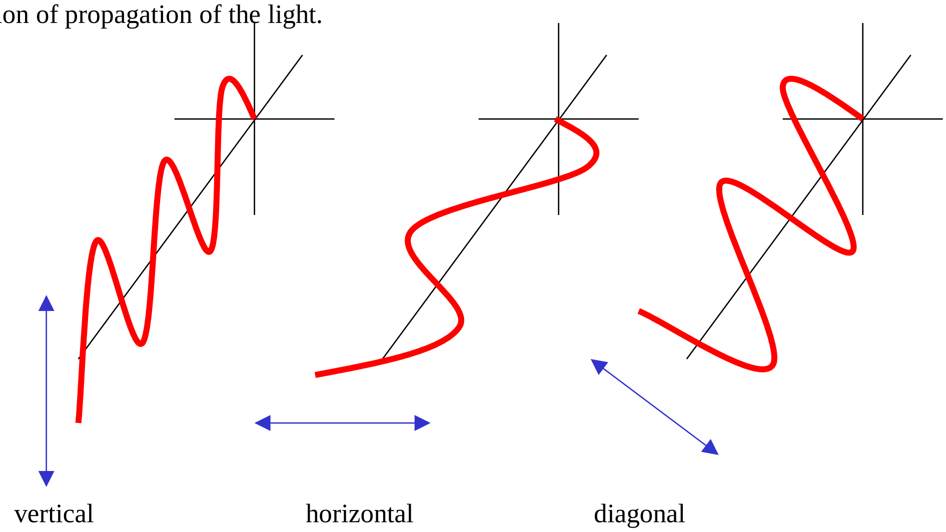
Polarization

Recall that I stated that we had to model light as a **transverse wave** so that we could use the model to explain polarization. The electric energy of a polarized beam acts in a specific direction that is perpendicular to the direction of propagation of the light.



Polarization arises whenever radiated energy, or light, comes from an excited molecule oscillating in one direction. In the natural environment these oscillations are oriented randomly and tend to shift over time so normal light is unpolarized (i.e. it is made up of components of every possible polarization.)

But when light is created in a controlled environment, such as in a laser, all the oscillations are correlated and you can selectively amplify one orientation of the polarization. Alternately, you can select one component of the polarization by...

•passing unpolarized light through a specially designed filter.

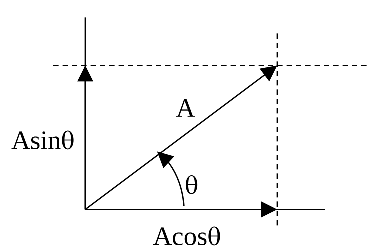
•reflecting unpolarized light off an appropriately tilted surface.

•scattering unpolarized light in a specific direction from small particles.

Components of Polarization: Malus' Law

Like any vector, the vector representing the polarization of light can always be split into a horizontal and vertical component.

$$I = A^2$$



Since the intensity is the square of the amplitude, it follows that the intensity of the horizontal and vertical components are:

$$I_x = A^2 \cos^2 \theta, \quad I_y = A^2 \sin^2 \theta$$

Malus' Law

where θ is the angle between the orientation of the light and the horizontal component.

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Polarizating Filter, Polaroid, Polarizers

For polarized light, the electric vector oscillates in a specific direction. When light strikes a conducting material, the free electrons within the material absorb the oscillating energy and begin to oscillate themselves. The ease with which the electrons can oscillate in a specific direction dictates how much light of that polarization gets absorbed. In many metals, the molecules are amorphous, or randomly arranged, so light of all polarizations are equally absorbed. That is why metal is reflective, but not transmissive (opaque).

To create a polarizer, you need to design a material that only allows oscillation of molecules in a single direction. One example is an array of thin vertical wires. If the wires are thin enough (on the order of wavelength) then electrons only oscillate in one direction and only that orientation of polarization is absorbed. The component of polarization in the orthogonal direction will transmit.

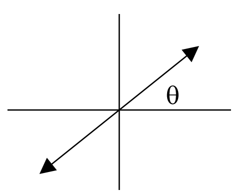
This had been difficult to do for visible light until Edwin Land invented the polaroid, which is is created by stretching hydrocarbon molecules on a sheet into long strands, then impregnating them with conducting iodine. In effect this acts like a set of thin wires. Light polarized in the direction of the molecules is absorbed by free flowing electrons. Light of opposite orientation is not absorbed and so is transmitted.

If a polarizer was perfect, then if one passed unpolarized light through the filter, only 50% of the light would be transmitted.

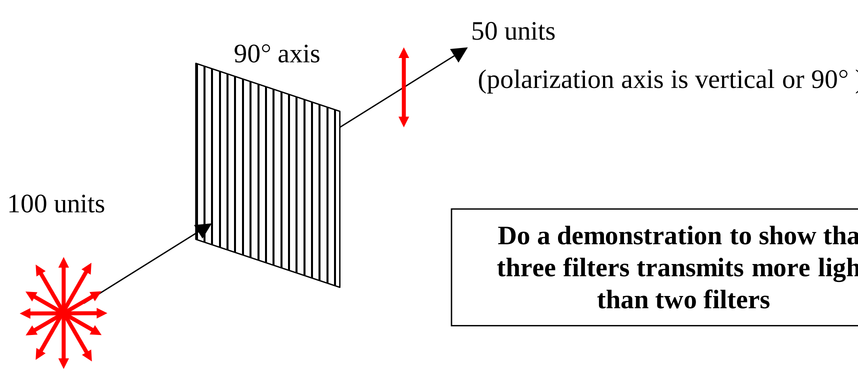
For linearly polarized light, the intensity of light that is transmitted is the projection of the polarization vector onto the transmitting axis of the polarizer. This is where Malus' law becomes very useful.

First, we will establish the convention of **units** of light, or intensity. You can think of them as photons.

Second we define a polarizer's transmission axis as the axis that is parallel to the polarization that is transmitted.



Rules for unpolarized light: 100 units of light passing through a linear polarizer, leaves 50 units of light, which will be polarized along the transmission axis of the polarizer.



Do a demonstration to show that three filters transmits more light than two filters

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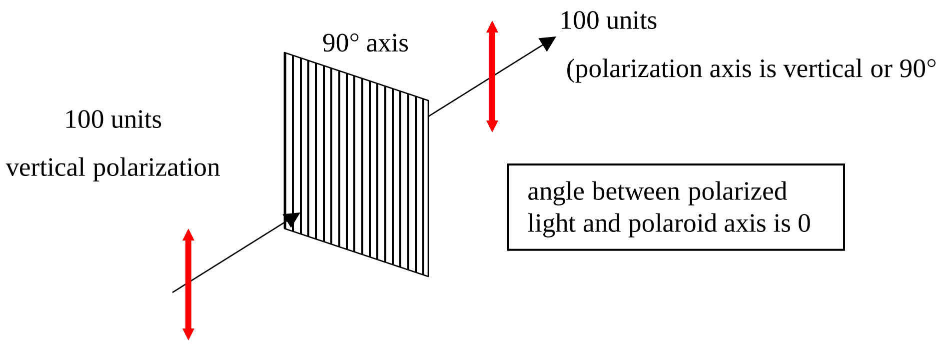
Rules for polarized light: The number of units of intensity that gets through is proportional to the square of the cosine of the angle between the orientation of the incident polarization and the transmission axis of the polarizer. In other words, the transmitted intensity is the component of intensity of the original polarization that lies along the transmission axis of the polarizer.



$$I = I_o \cos^2 \theta = I_o = 100 \text{ units}$$

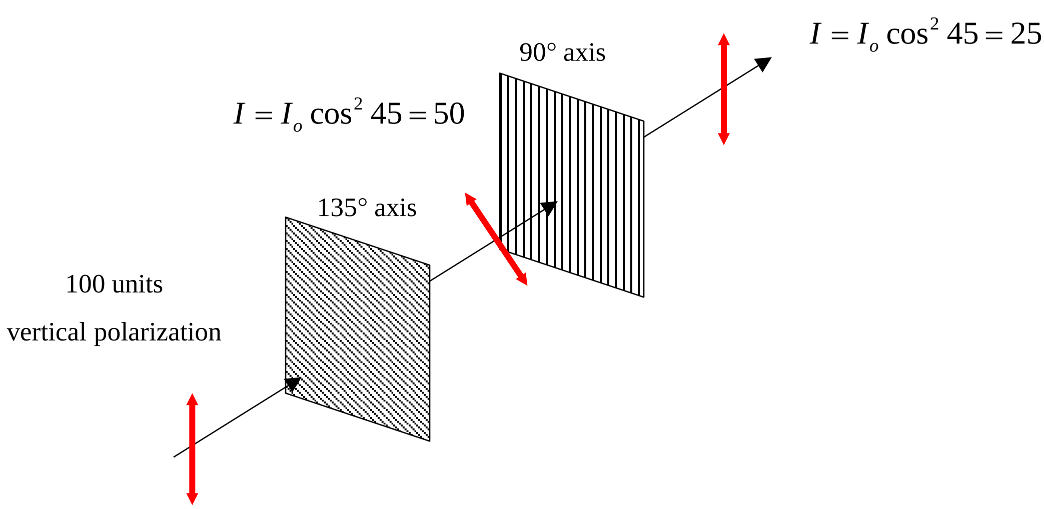
If you turn the polaroid 10 degrees (to 100 degrees), then the angle between the light polarization and the axis of the polaroid is 10, so:

$$I = I_o \cos^2 10 = 0.97 \times I_o = 97 \text{ units}$$

If you turn the polaroid another 80 degrees (to 180 degrees), then the angle between the light polarization and the axis of the polaroid is 90. At 0 and 180 degrees the polarization is the same – *horizontally polarized*.

$$I = I_o \cos^2 90 = 0 \text{ units}$$

The orientation of the emergent light is always the same as the transmission axis of the polarizing filter preceding it. So when polarizers are put in series, you can easily determine the polarization and the final emergent number of units provided that you go step by step through each polarizing filter.



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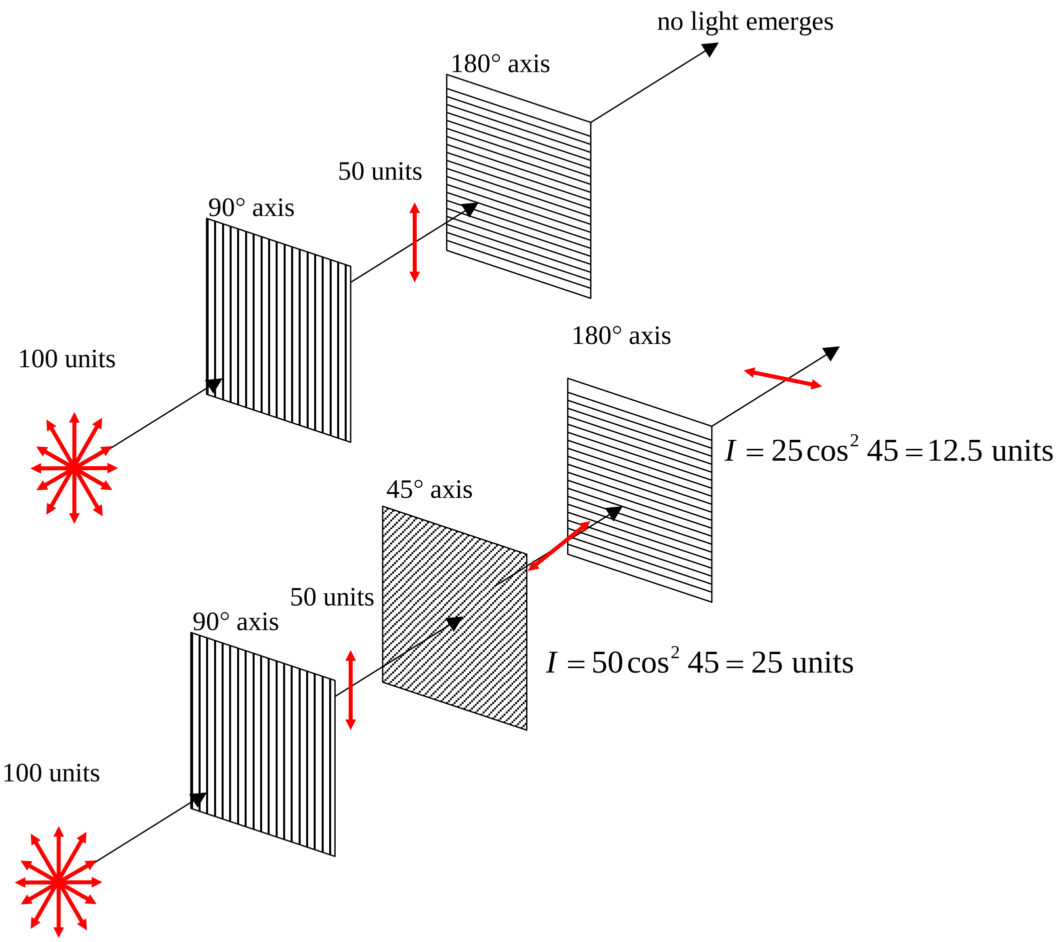
Example: Unpolarized light is incident on a polarizing filter whose orientation is vertical (90 degrees) It is followed by a filter whose orientation is 180 degrees. If 100 units of light intensity are incident on the pair of filters, how many units emerge?

If you add a third filter oriented at 45 degrees from horizontal, in between the two original filters, how much light emerges?



So adding another actually increases the amount of transmitted light!

Does the same improvement occur when you reorder the filters: Likely not!

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Polarization by Reflection:

When light reflects normally, or perpendicularly from a surface, the amount of reflectance is governed by the law:

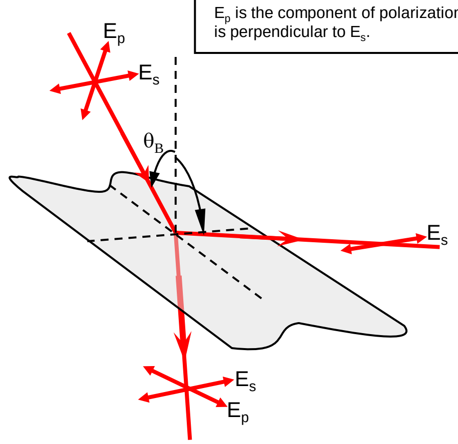
$$R = \left(\frac{n' - n}{n' + n} \right)^2$$

As the angle of incidence changes, the amount of reflected light depends on the polarization. If one orientation of polarization reflects more than the other, then the reflected light would be partially polarized.

The reflection for the two polarization components follows this graph:

E_s is the component of the polarization that is parallel to the reflecting surface.

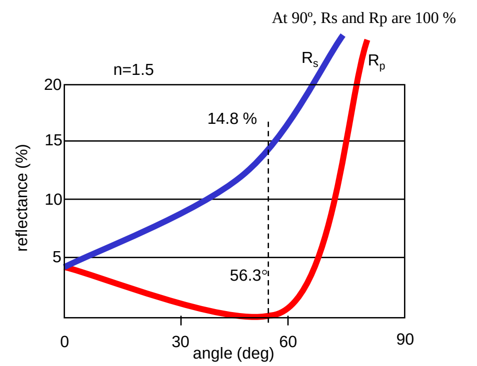
E_p is the component of polarization that is perpendicular to E_s.



In this figure, the angle of incidence is equal to **Brewster's angle**, θ_B; the angle for which only the *s-component* of the polarization is reflected. When the angle of incidence is not equal to Brewster's angle, there is still a tendency for one polarization to reflect more than the other (see graph on the right).

R_s is the reflectance of the Es component.

R_p is the reflectance of the Ep component.



This shows a typical plot for the reflectance of the *s*- and *p-components* of the polarization as a function of angle for a reflecting medium with an index of refraction of 1.5. At Brewster's angle (56.3º in this case), only the *s-component*, or the polarization component that is parallel to the reflecting surface, is reflected. The formula used to calculate Brewster's angle for any surface is:

$$\theta_B = \arctan\left(\frac{n'}{n} \right)$$

The angle at which light of only one polarization reflects is called **Brewster's Angle (θ_B)**. The actual angle depends on the index of refraction of the reflecting surface. The formula for Brewster's angle is:

$$\theta_B = \arctan\left(\frac{n'}{n} \right)$$

An oblique reflection can create polarized light. Unpolarized light that is diffusely reflected is generally not polarized. It comes in and gets reflected at all angles. But unpolarized light that is specularly reflected does have some polarization. Specular reflections follow the regular incidence-reflection rule. Specular reflections are mirror reflections and also appear as highlights when reflected off objects.

DEMO: A good demonstration is to look at a reflection from a table (a black book is also an excellent choice) Place a polarizer over your eye and rotate it and you'll see the reflections appear and disappear.

So what about polarized sunglasses? They minimize specular reflections from horizontal objects. 50-60 degrees is not an uncommon angle to see these specular reflections. (driving, boating, skiing etc.) So, if the transmission axis is vertical, one minimizes the amount of horizontally polarized light that reaches the eye. Blocking the horizontally polarized light increases contrast by reducing glare. If you are selling glasses with polarizers to your patients, it is very simple to demonstrate their advantage by looking at the reflection off a table.

With some LCD displays, the reflected light is linearly polarized. So, if you are looking at it through polarizing sunglasses, it will appear black. This also happens when you are looking at an LCD gas pump. Good LCD displays employ circular polarization to avoid this problem.

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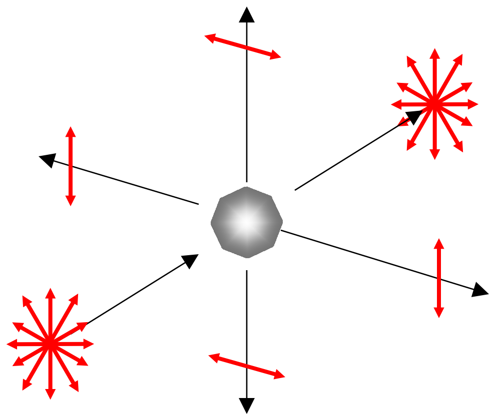
Polarization by Scattering:



Linearly polarized light is emitted at angle of 90º from the scattering particle.

DEMO: Use polarized laser pointer and pass it through a scattering liquid (milk powder in water) rotate it until the light scattered to the side disappears. Then use a linear polarizer to show that when the scattered light is at a maximum, it is also polarized.

Birefringence:

In a crystal, the structure is often **anisotropic** as opposed to glass or plastic, which is **isotropic**. That means that the atomic lattice that makes up the molecules looks different when viewed from different orientations. The electrons within the lattice will also vibrate differently depending on the direction and so light of one polarization will encounter a transparent material with a different refractive index than the other component of polarization. This dependency of index on the direction of polarization is called **Birefringence**. Birefringence gives rise to double refraction

Calcite crystal is a classic example.

Birefringence is often found in crystals but it is also found in ordered arrangements of molecules. In the latter case, it is called **form birefringence.**

The cornea is an example of a tissue that has **form birefringence**. Within the stroma, the lamellae are comprised of long colinear strands of collagen which are laid down in sheets. The strands are anisotropic so the component of light along the strands sees a slight different refractive index than the perpendicular component. If the layers of sheets were oriented randomly, then the form birefringence of one sheet would cancel the other. But the lamellae have a preferred orientation there is an overall birefringence. The actual index of refraction difference between the two polarization components is 0.001 so it is small. By comparison, calcite has a difference of about 0.2 so the double refraction is very strong.

Dichroism

If a crystal absorbs one of the polarization directions more than another, it is called **dichroic**. The polarizing filters in your glasses and the ones that you used for the demo are dichroic. The eye has dichroic crystals near the fovea (macular pigment granules) which gives rise to a selective absorption of some orientations of polarizations. It is subtle, and is likely just a byproduct of another system (i.e. there is no mechanistic reason for it) but when you rotate a polarizer in front of the eye you see a corresponding rotating pattern, called **Haidinger's Brushes**. They will sometimes appear colored because the preferential absorption also depends on the color of the light.

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