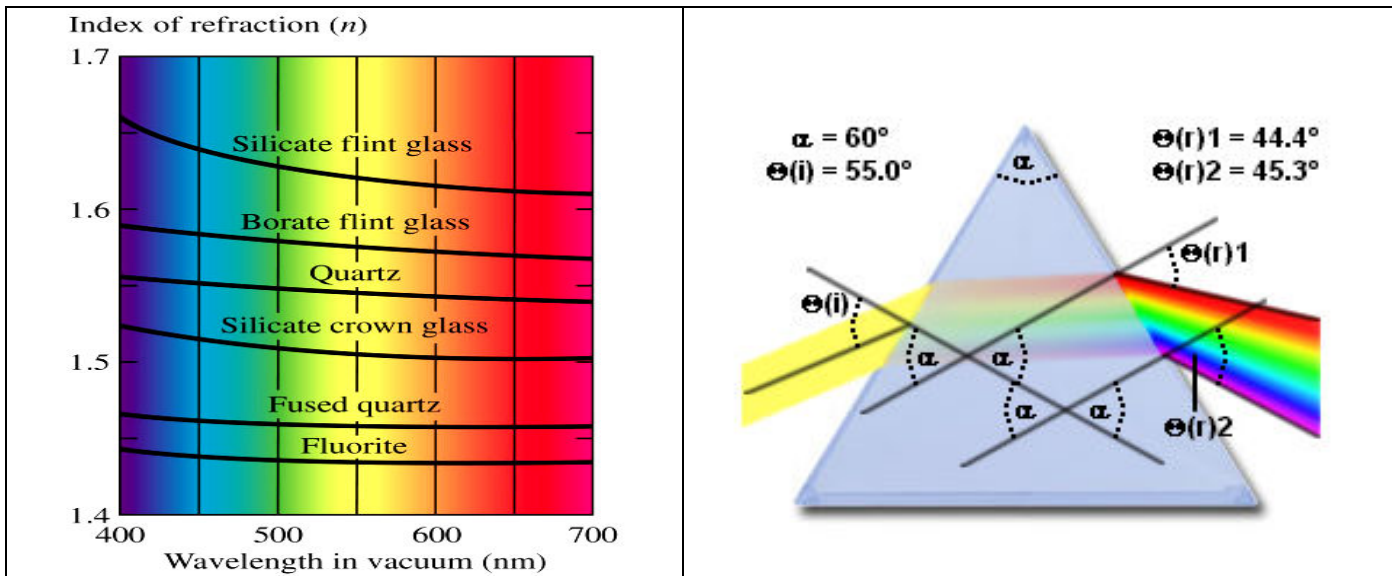
If light travels from medium **a** into medium **b** where $n_b < n_a$, then refraction is away from the normal and the possibility exist for total internal reflection when light from medium **a** is incident at a critical angle θ_c resulting in a 90° refraction angle:

$$\sin(\theta_a) = \frac{n_b}{n_a} \sin(\theta_b)$$

$$\sin(\theta_c) = \frac{n_b}{n_a} * 1 \quad \theta_c = \sin^{-1}\left(\frac{n_b}{n_a}\right)$$

The index of refraction of any given material is close to being constant, but is slightly greater for shorter wavelength light (the blue end of the visible spectrum).

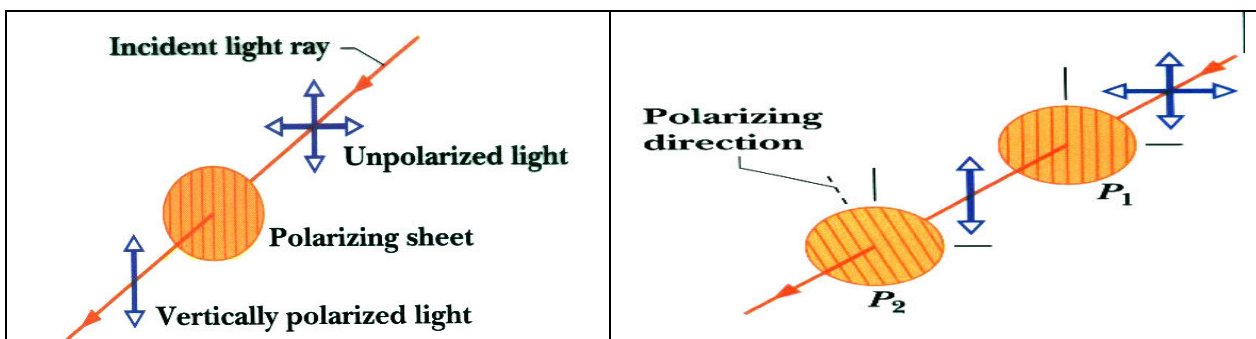
Chromatic dispersion occurs whenever white light, containing all wavelengths in the visible spectrum, undergoes refraction. Refraction is greatest at the blue end of the spectrum and lessens as wavelength increases. Rainbows and prismatic effects result from dispersion of white light.



Polarization

The electric field direction of an electromagnetic wave is in general **unpolarized** or randomly oriented in the plane perpendicular to the propagation direction. Sunlight and the light from an ordinary light bulb are unpolarized light sources.

Unpolarized light incident on a **polarizing filter** will transmit preferentially when any of the incident electric fields are **perpendicular to** the embedded molecular chains of the material comprising the polarizing sheet. [Oscillations parallel to the **polarizing axis**]

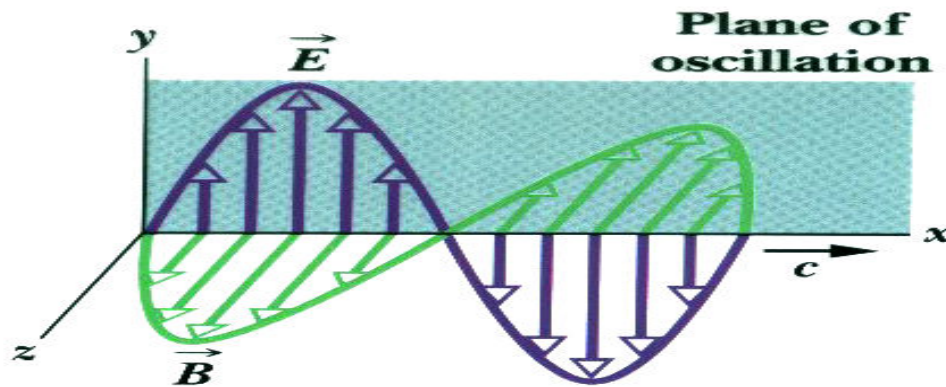


For unpolarized waves incident on polarizing film, the **one-half rule** is:

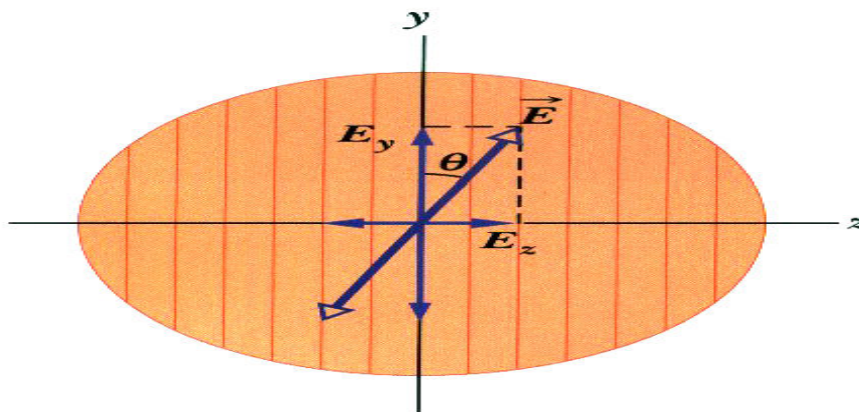
Given that incident waves are equally polarized along both axes, then only one-half the incident intensity survives after passing through the filter:

$$I_{Transmitted} = I_0 / 2$$

In plane-polarized or linearly polarized electromagnetic waves, the electric field oscillation direction defines a plane of oscillation:



Orienting a 2nd polarizing filter axis at angle θ with respect to the plane of oscillation of a previously polarized wave gives $E \cos(\theta)$ passing through the filter.



Then since

$$I = \frac{E_{RMS}^2}{c\mu_0}$$

$$\frac{I_{Transmitted}}{I_0} = \cos^2(\theta) \quad \Rightarrow \quad I = I_0 \cos^2(\theta)$$

This is **Malus's Law**. Applicable only when the incident wave is linearly polarized.

The second polarizing filter is termed an **analyzer** and one can determine the second filter's axis of polarization by rotating it into a position such that either:

$$I_{Transmitted,2} = I_1 \quad \Rightarrow \quad \theta = 0^\circ$$

Or

$$I_{Transmitted,2} = 0 \quad \Rightarrow \quad \theta = 90^\circ$$

Notice this analyzes the polarization direction of the electromagnetic wave transmitted through polarizer 1.

Polarization by Reflection

When incident light is not normal to a boundary interface, then rays reflected at this

surface will have some polarization. At one particular incidence angle, θ_B , the

reflected light becomes completely polarized. Light incident at the **Brewster angle** is reflected with polarized electric fields perpendicular to the plane of incidence and refracted with partially polarized electric fields parallel to the plane of incidence

For incidence at θ_B it is found that $\theta_{reflected} + \theta_{refracted} = 90^0$

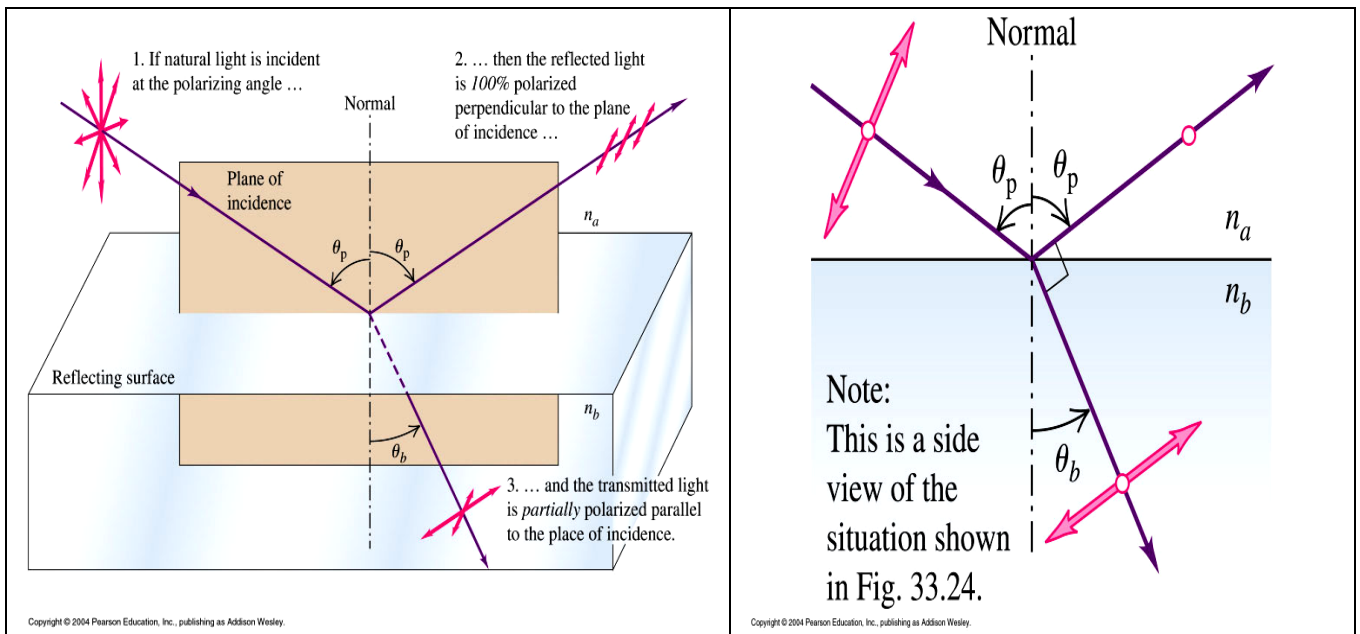
This is the statement that $\theta_B + \theta_{refracted} = 90^0$

From Snell's Law $n_1 \sin(\theta_B) = n_2 \sin(\theta_{refracted})$

$$n_1 \sin(\theta_B) = n_2 \sin(90 - \theta_B) = n_2 \cos(\theta_B)$$

$$\theta_B = \tan^{-1}\left(\frac{n_2}{n_1}\right)$$

If the ray is incident from air, $n_1 = 1$, then $\theta_B = \tan^{-1}(n_2)$

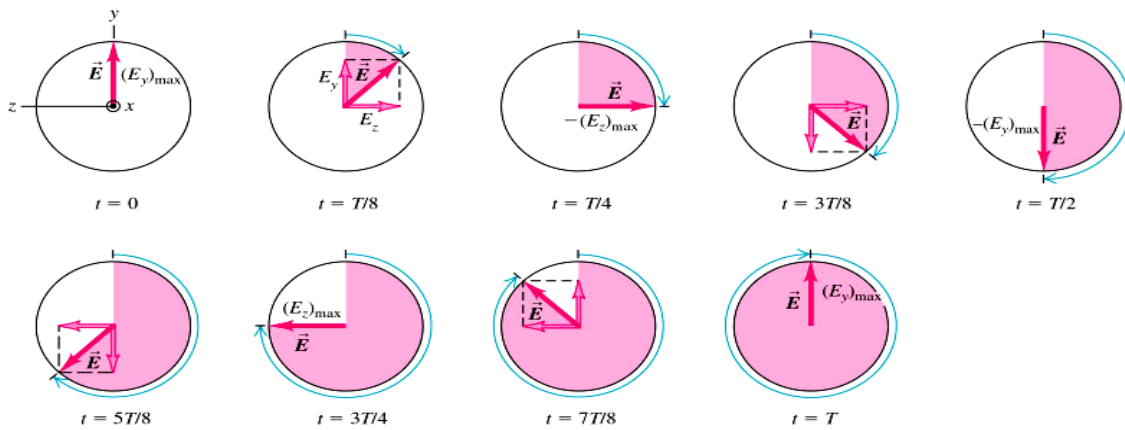


Circular Polarization and Birefringence

A right circular polarized wave may be formed from the superposition of two EM

waves with a $\frac{\pi}{2}$ phase difference. If each wave has electric field amplitude

E then the superposition viewed head-on, rotates clockwise and has constant amplitude E .



A birefringent material has a varying index of refraction depending on the incident light polarization direction. Of an appropriate thickness, birefringent crystals may be used to produce circularly polarized light from initially in phase incident waves by introducing a phase shift depending on the incident wave polarizations.

Blue Sky White Clouds

Preferentially scattered as $\frac{1}{\lambda^4}$ sunlight passing through the atmosphere is absorbed and reemitted toward the blue end of the spectrum with higher probability.

The water / ice laden clouds scatter all wavelengths of light leading to their full visible spectrum content.