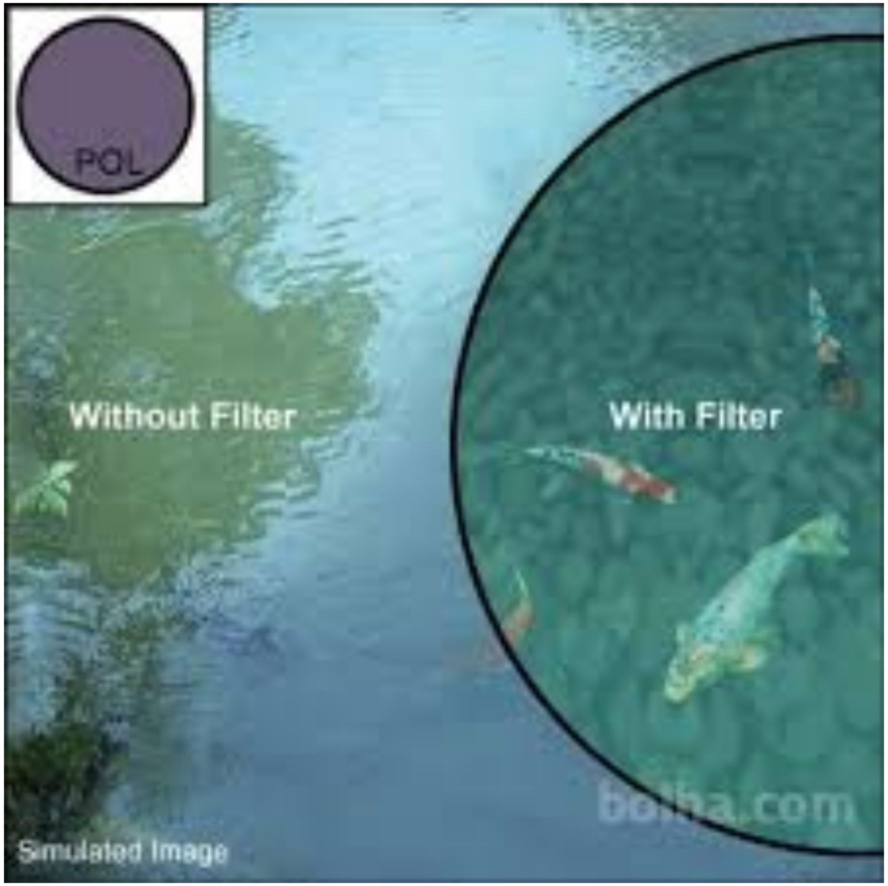

Nikon
D7100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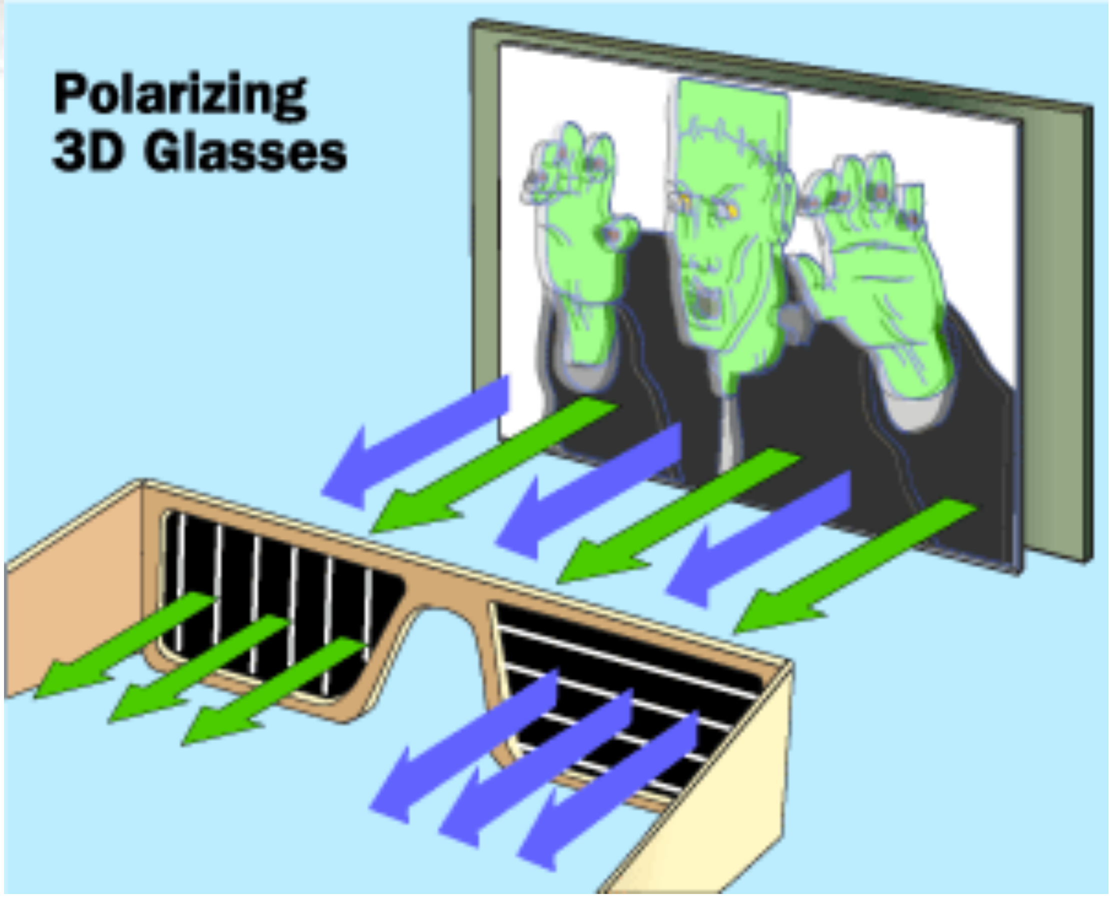
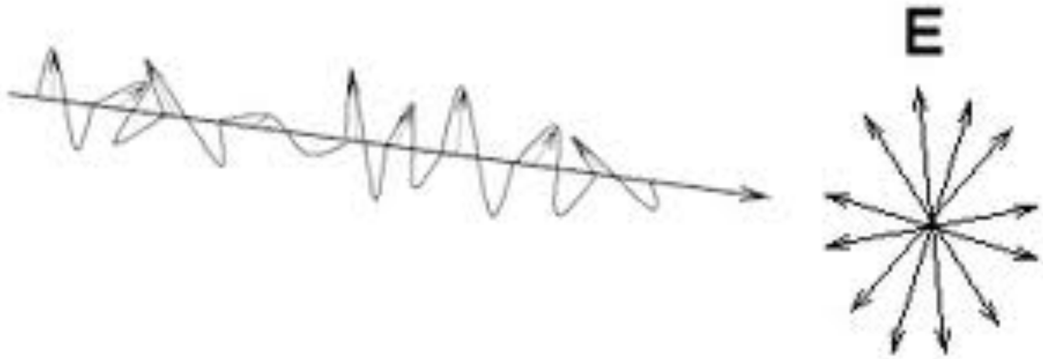
Polarized sunglasses


3D Polarized Glasses


Polarizing
3D Glasses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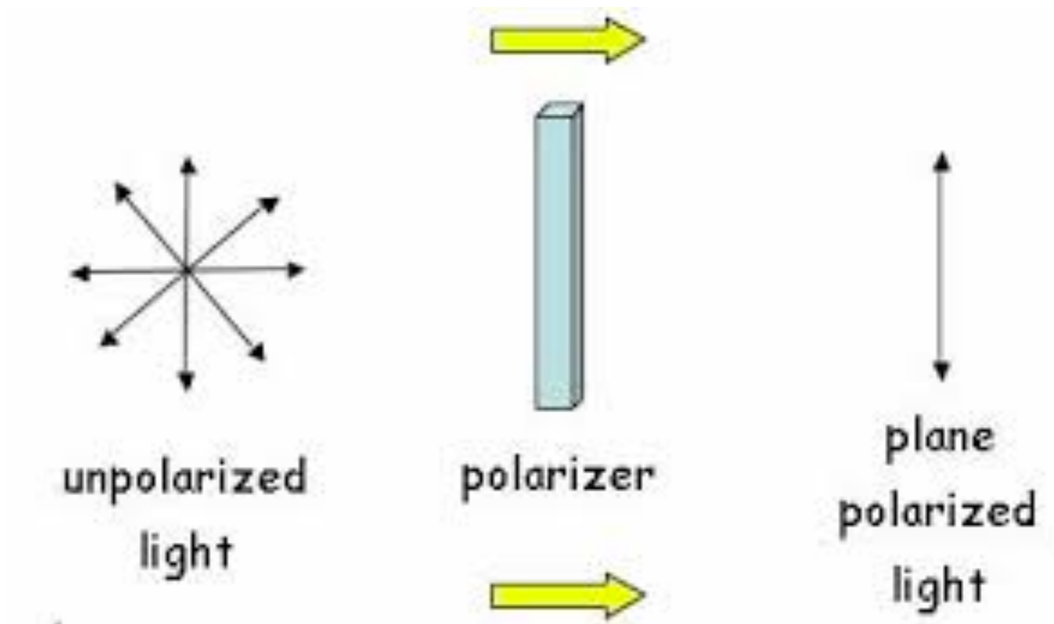
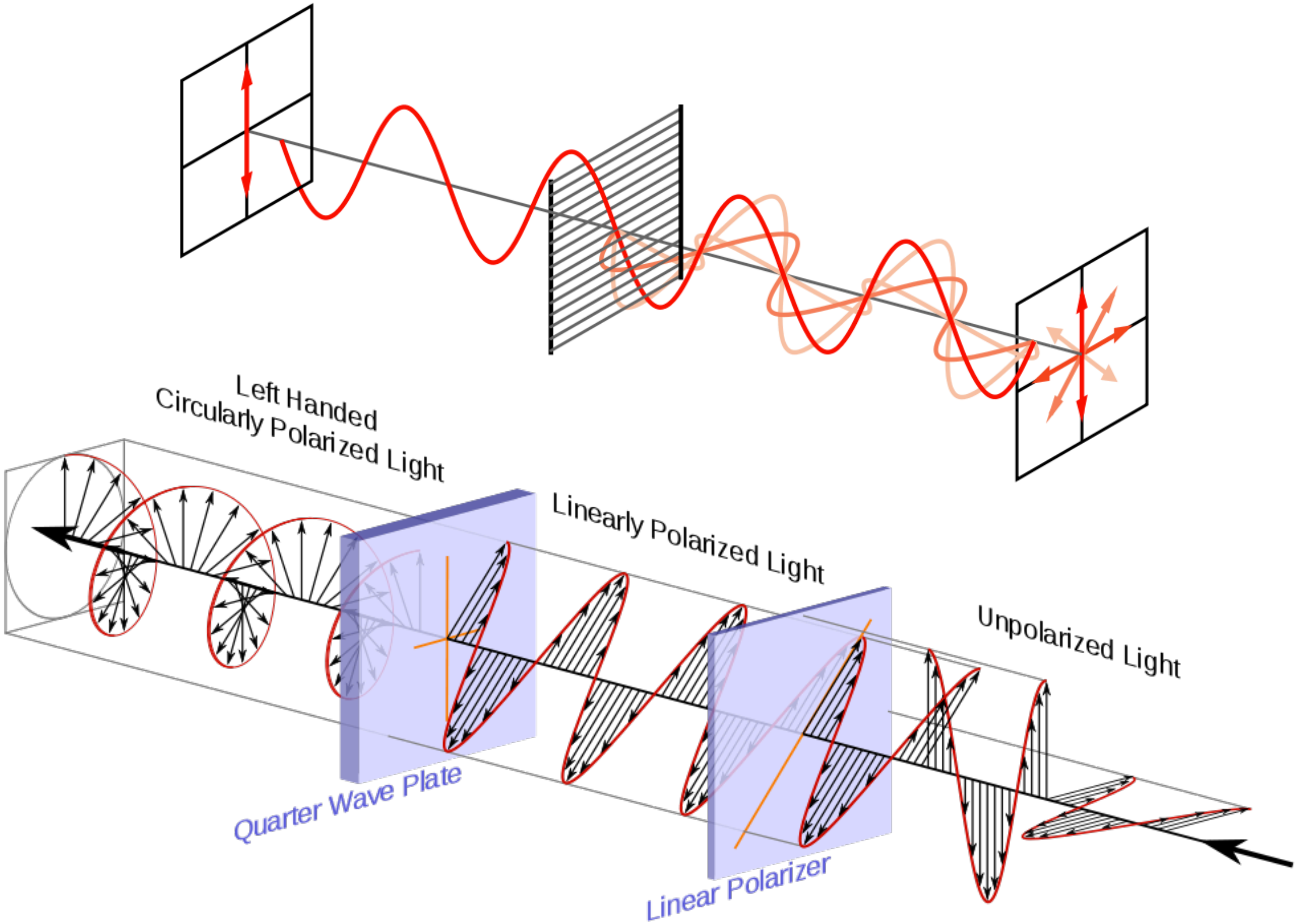

unpolarized
light
polarizer
plane
polarized
light



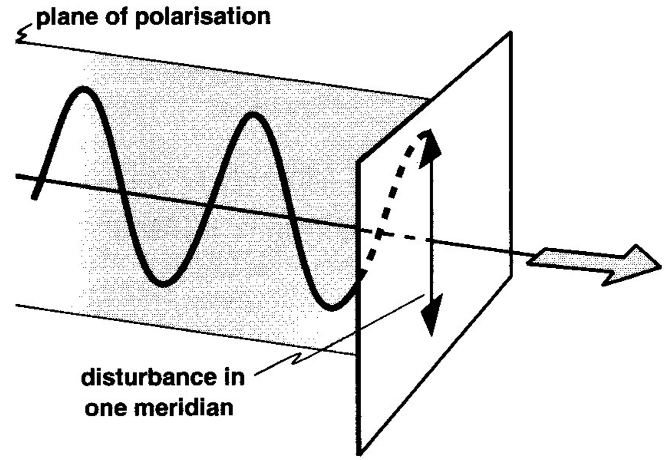
Polarization:

is a property of the wave of light that can oscillate with certain orientation; the wave exhibits polarization which has only one possible polarization, namely the direction in which the wave is travelling.

Polarization:

Consider the superposition of two plane polarized waves:

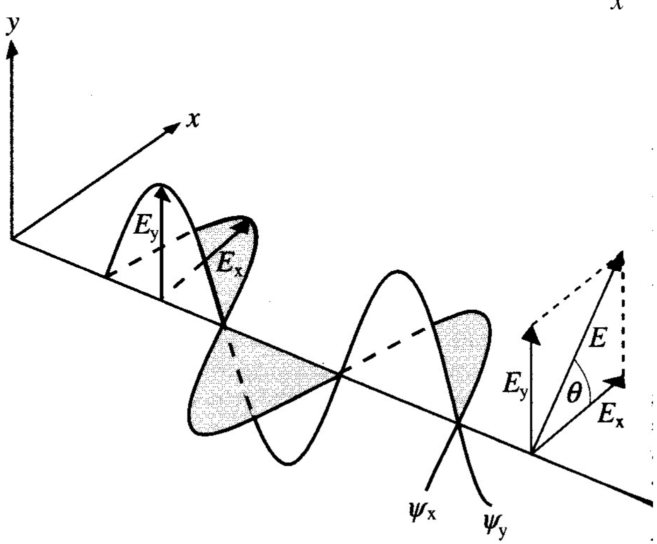
$$\begin{cases} \psi_x = E_x \sin(kz - \omega t) \\ \psi_y = E_y \sin(kz - \omega t + \varepsilon) \end{cases}$$



If ε=2$m\pi$, m being an integer,

$$\psi = \sqrt{\psi_x^2 + \psi_y^2} = E \sin(kz - \omega t)$$

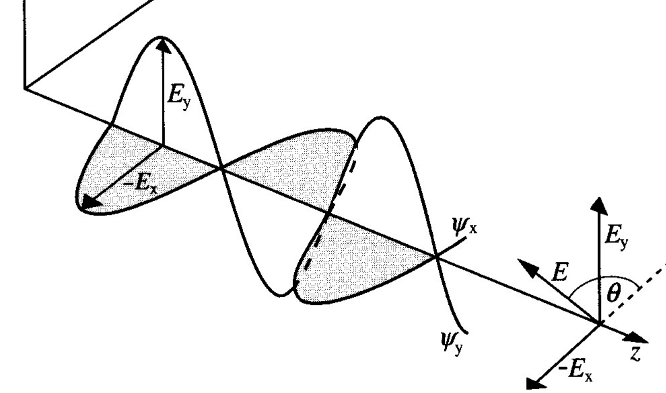
$$E = \sqrt{E_x^2 + E_y^2} \qquad \tan\theta = \frac{E_y}{E_x}$$



If ε=(2m+1)π, m being an integer,

$$\psi = \sqrt{\psi_x^2 + \psi_y^2} = E \sin(kz - \omega t)$$

$$E = \sqrt{E_x^2 + E_y^2} \qquad \tan\theta = -\frac{E_y}{E_x}$$



Right Circularly Polarized Light:

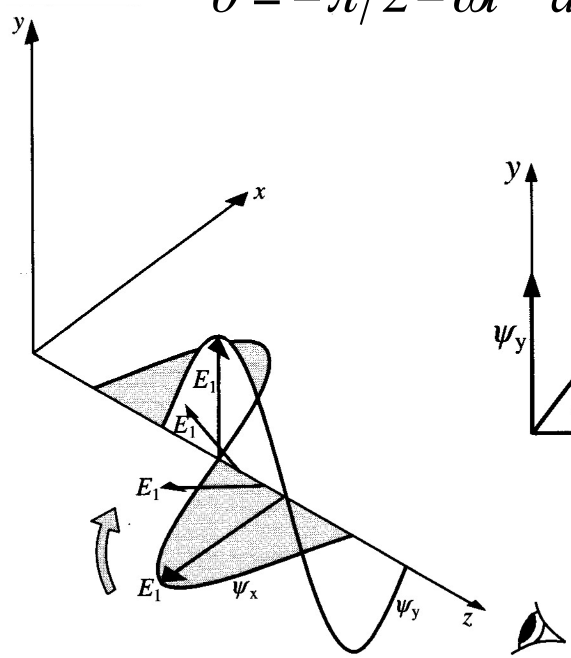
If ε=(2m-1/2)π, m being an integer,

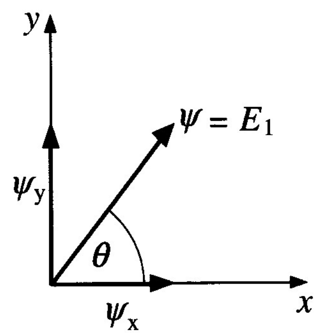
$$E_x = E_y = E_1$$

$$\psi = \sqrt{\psi_x^2 + \psi_y^2} = \sqrt{E_x^2 + E_y^2} = E_1$$

$$\tan\theta = \frac{\psi_y}{\psi_x} = \frac{\cos\omega t}{\sin\omega t}$$

$$\theta = -\pi/2 - \omega t \quad at\ z = 0$$





Left Circularly Polarized Light:

If ε=(2m+1/2)π, m being an integer,

$$E_x = E_y = E_1$$

$$\psi = \sqrt{\psi_x^2 + \psi_y^2} = \sqrt{E_x^2 + E_y^2} = E_1$$

$$\tan\theta = \frac{\psi_y}{\psi_x} = -\frac{\cos\omega t}{\sin\omega t}$$

$$\theta = \pi/2 + \omega t \quad at\ z = 0$$

Right and left circular light can be written as,

$$\mathbf{E_R}(z,t) = E_1[\mathbf{i}\sin(kz-\omega t) - \mathbf{j}\cos(kz-\omega t)]$$

$$\mathbf{E_L}(z,t) = E_1[\mathbf{i}\sin(kz-\omega t) + \mathbf{j}\cos(kz-\omega t)]$$

Their superposition becomes

$$\mathbf{E}(z,t) = 2\mathbf{i}E_1\sin(kz-\omega t)$$

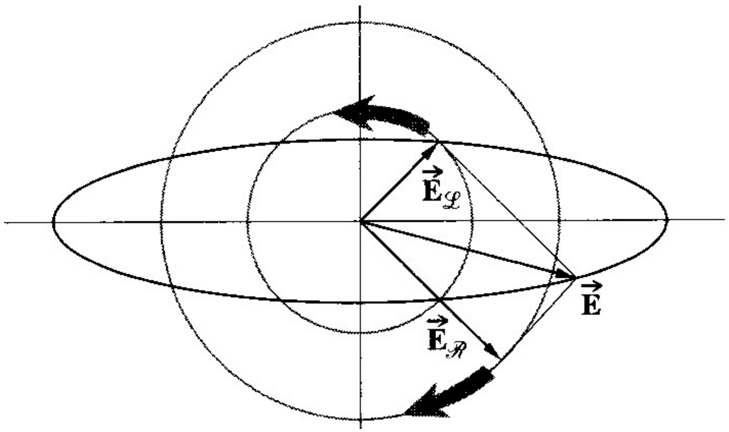
A plane polarized wave can be synthesized from two oppositely polarized circular waves.

Elliptically Polarized Light:

Suppose $E_x \neq E_y$ and ε=(2*m*+1/2)π, *m* being an integer.

$$\psi_x = E_x \sin(kz - \omega t) \qquad \psi_y = E_y \sin(kz - \omega t + \pi/2) = E_y \cos(kz - \omega t)$$

$$\left(\frac{\psi_x}{E_x}\right)^2 + \left(\frac{\psi_y}{E_y}\right)^2 = 1$$



State of Polarization:

P-state

R-state and *L*-state

E-state

Natural Light:

Natural light is randomly polarized. We can mathematically represent natural light in terms of two arbitrary, incoherent, orthogonal, linearly polarized waves of equal amplitude (i.e., waves for which the relative phase difference varies rapidly and randomly).

Example:

A wave ψ has the components $\psi_x = E_1\cos(kz-\omega t)$ and $\psi_y = -E_1\cos(kz-\omega t)$. What is its state of polarization?

$$\psi = \sqrt{\psi_x^2 + \psi_y^2} = \sqrt{2}E_1\cos\left(kz - \omega t\right)$$

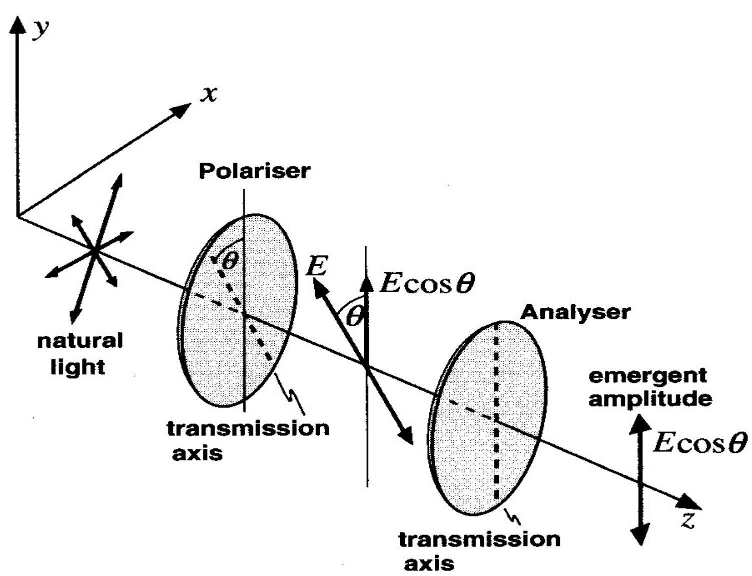
$$\tan\theta = \frac{\psi_y}{\psi_x} = -1 \qquad \therefore \theta = 135^\circ$$

Polarizers:

a device to generate polarized light out of natural one. It can also be used as an analyzer to allow all **E**-vibrations parallel to the transmission axis to pass.

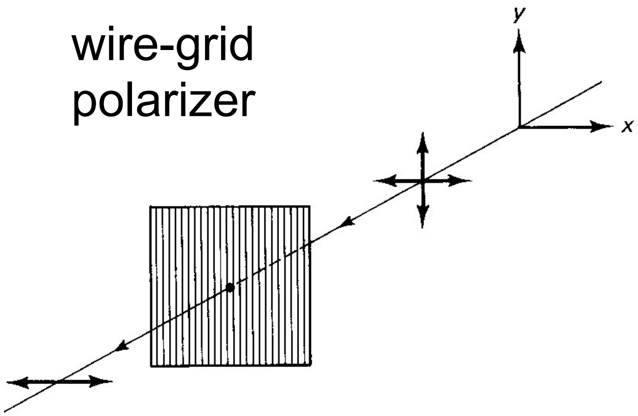
Malus' Law: $$I_\theta = I_0 \cos^2 \theta$$

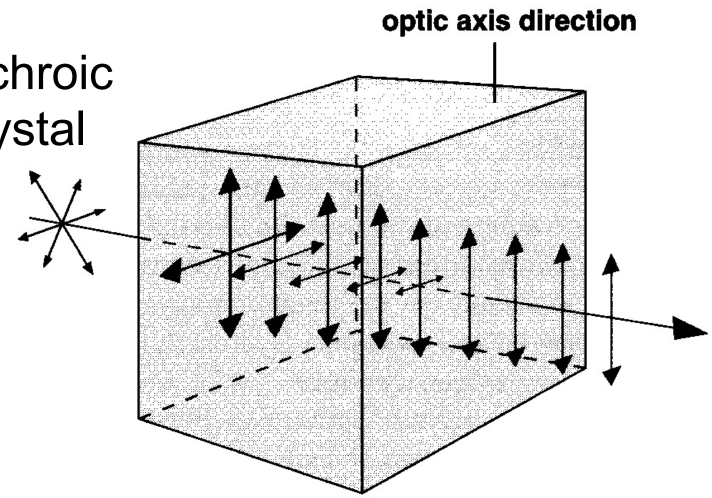
When a natural light passes though an ideal polarizer, its intensity is reduced by half.



Dichorism:

selective absorption of one of the two orthogonal P-state in incident natural light.





Commercial *Polaroid H-Sheet*:

- It's a dichroic sheet polarizer.
- An ideal H-sheet would transmit 50% of the incident natural light and is designated HN-50.
- In practice, due to loss, the H-sheet might be labeled HN-46, HN-38, HN-32, and HN-22 with the number indicating the percentage of natural light transmitted through the H-sheet.

Example:

Natural light of intensity I_i is incident on three HN-46 sheets of Polaroid with their transmission axes parallel. What is the intensity of the emergent light?

$$I_1 = I_i \times 46\%; \qquad I_2 = I_1 \times 46\%; \qquad I_3 = I_2 \times 46\% = I_i \times (0.46)^3 = 0.097 I_i$$

Example:

Suppose the third Polaroid in the last question is rotated through 45°. What is now the intensity transmitted?

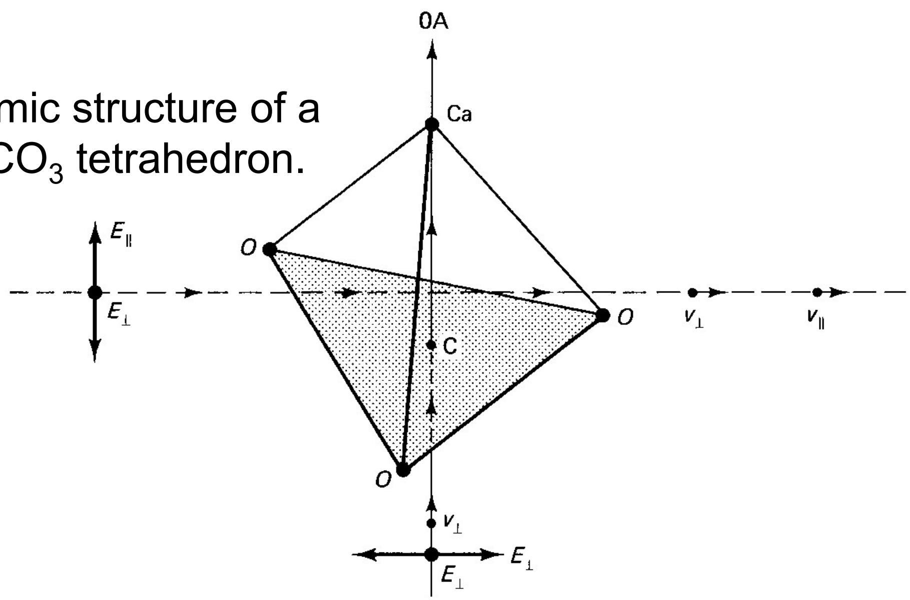
$$I_3 = I_2 \cos^2 45^\circ \times 46\% = I_i \times (0.46)^3 \times 0.5 = 0.049 I_i$$

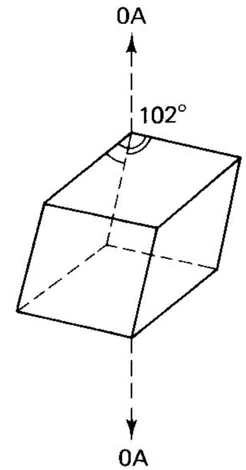
Birefringence:

A material which displays two different speeds of propagation in fixed and orthogonal directions, and therefore displays two refractive indices, is known as *birefringent*.

Distinction: A dichroic material absorbs one of the orthogonal P-states is dichroic while in birefringent material we usually neglect the absorption.

Atomic structure of a $CaCO_3$ tetrahedron.





Rhombohedron of calcite. The optic axis passes symmetrically through a blunt corner where the three face angles equal 102°.

$$n_e = \frac{c}{v_{//}} \qquad n_o = \frac{c}{v_{\perp}}$$

$\Delta n = n_e - n_o$ is called birefringence.

If $\Delta n > 0$ uniaxial positive

If $\Delta n < 0$ uniaxial negative

Example:

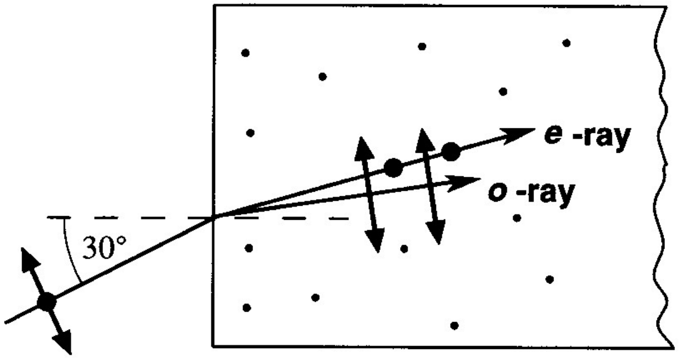
A calcite plate is cut as shown in figure with the optic axis perpendicular to the plane of the paper. A ray of natural light, λ=589.3 nm, is incident at 30° to the normal. The plane of the paper is the plane of incidence. Find the angle between the rays inside the plate.

$$n_e = 1.4866; \qquad n_o = 1.6584$$

$$n \sin i = n_e \sin i_e' \qquad \therefore i'_e = 19.65^\circ$$

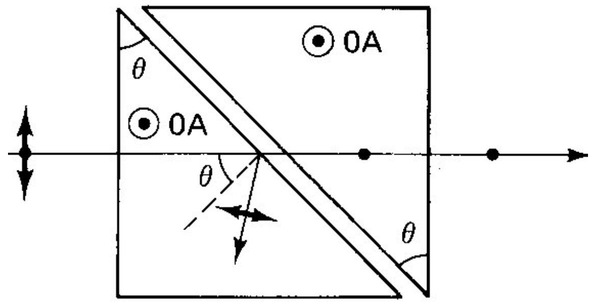
$$n \sin i = n_o \sin i_o' \qquad \therefore i_o' = 17.55^\circ$$

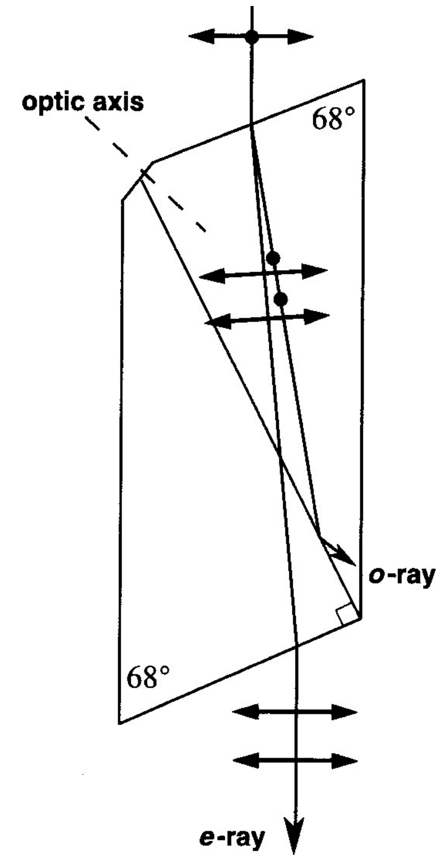
$$\alpha = i_e' - i_o' = 2.10^\circ$$



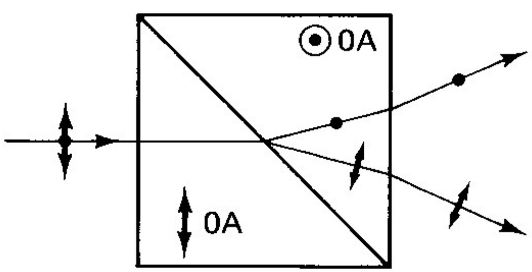
Various Types of Plane Polarizers:

Glan-Air prism

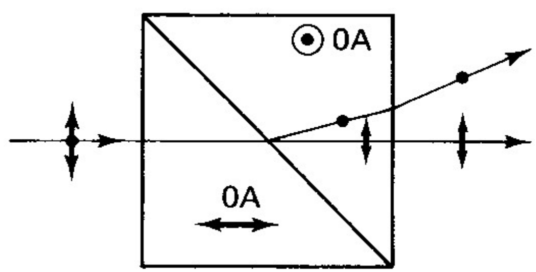




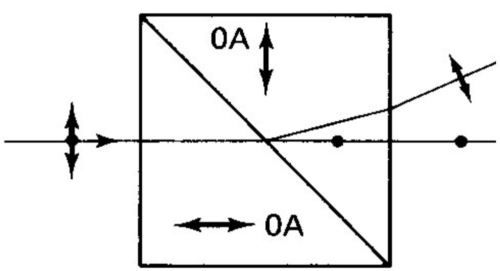
Nicol prism



Wollaston prism



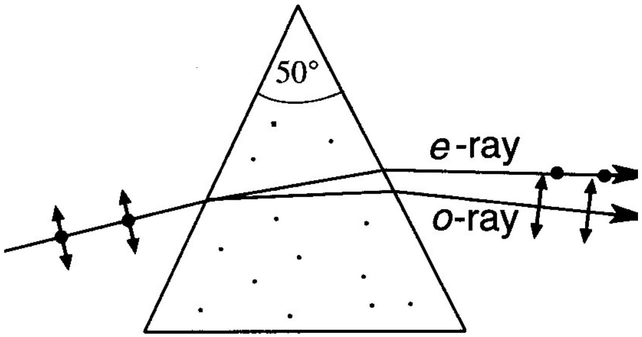
Rochon prism



Sernarmont prism

Example:

A 50° calcite prism is cut with its optic axis as shown in the figure. Sodium light is used in a spectrometer experiment to find n_o and n_e. Two images of the slit are seen and minimum deviation is measured for each. Find n_o and n_e if the angles of minimum deviation are 27.83° and 38.99°. Explain how you would decide which image was formed by the *o*-rays and which was formed by the *e*-rays.



When $d_{\min} = 27.83^\circ$

$$n = \frac{\sin\frac{1}{2}(a + d_{\min})}{\sin\frac{1}{2}a} = \frac{\sin\frac{1}{2}(50^\circ + 27.83^\circ)}{\sin\frac{1}{2}(50^\circ)} = 1.4864$$

When $d_{\min} = 38.99^\circ$

$$n = \frac{\sin\frac{1}{2}(a + d_{\min})}{\sin\frac{1}{2}a} = \frac{\sin\frac{1}{2}(50^\circ + 38.99^\circ)}{\sin\frac{1}{2}(50^\circ)} = 1.6584$$

Since calcite is uniaxial negative, therefore

n_e=1.4864 and n_o=1.6584

Scattering: The displacement of an electron oscillating harmonically under an external field is

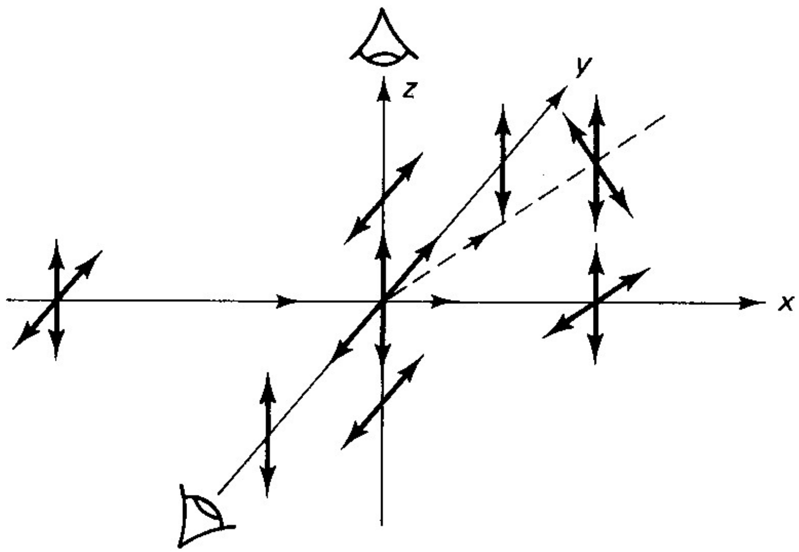
$$x = \frac{q/m}{\omega_0^2 - \omega^2} E \sin \omega t$$

where ω_0 is the natural frequency (*resonant frequency*) of the oscillation of the bound electron. At resonant frequency, strong absorption occurs. At non-resonant frequencies the absorption of the wave packet and its subsequent emission is known as *scattering*.

Rayleigh Scattering:

Scattering centers have dimensions smaller than the wavelength. The radiated power is inversely proportional to the fourth power of the wavelength of the incident radiation.

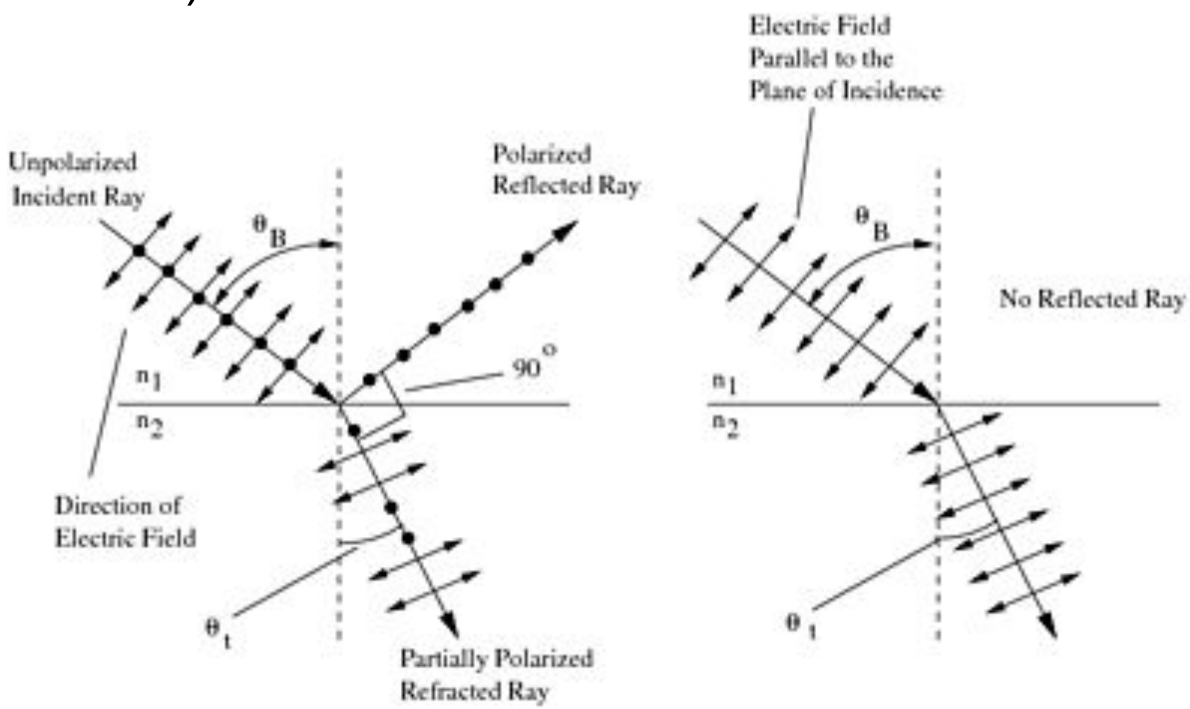
Polarization due to scattering:



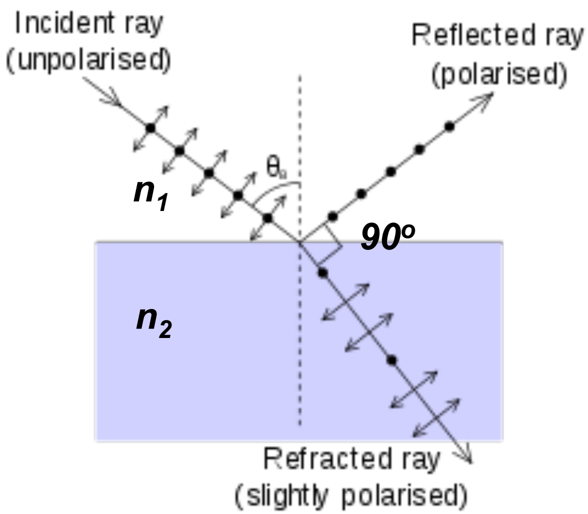
Brewster's angle

Brewster's angle (also known as the polarization angle) is an angle of incidence at which light with a particular polarization is perfectly transmitted through a transparent dielectric surface, with no reflection.

When unpolarized light is incident at this angle, the light that is reflected from the surface is therefore perfectly polarized. This special angle of incidence is named after the Scottish physicist Sir David Brewster (1781–1868)



Brewster's angle



With simple geometry, this condition can be expressed as

$$i + i' = 90^o$$

where i is the angle of reflection (or incidence) and i' is the angle of refraction.

Using **Snell's law**:

$$n_1 \sin i = n_2 \sin i'$$

one can calculate the incident angle $i = i_p$ at which no light is reflected:

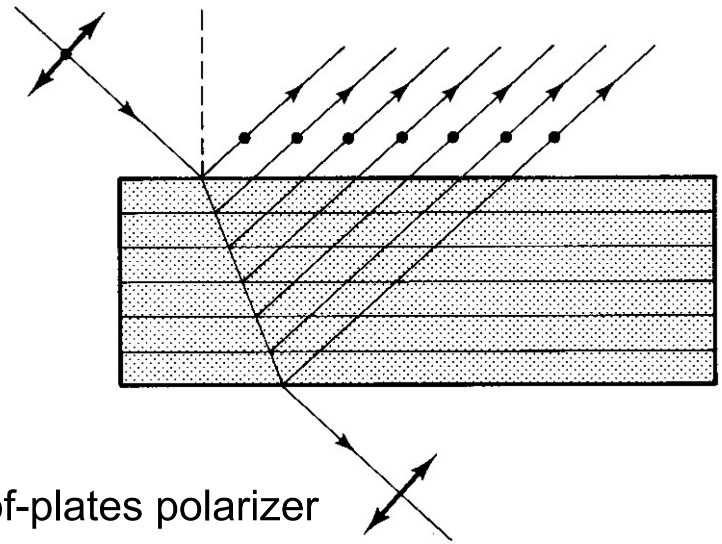
$$n_1 \sin i_p = n_2 \sin(90^o - i_p) = n_2 \cos i_p$$

Solving for i_p gives

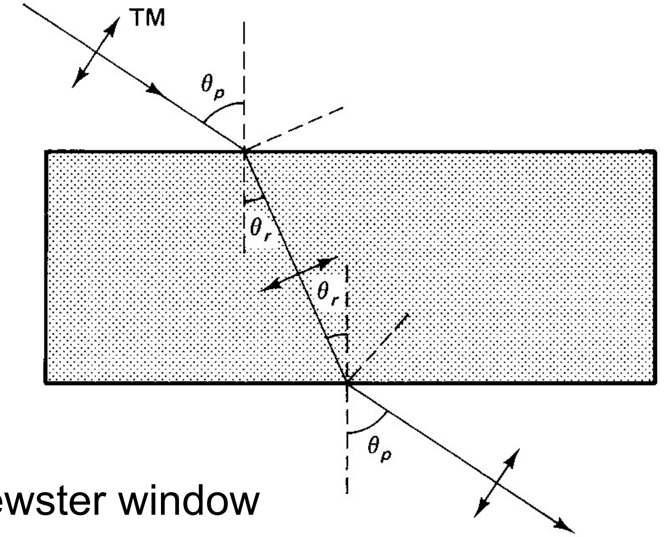
$$i_p = \tan^{-1}\left(\frac{n_2}{n_1}\right)$$

Polarization by Reflection:

At Brewster's angle i_p, $r_{//} = \dfrac{\tan(i_p - i')}{\tan(i_p + i')} = 0$ the reflected light becomes plane polarized perpendicular to the plane of incidence.



pile-of-plates polarizer



Brewster window

Degree of polarization: $$P = \frac{I_p}{I_p + I_u} = \frac{(I_p + I_u/2) - I_u/2}{(I_p + I_u/2) + I_u/2} = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}$$

Example:

Calculate the Brewster's angle of natural light is incident on (i) a plane air/water boundary, (ii) a plane air/glass.

$$\theta_B = \tan^{-1}\left(\frac{n_{water}}{n_{air}}\right) = \tan^{-1}\left(\frac{1.33}{1}\right) = 53^o$$

$$\theta_B = \tan^{-1}\left(\frac{n_{glass}}{n_{air}}\right) = \tan^{-1}\left(\frac{1.5}{1}\right) = 56^o$$

Example:

Natural light is incident on a plane air/glass boundary. Suppose the angle of incidence is about 55° and the refractive index of glass is 1.5. Calculate the degree of polarization.

$$n_{air}\sin i = n_g \sin i' \qquad \therefore i' = 33.1^\circ$$

$$R_{//} = \frac{I_{r//}}{I_{i//}} = \frac{E_{r//}^2}{E_{i//}^2} = r_{//}^2 = \frac{\tan^2(i-i')}{\tan^2(i+i')} = 1.778\times10^{-4}$$

$$R_{\perp} = \frac{I_{r\perp}}{I_{i\perp}} = \frac{E_{r\perp}^2}{E_{i\perp}^2} = r_{\perp}^2 = \frac{\sin^2(i-i')}{\sin^2(i+i')} = 0.1393$$

$$P = \frac{I_p}{I_p + I_u}$$

$$= \frac{R_{\perp} - R_{//}}{R_{\perp} + R_{//}} = 0.997$$

Retarders:

Retarders are devices that cause one orthogonal P-state component to lag behind the other on emerging from the retarders.

The path difference is $OPD = \left(\left|n_e - n_o\right|\right)t$

Full wave plate:

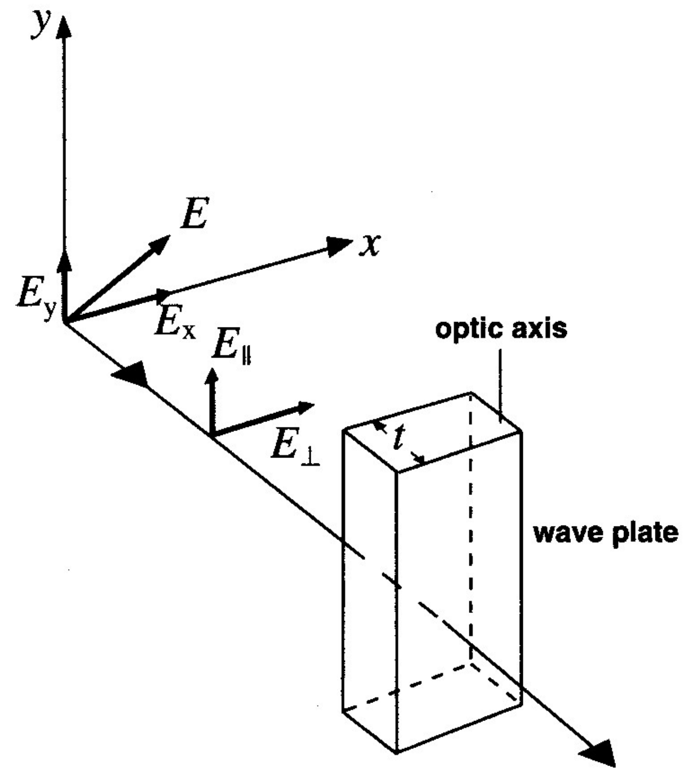
$$OPD = \left(\left|n_e - n_o\right|\right)t = m\lambda, \quad m = 1,2,3\ldots$$

Half-wave plate:

$$OPD = \left(\left|n_e - n_o\right|\right)t = \left(m + \frac{1}{2}\right)\lambda, \quad m = 1,2,3\ldots$$

Quart-wave plate:

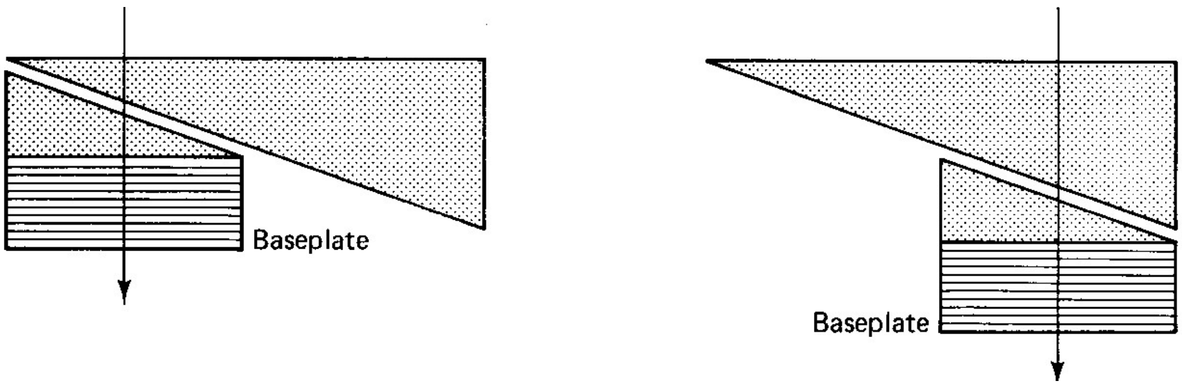
$$OPD = \left(\left|n_e - n_o\right|\right)t = \left(m + \frac{1}{4}\right)\lambda, \quad m = 1,2,3\ldots$$



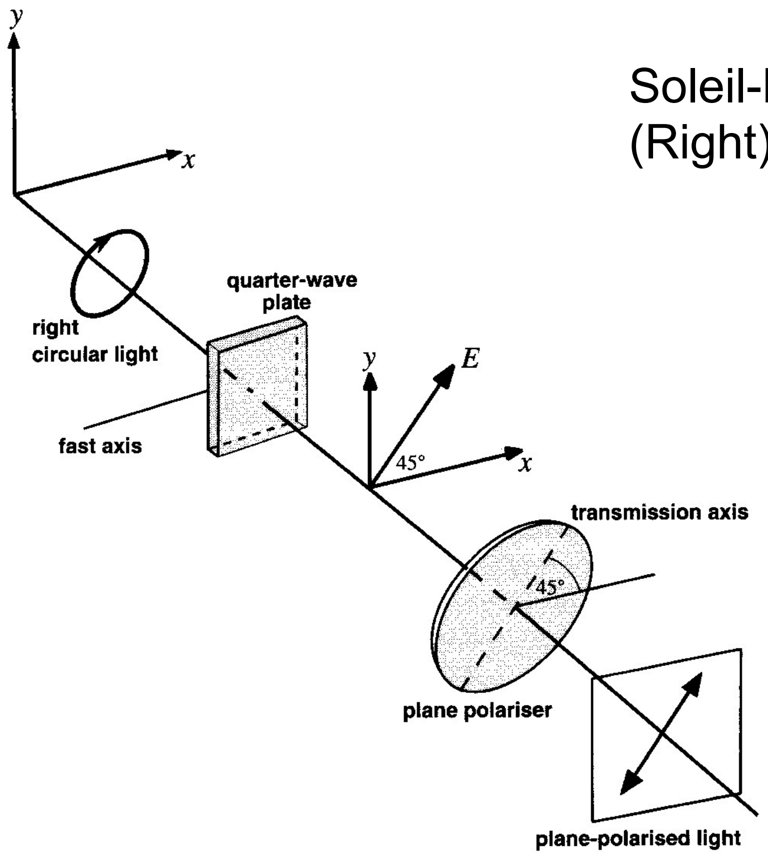
The component $E_{//}$ and $E_\perp$ that travels faster defines the *fast* axis of the plate.

Compensator:

—A device that allows a continuous adjustment of the relative phase shift, the retardance.



Soleil-Babinet compensator. (Left) Zero retardation. (Right) Maximum retardation.



A circular light can be changed into P-state with a quarter-wave plate.

The handiness of circular light can be checked by this method.