How can I tell what the polarization axis is for a linear polarizer?
The axis of a linear polarizer determines the plane of polarization that the polarizer passes. There are two ways of finding the axis of a polarizer. A simple method is to start with a known polarizer with a marked axis. Place both the known and unknown polarizer together and transmit light through them. Rotate the unknown polarizer until no light passes through the pair of polarizers. In this orientation, the unknown polarizer's axis is 90° from the axis of the known polarizer.

If a known polarizer with a marked axis cannot be found, the axis can be found by taking advantage of the Brewster effect. When light reflects at glancing incidence off of a non-metallic surface, the S-polarization is reflected more than the P-polarization. A quick way to do this is to look at the glare off of a tiled floor or another non-metallic surface. Rotate the polarizer until the glare is minimized. In this position, the polarizer is oriented so that the axis is vertical. As an example, sunglasses use polarizers that have the polarization axis vertically oriented.

When you list the average transmission of a polarizer, what is the difference between single, parallel, and crossed?
The value of transmission for a single polarizer refers to the percentage of the incident light that passes through one single polarizer. The value of transmission for parallel polarizers refers to the percentage of the incident light that passes through two polarizers, where the axis of polarization for each polarizer is aligned in the same direction. The value of transmission for crossed polarizers refers to the percentage of the incident light that passes through two polarizers, where the axis of polarization for each polarizer is separated by a 90 degree angle. The average value stated refers to the actual average of all transmission values from 400 to 700nm.

What are the meanings for the different terms used for polarizers?
Extinction is described generally as a polarizing filter's ability to absorb polarized light that has an orientation 90° to the polarizer's axis of polarization.

The *Extinction Ratio* is the ratio of power for plane-polarized light going through a polarizer with its axis oriented parallel to the plane of polarization over the power of plane-polarized light going through that same polarizer with its axis oriented perpendicular to the plane of polarization (for example, 700:1). A more technical definition of Extinction Ratio, follows from the *Handbook of Optics* (Vol. I, 5-13):

Extinction Ratio = $\rho = T_2 / T_1 \approx ½ (T^{\perp} / T||)$

where:

T_1 = maximum transmittance parallel to plane of polarized beam

T_2 = minimum transmittance perpendicular to plane of polarized beam

T|| = maximum transmittance of two polarizers parallel in unpolarized beam

$T^{\perp}$ = minimum transmittance of two polarizers perpendicular in unpolarized beam

Note: all "T" values are for monochromatic light.

Example : If using an unpolarized light source, a direct reading of the extinction ratio is not possible but can be estimated. If the unpolarized source has a wavelength of 550nm and the parallel transmission is 27.17% and the crossed transmission is 0.02%, then the extinction ratio at 550nm is approximately 3.7×10^{-4}.

Polarization Efficiency is the percentage of how efficiently one polarizer polarizes incident light over the total amount of polarized light. For example, a linear polarizer with 99% efficiency transmits 99% of the incident light in the intended polarization (p-polarization state) and 1% in the opposite polarization (s-polarization state). Again a more technical definition exists, as based from the *Handbook of Optics* (Vol. I, 5-13):

Polarization Efficiency = P.E. (%) = $[(H_0-H_{90}) / (H_0+H_{90})]^{1/2} \times 100$

where:

H_0 = average transmittance (unpolarized incident light) of parallel polarizers, over 400-700nm

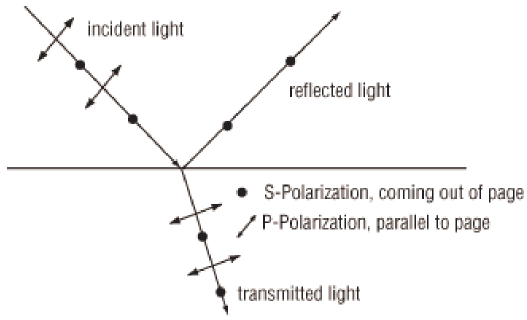
H_{90} = average transmittance (unpolarized incident light) of crossed polarizers, over 400-700nm

Note: "H" values are averages from 400 to 700nm (not the same as "T" values)

Example : If the source is again unpolarized and the average parallel transmission across the visible is 26.53% and the average crossed transmission across the visible is 0.01%, then the polarization efficiency is 99.96%

What is the difference between s- and p-polarization states?
S&P polarization refers to the plane in which the electric field of a light wave is oscillating. S-Polarization is the plane of polarization perpendicular to the page (coming out of the monitor screen). P-polarization is the plane of

polarization parallel to the page (in the plane of the monitor screen). See figure below:



When referring to polarization states, the p-polarization refers to the polarization plane parallel to the polarization axis of the polarizer being used ("p" is for "parallel"). The s-polarization refers to the polarization plane perpendicular to the polarization axis of the polarizer. A linear polarizer, by design, polarizes light in the p-polarization.

Does the circular polarizer material have to face a particular direction?
The linear polarizing side of the circular polarizer must face the observer. In this alignment, randomly polarized ambient light will be linearly polarized before it passes through the retarder side of the film and becomes circularly polarized. A quick test for orientation is to place a mirror behind the circular polarizer with a light source on the opposite viewing side. Upon reflection, the circularly polarized light is blocked from reaching the observer (in the form of glare). When the orientation is correct, the light reflecting from the mirror should not be visible. Randomly polarized light from the non-viewing side of the polarizer is allowed to pass through the material.

What is the fast and slow axis of a retarder and how do they differ?
In a birefringent material, such as a retarder, the fast axis is the axis through which the light travels faster. For a retarder, the fast axis is typically labeled and marks the axis on the retarder that is used as a reference for whichever desired effect is needed. For a ½ wave (½λ) retarder, the orientation of the fast axis is what determines the orientation of the linearly polarized light emitting from the retarder. For instance, if you rotate a ½ wave retarder 45° with respect to the linear polarized light entering the retarder, then the light emitted by the retarder will be rotated 90° from the incident polarized light. The slow axis in a retarder is the axis through which the light travels slower.

How can I find the fast and slow axes of a retarder?
There is also a simple way to find the axes of a retardation plate. This requires two linear polarizers. Orient one linear polarizer so the axis is horizontal. Put the other linear polarizer in front of the first, oriented so that

the axis is vertical. Place the retardation plate between the two crossed polarizers. Rotate only the retardation plate until maximum transmission is reached. The fast and slow axes will be at ±45° from horizontal.

To determine which axis is fast and which is slow, hold the retarder along one of the axes. For example, hold the plate by the left side and the right side. Rotate the retardation plate about this axis, so that the light is passing though a slightly thicker cross section of the retardation plate. Then repeat, using the other axis. If the color of the light changes from a bluish color to gray and then to black, then you are rotating about the fast axis. If the color changes from white to yellow and then to interference colors, then it is the slow axis.

What does the wavelength designation mean for quartz retarders and how does this relate to the film specifications?
To achieve the phase shift designated for any given retarder, the optical thickness of the material is selected to give the desired shift at a specific wavelength. Retarders are very wavelength dependent. Wavelengths close to the design or slight thickness differences will result in a slightly inaccurate phase shift of the transmitted beam. Since white light is composed of a range of wavelengths, no single material thickness can correspond to the proper shift across the entire region and, as a result the design must be generalized for the region of interest. The film material achieves the desired retardation for the visible due to its design at the center of the visible spectrum (560nm). Our quartz and film retarders are available in phase shifts of $\lambda/2$ and $\lambda/4$ in several wavelength options

What is the difference between multiple and zero-order retarders and when should I pick one over the other?
Multiple-order retarders (or waveplates) and zero-order retarders are interchangeable. Zero-order waveplates should be considered for more critical applications. The advantages of a zero-order waveplate include an increased bandwidth and a lower sensitivity to temperature changes. A ±2% change from the design wavelength will cause only a minor change in the retardation of a zero-order waveplate. With a multiple-order waveplate, a ±1% change from the designed wavelength will cause considerable problems with the retardation.

How can I determine if a retarder is ¼ or ½ wave?
An easy way to determine if a retarder is a ¼ wave of a ½ wave is to use the set-up outlined below. First, transmit linearly polarized light through the retarder. This light can either come from a light source that is already linearly polarized or be randomly polarized light that is sent through a linear polarizer. After the light is passed through the retarder, it can have one of two characteristics: if the retarder is ¼ wave, then the light is circularly polarized; if the retarder is ½ wave, then the light is linearly polarized, but at a different angle than the incident light.

Finally, you can use a second linear polarizer (typically called an "analyzer") to determine which retarder you possess. Place the analyzer in the path of the light coming from the retarder and rotate it. If, at certain angles of rotation, the light being emitted from the analyzer gets more intense and then is completely blocked out, you have a ½ wave retarder. If the light emitted is of similar intensity no matter how the analyzer is rotated, then you have a ¼ wave retarder. Please note that there are other types of retarders than ¼ wave and ½ wave, and this test does not take that into consideration.

Can I adapt a retarder for use with a specific wavelength other than the design wavelength?

A retarder can be used at a different wavelength than the design wavelength and still maintain its phase, if it is tilted about its fast or slow axis. If tilted about the fast axis, the design wavelength can only be changed to a shorter wavelength. If tilted about the slow axis, the design wavelength can only be changed to a longer wavelength. To determine the amount of tilt required, use the following equation:

$$\theta = \sin^{-1} (\lambda_{new} / \lambda_{design}) \text{ , where}$$

θ = the angle on the output side of the retarder from the optical axis to the back surface of the retarder

<u>Example:</u> If a ¼λ retarder is tilted about the fast axis and it is designed at 1064nm, then it can still be used as a ¼λ retarder for a 670nm source if it is tilted by 39 degrees.

If on the other hand the retarder is not tilted and a wavelength other than the design wavelength is used, there will be a phase shift. A ¼λ retarder has a phase shift of 90° . A ½λ retarder has a phase shift of 180° . To determine the amount of the phase shift, use the following equation:

$$\delta = 360^\circ (\Delta n\tau / \lambda) \text{ , where}$$

δ = the retardation angle

Δn = the birefringence factor

τ = the thickness of the sheet

λ = the wavelength of light

<u>Example</u> : For a ¼λ retarder, since the phase shift (δ) is 90° , $\Delta n\tau = \lambda/4$ = 140nm (for λ =560nm). So if a source at 850nm is used for a 1/4λ retarder with a design wavelength of 560nm, then δ = 360° multiplied by (140nm/850nm)= 59.29° . Solving now for $\Delta n\tau$ is ($\delta \lambda$ / 360°)= λ (59.29° / 360°) = 0.165$\lambda \approx \lambda/6$, the phase shift.