EENS 2110	Mineralogy
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Interference Phenomena, Compensation, and Optic Sign	

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As you have probably noticed by now, viewing an anisotropic crystal under crossed polars (analyzer inserted) the crystal is extinct when either of the two privileged directions in the crystal are lined up parallel to the polarizing direction of the microscope. This is because when the privileged directions are parallel to the polarizer, the crystal does not change the polarization direction and the light will thus be vibrating perpendicular to the analyzer. When the privileged directions are not parallel to the polarizer some light is transmitted by the analyzer and this light shows a color, called the interference color. In this lecture we will discover what causes this interference color and how it can be used to determine some of the optical properties of the crystal.

The Interference of Light

Waves Polarized in the Same Plane

As we discussed in the lecture on X-rays, when electromagnetic waves emerge from a substance, they can interfere with each other and either become enhanced, partially destroyed, or completely destroyed. The same is true for polarized light. In the upper diagram below, labeled A, two waves polarized in the vertical plane are emerging from the polarizer. These waves are in phase, and thus we only see one wave. The difference between points on the same wave is called the path difference, symbolized as Δ. If the path difference is an integral number of wavelengths, $n\lambda$, the waves are in phase. For points that are completely out of phase, for example between crests and troughs of the wave, Δ will be equal to $1/2\lambda$, $3/2\lambda$, $5/2\lambda$, etc. or $[(2n+1)/2]\lambda$. For path differences where the waves are completely out of phase, complete destructive interference will occur and no wave will emerge from the polarizer.

For path differences that are neither in phase or completely out of phase, the waves will be summed together to produce a resultant wave with crests and troughs at different positions than the original waves.


After Bloss (1961)
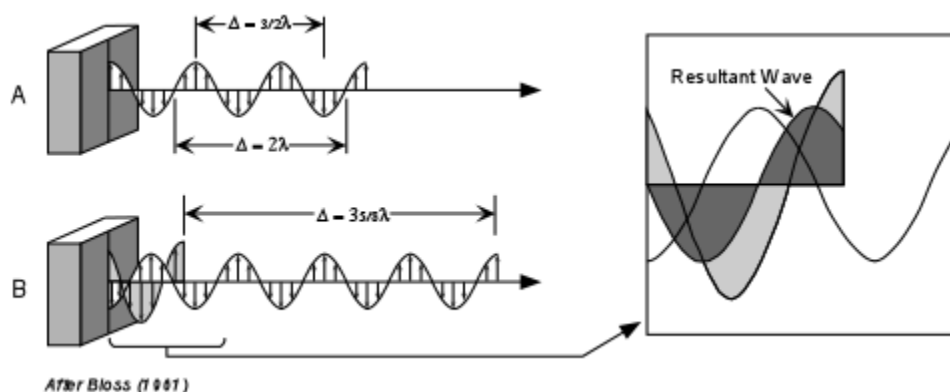
This is shown in the part of the diagram labeled B, and the blow-up to the right.

Furthermore, the vector sum of the two waves will produce a resultant wave with a different amplitude than the two original waves.

Waves Polarized in Perpendicular Planes

If the waves are traveling on the same path, but are polarized at 90° to each other, again the resultant wave becomes the vector sum of the two waves. To see this we need to look at a three dimensional view.

In this case, the waves have emerged from a crystal polarized in the directions of the privileged directions in the crystal, but they are otherwise in phase. The resultant wave, shown here in dark gray, is the vector sum of the two waves, and is thus polarized at a 45° angle to the original waves.
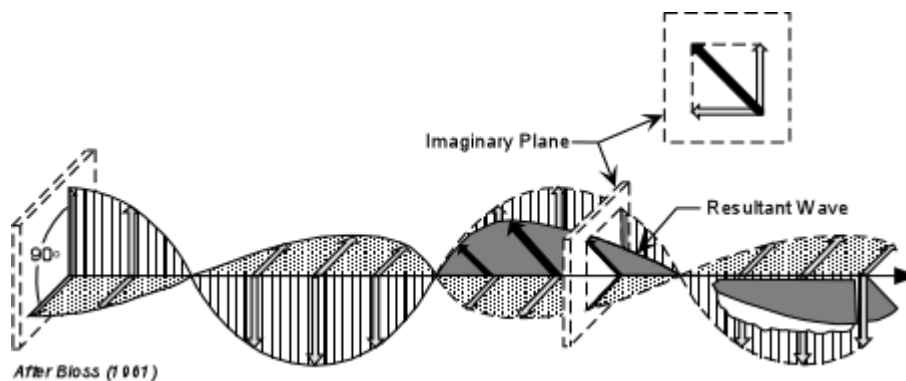

Path Difference or Retardation Resulting from Passage Through a Crystal

- When polarized light enters an anisotropic crystal from below, and neither of the privileged directions in the crystal are parallel to the polarizer, the light is broken up into two mutually perpendicular polarized waves that travel through the crystal.

- One of these waves will be vibrating in the direction of high refractive index, N, and the other will be vibrating in the direction of the low refractive index, n.

- Because refractive index is inversely proportional to the velocity of the wave, the wave vibrating in the direction of the larger refractive index will travel more slowly in the crystal than the wave vibrating in the direction of the lower refractive index.

- Thus, we refer to the wave vibrating in the higher refractive index direction, N, as the *slow wave*, and the wave vibrating in the lower refractive index direction, n, as the *fast wave.*

- Since the wave velocity, V, is given by: $V = \lambda\nu$, if the velocity of the wave becomes lower, the wavelength, λ, will also decrease, since the frequency, ν, remains constant.

- Thus, since the slow wave has a lower velocity, it will have a shorter wavelength while passing through the crystal.

- Further, when the two waves emerge from the top of the crystal, they may not be in the same position in their vibration as when they entered the crystal (i.e. they may be out of phase, depending on the path difference acquired while in the crystal).

To see this, examine the figure shown below. Polarized light vibrating E-W enters the crystal from below. Upon entering the crystal this light is broken into a slow ray, vibrating parallel to the larger refractive index direction, N, and a fast ray, vibrating parallel to the lower refractive index direction, n. While in the crystal, the slow wave's wavelength decreases and it passes through 1½ wavelengths, while the fast wave passes through 1 wavelength. At the instant the slow wave emerges from the crystal, the fast wave has traveled a distance Δ. This is the path difference or retardation.
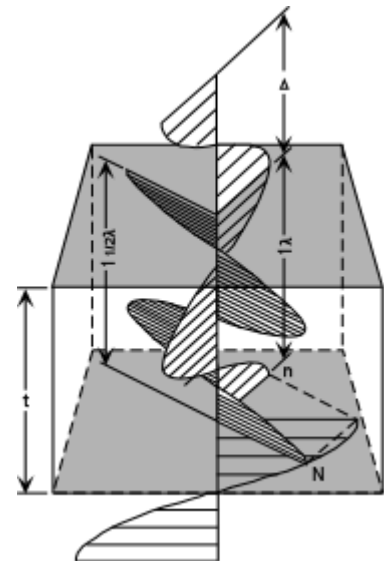
- If the time required for the slow ray to pass through the crystal is T_N and the time required for the fast ray to pass through the crystal is T_n, then the distance traveled by the fast wave as it waits for the slow wave to emerge from the crystal is $C(T_N - T_n)$, where C is the velocity of light in air. This is the path difference between the two waves.

- Thus, $\Delta = CT_N - CT_n$

- The actual velocities of the two waves while in the crystal are:

 $C_N = t/T_N$ and $C_n = t/T_n$, where t is the thickness of the crystal.

- Then $T_N = t/C_N$ and $T_n = t/C_n$

- Substituting this into our equation for Δ, gives the result:

   $\Delta = t(C/C_N - C/C_n)$

- But, C/C_N is the refractive index, N, of the slow wave, and C/C_n is the refractive index of the fast wave, n.

- So, $D = t(N - n)$

- Note that (N - n) is the birefringence, so the equation above tells us that the *retardation is equal to the thickness of the crystal times the birefringence.* (Note that this is not necessarily the absolute birefringence of the crystal [|ε -ω|] but only the difference between the high and low refractive index for this orientation of the crystal).

Polarization of the Resultant Wave

As discussed above, when the waves emerge from the crystal they will be polarized at 90° to each other. But, they will then interfere with each other and the resultant wave will be polarized in a plane that is the vector sum of the two waves. Thus, the resultant wave will have a vibration direction that may or may not be the same as when it entered. First we will look at two extreme cases, both of which are illustrated in the diagram below.


After Bloss (1961)
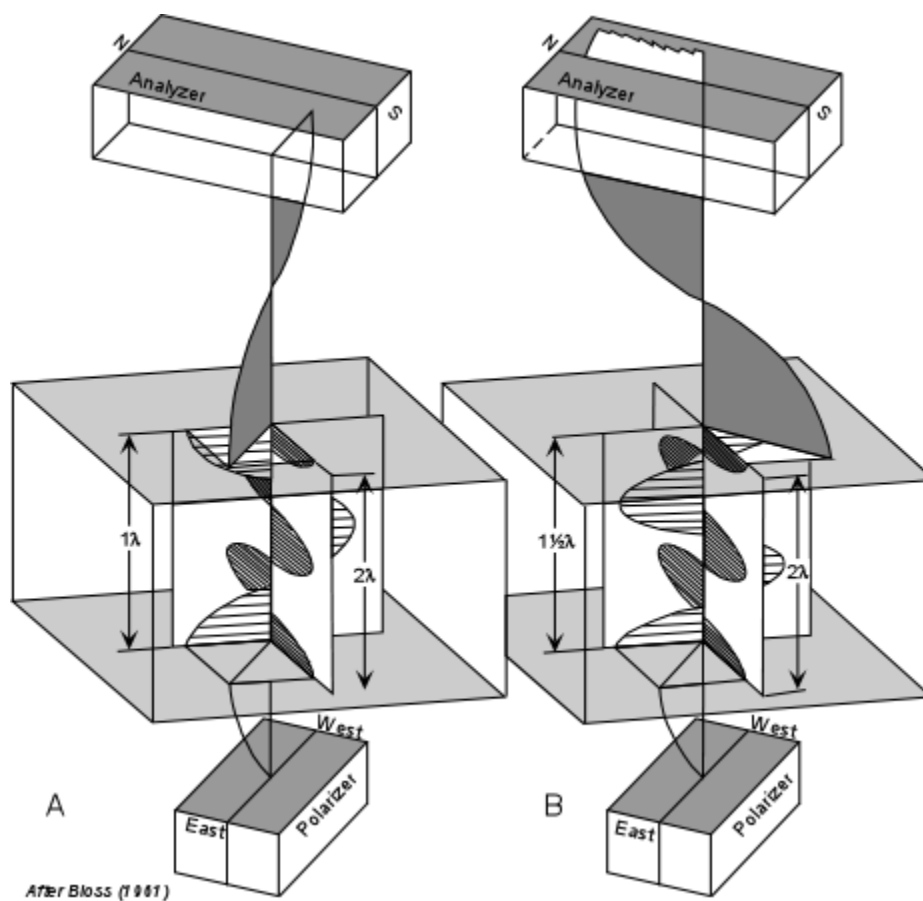
A. **Waves are in phase on exit at the top of the crystal.** (Diagram A, above) In this case, the crystal is viewed at some angle off extinction. Monochromatic light polarized in the E-W direction enters the crystal from below and is broken into two waves, each vibrating parallel to the crystals privileged directions. While in the crystal, the slow wave passes through two wavelength and the fast wave passes through 1 wavelength. Thus, upon emergence from the crystal the waves are in phase and the path difference between the waves is 1λ. After emergence from the crystal the two waves are recombined to produce a resultant wave that vibrates in the same direction as the polarized light entering from below. This light will be extinguished by the analyzer, since it is vibrating at 90° to the polarization direction of the analyzer. Such will be the case if Δ is an integer number of wavelengths.

B. **Waves are exactly out of phase upon emergence from the crystal.** (Diagram B, above) Again, the crystal is viewed at some angle off extinction, with E-W polarized monochromatic light entering from below. This time, however, the slow ray again travels through 2 wavelengths in the crystal and the fast wave travels through 1½ wavelengths in the crystal. Thus, upon emergence from the crystal, the path difference between the two waves will be ½λ. With this path difference, the resultant wave that results from recombination of the two waves will be vibrating at an angle of 90° to the direction of the entering polarized light. Since this resultant wave is now vibrating parallel to the polarizing direction of the analyzer, it will pass through the analyzer. This will be the case anytime the path difference, Δ, is $[(2n + 1)/2]λ$.

Another way of looking at this is by examining the diagrams below.

Again, looking at Case A, with the privileged directions lined up 45° off extinction, on entering the crystal the light is broken into two polarized rays vibrating parallel to each of the privileged directions. Imagine that the vectors shown are pointing at the crests of these waves.
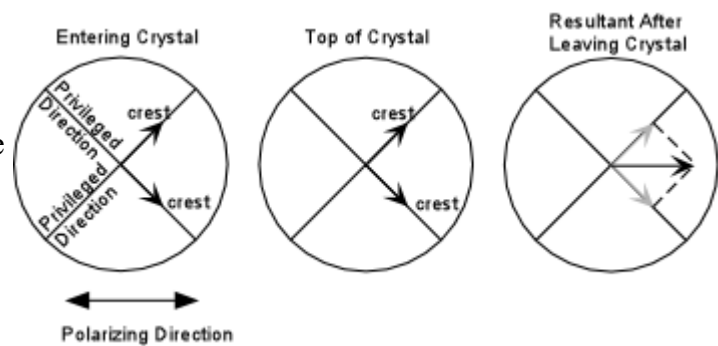

At the top of the crystal, the waves are still in phase (i.e. their path difference is nλ), and thus their wave crests are at the same positions as when they entered the crystal. These waves are then resolved into a single polarized waved that is vibrating parallel to the polarizer. Such a wave will be extinguished by the analyzer.

Looking at case B, again polarized light entering from below is broken into two waves in the crystal both of which vibrate parallel to the privileged directions in the crystal. But this time, one wave lags behind the other by ½ λ, so that at the top of the crystal it is at a trough on the wave path.
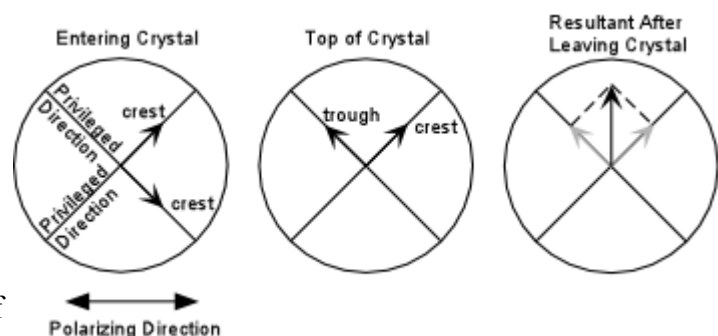
This time, the resultant wave produced by recombination of the two polarized waves after leaving the crystal will have a resultant wave vibrating perpendicular to the polarizer (parallel to the analyzer), and thus this light will pass the analyzer. The color will be that of the monochromatic light that entered the crystal from below. Again, this will occur if the path difference is equal to an odd multiple of ½λ.

For path differences of anything other than nλ or odd multiples of ½λ, some of the light emerging from the crystal will have a component parallel to the polarizing direction of the analyzer, and will thus be transmitted. For monochromatic light, the color transmitted will be the same as the color of the monochromatic light used to illuminate the crystal. (Note, in reality path differences of 1/4λ, 3/4λ, 5/4λ, etc. produce circularly polarized light, and all other fractions of full λ produce elliptically polarized light. To make things simpler, we have ignored these complications, and will assume all light leaving the crystal becomes plane polarized.
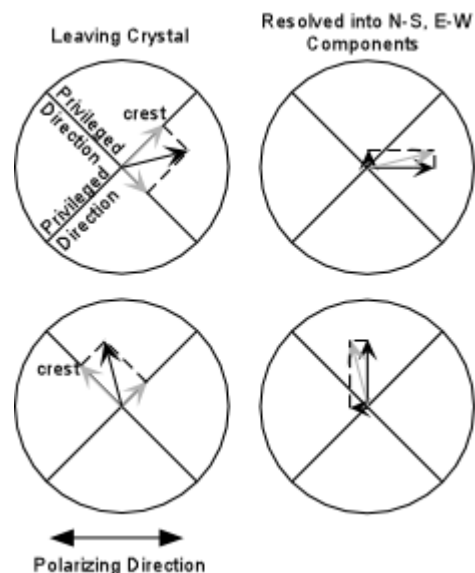
Transmission by the Analyzer (Monochromatic Light)

First we will consider only the case of a single wavelength of light (monochromatic light) as being incident on the crystal from below. In this case, the % of light transmitted by the analyzer, L depends on:

- Φ, the angle between privileged directions of the polarizer and analyzer (in most cases 90°),

- τ, the angle between the polarizer's privileged direction and the crystal's closest privileged direction,

- $\Delta = t(N - n)$, the retardation or path difference produced during passage through the crystal, and

- λ, the wavelength of light, as follows:

$$L = 100\{\cos^2 \Phi - \sin 2(\tau - \Phi) \sin 2\tau \sin^2 [(\Delta/\lambda)180^o]\}$$

For the case where the analyzer is polarized 90° to the polarizer ($\Phi = 90^o$), and the crystal is viewed 45° off extinction ($\tau = 45^o$), this reduces to:

$$L = 100 \sin^2 [(\Delta/\lambda)180^o]$$

Below, we plot this function. Note that for crystals that produce a path difference of $n\lambda$, 0% of the light is transmitted by the analyzer, for those that produce a path difference of odd multiples of $\frac{1}{2}\lambda$, 100% of the light is transmitted. Intermediate values of path difference produce intermediate results.
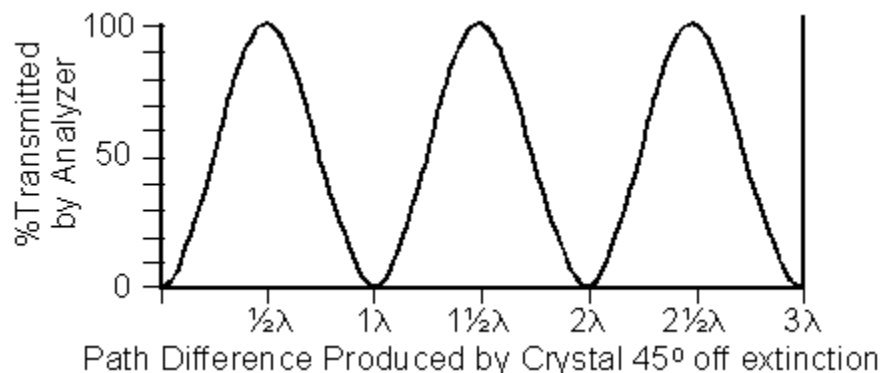
Because path difference, Δ, depends on the thickness of the crystal, a crystal that varies in thickness will show the following effects.

Imagine that the crystal is illuminated with light having a wavelength corresponding to yellow. Path differences that vary between 0 and slightly more than $1\frac{1}{2}\lambda$ will be produced by the crystal due to its variable thickness. The top figure shows contours of where light retarded by $\frac{1}{2}\lambda$, 1λ, and $1\frac{1}{2}\lambda$ will emerge from the crystal. The lower left figure shows that light will be polarized in the N-S direction along the zones of $\frac{1}{2}\lambda$ and $1\frac{1}{2}\lambda$ retardation, and thus light emerging from these zones will pass through the analyzer, as well as light retarded by intermediate multiples of λ. Along the zone where light is retarded by 1λ it will be vibrating perpendicular to the analyzer and thus will show as a dark band. A dark band will also occur along the edges of the crystal where $\Delta = 0$.
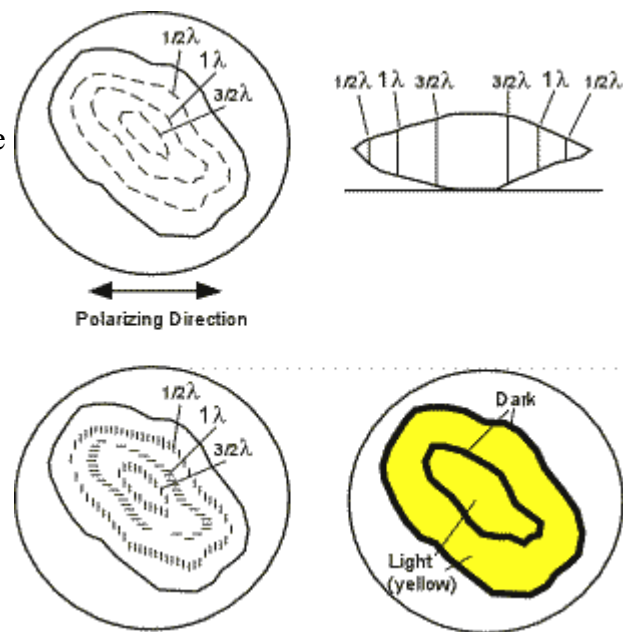
**Interference Colors Produced by Polychromatic Light**

Next, we consider the case that we will encounter in our studies, that is illumination with white light (polychromatic light). If a crystal illuminated by white light is viewed with the crossed polarizers off the extinction position, colors, known as interference colors will be seen. These

colors result from unequal transmission by the analyzer of the various components of white light. What wavelengths are seen depends on the retardation or path difference produced in the crystal for each of the wavelengths. Let's look at a couple of examples.

Imagine a crystal that has a thickness and birefringence that produces a retardation of 550 nm, viewed 45° off extinction. If we look at the graph above, or solve the equation above, we can determine the % transmission by the analyzer of some of the components of white light to construct a curve of %Transmitted by the Analyzer versus Wavelength of Light.

Wavelength (nm)	Retardation	%Transmitted by Analyzer
400	550/400 = 13/8λ	85
440	550/440 = 11/4λ	50
488.9	550/488.9 = 11/8λ	15
550	550/550 = 1λ	0
628.6	550/628.6 = 7/8λ	15
733.3	550/733.3 = 3/4λ	50

This is plotted in the solid curve in the graph shown here. Note that violet and some blue, as well as some red wavelengths are transmitted, while less of the green yellow and orange wavelengths will not be transmitted by the analyzer. Thus the crystal will show an interference color that is reddish violet. We call this color first order, or 1° red.
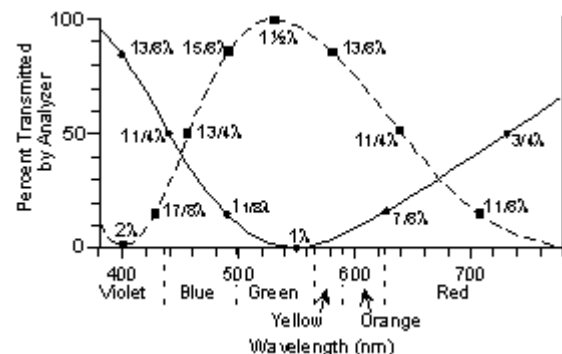

If the crystal produces a retardation of 800 nm, the dashed curve would be obtained. This curve shows little transmission of the violet and red wavelengths, and partial to full transmission of the green, yellow, and orange wavelengths. Thus the crystal will have a greenish interference color.

The Interference Color Chart

If this is done for all possible retardations and all wavelengths of light, it produces what is called an interference color chart, shown below. This chart has thickness of the crystal plotted on the y-axis and path difference or retardation, Δ, plotted on the x-axis. The interference colors are divided into orders, every 550 nm of path difference, only 3 orders are shown. Note that first order colors (1°) range from black to reddish violet, Blue only appears in the 2nd and

3rd order colors, higher orders have mainly pink and green shades.
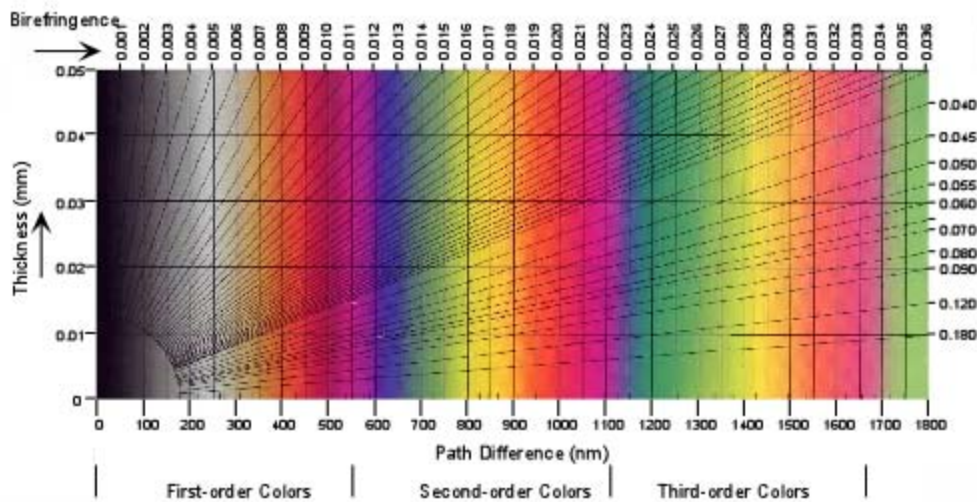
Also plotted on the chart are diagonal lines representing various values of birefringence (N - n) in this case. Thus, if the thickness of the crystal is known, the birefringence for the privileged directions can be determined from the interference color. This becomes important when we look at thin sections of minerals, which are cut to a thickness of 0.03mm. Thus for example a mineral in thin section that shows 1° red interference colors has a birefringence of about 0.018. (Again, note this may not be the absolute birefringence [|ε - ω|], but only the birefringence for the fast and slow vibration directions exposed by the orientation of the crystal [N - n]).

The interference colors at orders greater than order 6, become a blend of colors that is referred to as high order white. This high order white is different from 1° white for the following reason.

A crystal with an interference color of 1° white produces a retardation of about 200 nm. This results in a transmission curve shown by the dashed line in the figure below. Note that this low order white results from all wavelengths being transmitted, but less of the orange and red colors and more of the violet, blue, and green colors, and thus appears more bluish to the eye

For crystals that produce a very high retardation, like 4000 nm, the transmission curve is the solid curve in the diagram. Again, all wavelengths are represented, but there are small gaps of wavelength where wavelengths are not transmitted. This high order white appears more creamy to the eye, and sometimes has kind of a light brownish white hue.
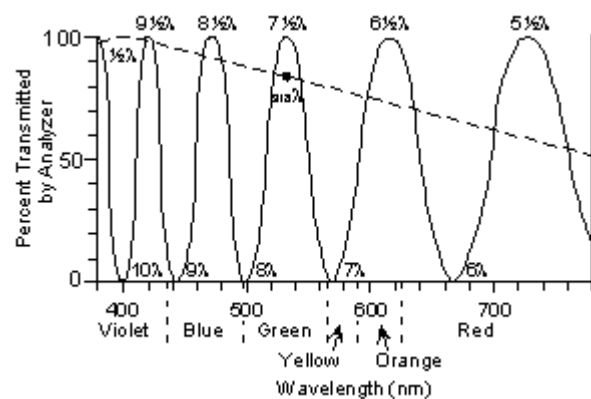

With practice high order white is easily distinguished from low order white interference colors, as you will see in lab.

Accessory Plates and Compensation

Accessory plates or compensators are crystals mounted in a frame that be inserted in the light path to produce further retardation of light after it has passed through the crystal. While several different accessory plates are commonly described, in this course we will use only one type. Still, you may encounter the other types in the future, so it is worthwhile to describe all of them here.

- Quartz Wedge

  This is a crystal of quartz cut into a wedge shaped. Since its thickness varies along the wedge, it can produce a range of retardations that correspond to interference colors from 0 (1° black) up to 3800nm (5° green).
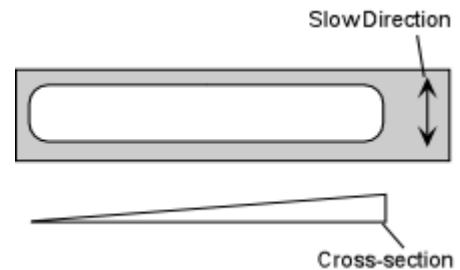
  The wedge, like all compensators usually has its slow direction clearly marked, and is inserted into the microscope tube such that slow direction in the compensator is at a 45° angle to the polarizing direction. You will see a quartz wedge in the lab, but the microscopes we use do not have a slot that accommodates these older wedges. In today's economy, quartz wedges are too expensive to equip student microscopes with them.

- Quarter Wave Plate.

  This plate is found on your microscopes in lab, but we do not use it extensively. As the name implies it produces a retardation of ¼λ. It is also called a mica plate, 150 nm plate, and 1° gray plate, because it is usually made of muscovite (glimmer in German) and produces a retardation of 150 nm, or 1° gray.

- Full Wave Plate

  This is the compensator you will encounter most frequently. The lab microscopes are equipped with one, and we will use it extensively. The full wave plate is also called a gypsum plate, 1λ plate, 550 nm plate, or 1° red plate (1° rot, in German) because it is usually made of gypsum and produces a 550 nm or 1° red retardation.

Use of 550 nm Plate (Compensator)

The 550 nm or 1° red compensator can be used to determine the fast and slow direction in a crystal. To do this, the crystal must be aligned on the microscope stage with one of its privileged directions oriented at 45° to the polarizing direction of the microscope. We here consider both cases.

- **Slow Direction (High R.I. direction) in crystal parallel to the slow direction in the compensator.** Imagine that the crystal produces 100 nm of retardation. This would correspond to 1° gray interference color with the analyzer inserted. Inserting the compensator with its slow direction, N, parallel to the slow direction in the crystal will produce an additional 550 nm of retardation for the wave that had vibrated in the slow direction, N_c, in the crystal (diagram on left). $550 + 100 = 650$nm. 650 nm corresponds to 2° blue which is what we will see looking down the microscope tube. In this case we say that *addition* has occurred.

After Bloss (1961)

N_c = Slow Ray in Crystal
n_c = Fast Ray in Crystal
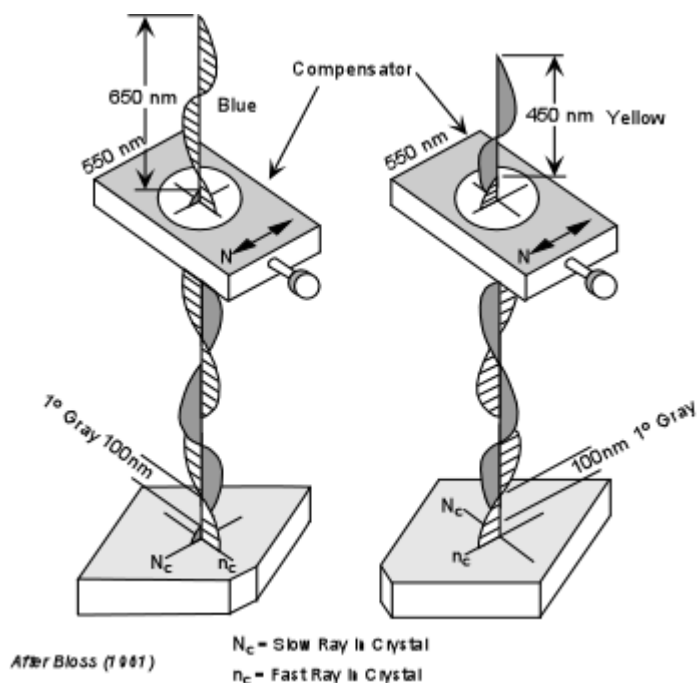
More importantly, if an area on the crystal that was 1° gray turns blue on insertion of the compensator, we know the direction in the crystal parallel to the slow direction in the compensator is the slow direction or higher R.I. direction.

- **Fast Direction (Low R.I. direction) in crystal parallel to the slow direction in the compensator.** In this case the 100 nm retardation produced by the crystal again appears as a 1° gray interference color with the analyzer inserted. But this time (right hand diagram above), the wave that had vibrated in the fast direction in the crystal, n_c, is slowed by the compensator, and the wave that had vibrated in the slow direction in the

crystal, N_c, becomes the fast wave in the compensator. Thus the previously fast wave will be slowed down and previous slow wave will have overtaken it by 450 nm. In this case, we say that subtraction has occurred, since 550 - 100 = 450 nm. 450 nm corresponds to 1° yellow, which is what we see for all areas of the crystal that had a color of 1° gray prior to insertion of the compensator.

If subtraction occurs, we know that the fast direction in the crystal is aligned parallel to the slow direction in the compensator.

These principles are illustrated further in the diagrams shown below. In the upper diagram the crystal has its slow direction oriented in a NE - SW position.

With the analyzer inserted one can usually find an area near the edge of the crystal that shows a 1° gray interference color. When the 550 nm compensator is inserted this gray area turns blue, addition has occurred, and we know that the slow direction in the crystal is parallel to the slow direction in the compensator.
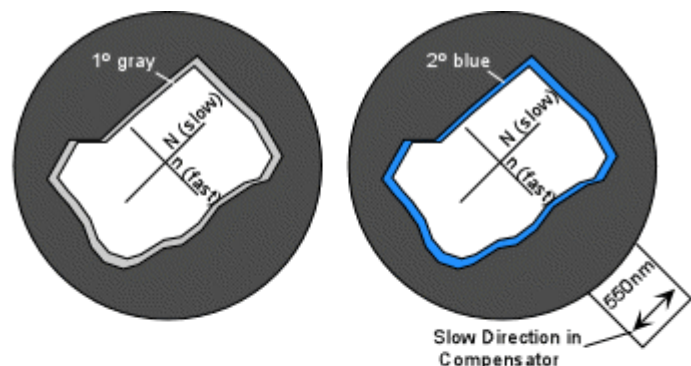
In the lower diagram the crystal has been rotated so that its fast direction is now oriented in a NE - SW position. Again, an area near the thin edge of the crystal can be found that exhibits a 1° gray interference color. Insertion of the 550 nm compensator causes this area to become 1° yellow. This means subtraction has occurred and we now know that the fast direction in the crystal is parallel to the slow direction in the compensator.
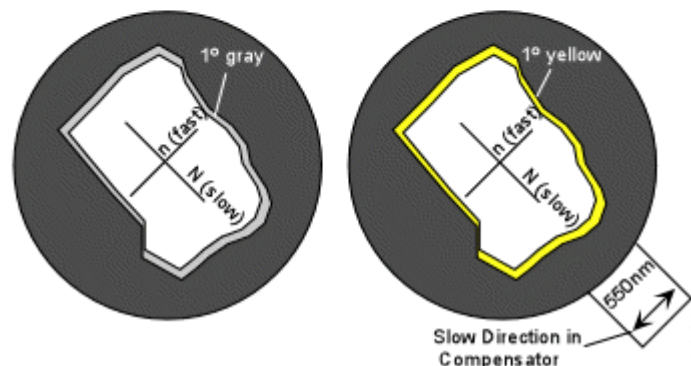
Determination of Optic Sign in Uniaxial Crystals

In a practical sense this can be used to determine the optic sign in uniaxial minerals. To do this one would first have to determine which directions in a crystal correspond to the ε and ω directions.

- The ω direction can easily be identified by finding a grain that does not change relief on rotation of the stage with the analyzer not inserted.

- Then determine if the ω direction is the high relief direction or the low relief direction
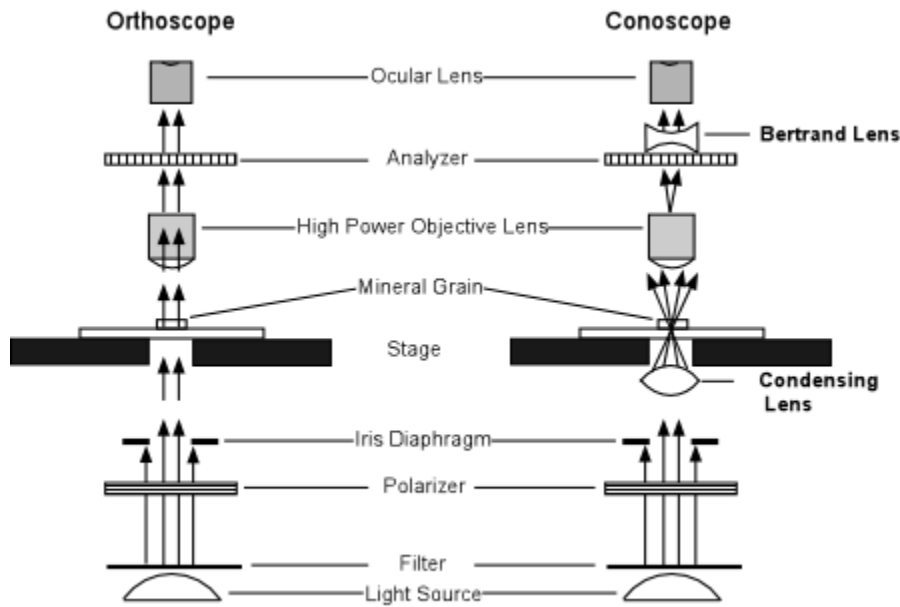
with respect to the immersion oil.

- Next find a grain that exhibits a large change in relief with respect to the oil. In this grain you will know which direction is ω, because you will have determined if it is the high relief direction or the low relief direction.

- Position the grain so that the ω direction is parallel to the polarizer (it should be extinct in this position with the analyzer inserted). In this orientation the ε direction or ε' direction will be perpendicular to the polarizer (N - S).

- Rotate the grain 45° so that the ω direction is oriented NE - SW, parallel to the slow direction in the compensator.

- Find a part of the grain that exhibits a 1° gray interference color with the analyzer inserted. Observe what happens to this area as the compensator is inserted.

    - If addition occurs, it means that the slow direction in the crystal, which you now know is ω, is parallel to the slow direction in the compensator. Since ω is the slow direction you know it has the higher refractive index, or $\omega > \varepsilon$, and the crystal is optically negative.

    - If subtraction occurs (1° gray turns to 1° yellow), it means the fast direction in the crystal, which you now know is ω, is parallel to the slow direction in the compensator. Since ω is the fast direction, you now know it has the lower refractive index, or $\omega < \varepsilon$, and the crystal is optically positive.

In fact, there is yet an easier way to determine optic sign in uniaxial minerals that we will discuss after looking at another way to set up the microscope.

Conoscopic Examination of Uniaxial Minerals - Uniaxial Interference Figures

All of the work you have done so far in lab has been with the microscope arranged in mode called orthoscope. In the orthoscope mode, light incident on and passing through the crystals on the microscope stage is perpendicular to the lower and upper surfaces of the crystals. In conoscope mode, a lens, called a condensing lens is inserted between the light source and the crystals, and is focused such the incident light is no longer perpendicular to the top and bottom of the crystal, but crosses within the crystal. In addition, another lens, called the *Bertrand Lens* is inserted between the objective and ocular lenses.

Orthoscope   Conoscope

Ocular Lens
Bertrand Lens
Analyzer
High Power Objective Lens
Mineral Grain
Stage
Condensing Lens
Iris Diaphragm
Polarizer
Filter
Light Source

After Perkins & Henke, 1999

To put the microscope in the conoscope mode you must do the following:

1. Switch to the highest power objective lens.
2. Switch in the condensing lens located beneath the stage, and raise it to a position so that the top is just below the stage.
3. Switch in the Bertrand lens, located just below the ocular lenses.
4. Initially make sure that the compensator plate is not in (i.e. the compensator plate should be at the intermediate position.)
5. Put the analyzer in.

Now imagine that we have a grain of some uniaxial mineral on the stage oriented in a position such that the C axis (optic axis) is perpendicular to the stage. Recall from previous discussions how we could recognize such a grain.

- It is a grain that shows only the ω refractive index,
- one that shows no relief change upon rotation,
- and one that would remain extinct on rotation if the analyzer is inserted in orthoscope mode.

If we can find such a grain and we put the microscope in conoscope mode, we will see a centered uniaxial interference figure as discussed below.

Centered Uniaxial Interference Figure

A centered uniaxial interference figure is shown in the diagram below.

It consists of dark bands that cross the field of view to form a black cross called *isogyres*. Depending on the thickness and birefringence of the mineral one may also see bands of color that form circles that are concentric with the center of the cross. These color bands are called *isochromes*. At the intersection of the bars of the cross is the *melatope*, where light that has traveled along the optic axis exits in the field of view. For a perfectly centered uniaxial interference figure, that is where the optic axis is exactly perpendicular to the microscope stage, the cross will not change position or orientation during a full 360° rotation of the stage.
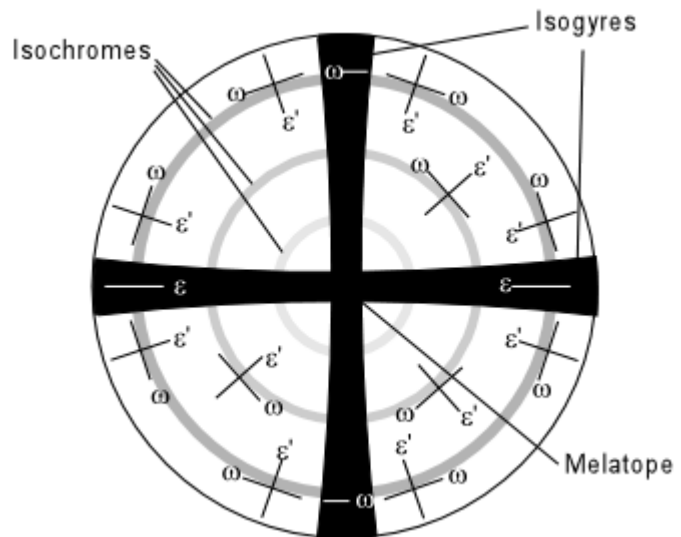

Note that light that has vibrated parallel to an ω direction while in the crystal comes out in the interference figure in a pattern that is concentric to the melatope, and light that has vibrated parallel to an ε' direction in the crystal comes out vibrating in a radial pattern, as indicated in the figure above. The order of the interference colors seen in the isochromes increases away from the melatope. As the thickness and birefringence of the crystal increase, the number of isochromes seen in the interference figure increases.

Determination of Optic Sign

A uniaxial interference figure can be used to easily determine the optic sign of a mineral. In such a figure there will usually be an area close to the melatope that shows an interference color of 1° gray. Observe the effects of inserting the 1° red or 550 nm compensator on this gray area.

- If the minerals is **optically positive**, the NE and SW quadrants of the interference figure turn 2° blue, because addition will have occurred in these quadrants. The NW and SE quadrants will turn 1° yellow, because subtraction will have occurred in these quadrants.

  If one remembers where the yellow color occurs, note that drawing a line connecting the yellow quadrants would cross the slow direction in the compensator, like the vertical stroke on a plus sign.
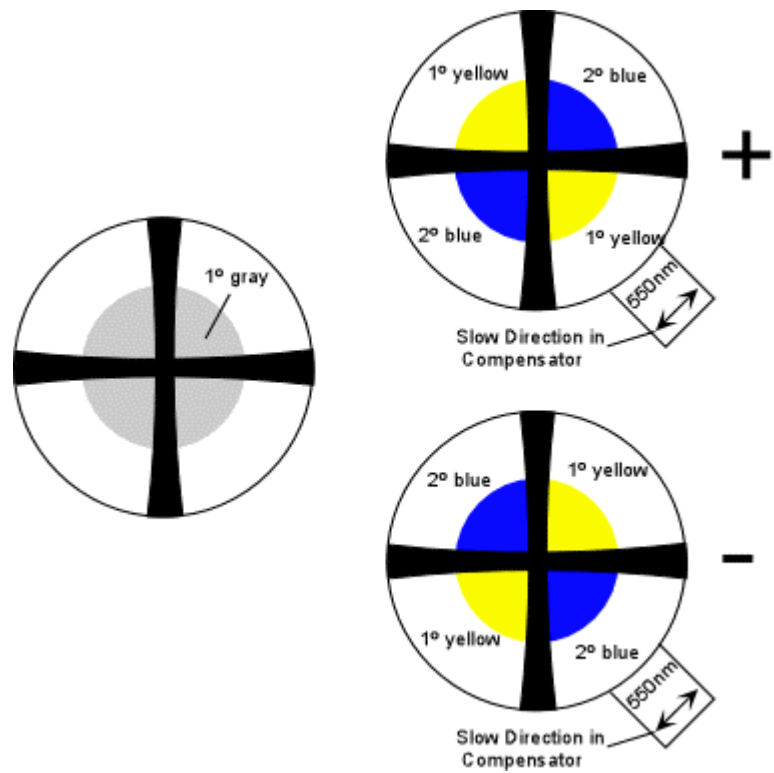
- If the minerals is **optically negative**, the NE and SW quadrants of the interference figure turn 1° yellow, because subtraction will have occurred in these quadrants. The NW and SE quadrants will turn 2° blue, because addition will have occurred in these quadrants.

  If one remembers where the yellow color occurs, note that drawing a line connecting the yellow quadrants would be parallel to slow direction in the compensator, like the single stroke on a minus sign.
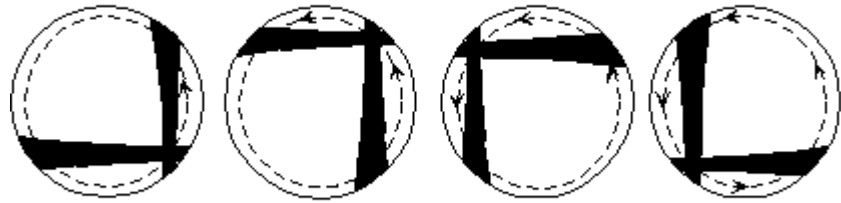
Off-Centered Uniaxial Interference Figure

Finding a grain with the optic axis oriented exactly perpendicular to the stage will sometimes be very difficult. It would be much more common to find one wherein the optic axis is at a slight angle to being perpendicular to the microscope stage. Such a grain will exhibit the following properties:

- It is a grain that shows ω refractive index and an ε' refractive index that is close the ω refractive index,

- Thus, it will show only a small change in relief change upon rotation.

- It would also show very low order (1° gray interference colors between extinction positions if the analyzer is inserted in orthoscope mode.

Such a grain would show an off centered optic axis figure as shown here. On rotation of the stage, the melatope would rotate in a circle around the perimeter of the field of view, and the bars of the isogyres would remain oriented E-W and N-S

Optic Sign from Off-Centered Interference Figure

Even with an off centered interference figure, optic sign can still be determined because one can keep track of the isogyres and still divide the figure into quadrants.

Again for an optically positive crystal, all NE and SW quadrants will turn blue and the NW and SE quadrants will turn yellow, both colors replacing the 1° gray color present before insertion of the compensator.
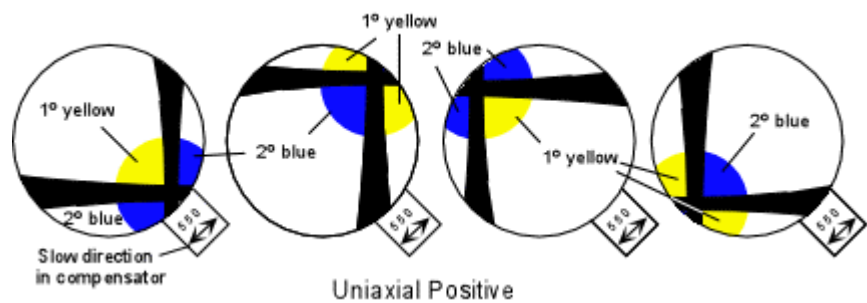
Similarly for an optically negative crystal, all NE and SW quadrants will turn yellow and all NW and SE quadrants will turn blue, both colors replacing the 1° gray color present before insertion of the compensator.
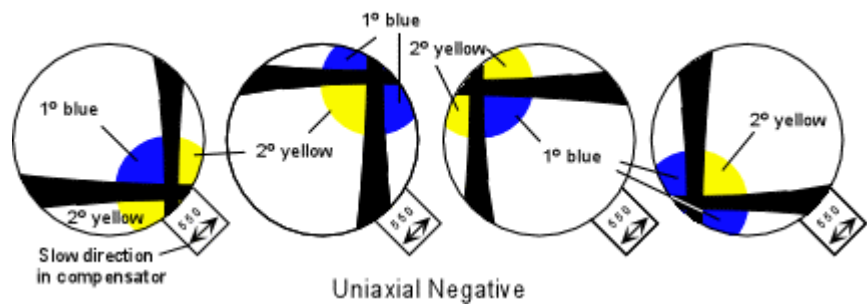
We next turn to some other optical properties that can be determined for uniaxial minerals that can provide some additional diagnostic tools in the identification of minerals. Some of these you will already have covered in lab, but it is still worthwhile to review them here.

Extinction Angles

Extinction angle is defined as the angle between a crystal's privileged directions and any linear

(in 2 dimensions) feature of the crystal. For crystals that show cleavage as the prominent linear feature, the cleavage traces may intersect or may be parallel to each other.   In either case, the extinction angle can be determined by aligning the cross hairs of the microscope with one of the cleavage traces, inserting the analyzer, and measuring the smallest angle between the cleavage and the position where the crystal goes extinct. Because of the symmetry in tetragonal and hexagonal minerals, most cleavages will also show symmetry, and this will result in two possible cases, one for intersecting cleavages, called *symmetrical extinction*, and one for parallel cleavages, called *parallel extinction*.

For the case of symmetrical extinction, the crystal will be at the extinction position and show an extinction angle that is the same on either side of the cross-hair. The example shown here is for a tetragonal mineral with a cleavage like {110} or {011}. In the example, the crystal shown at its extinction position is not shown completely extinct, so that one may view the cleavages. Under the microscope the crystal would be completely black at the extinction position.

Symmetrical Extinction
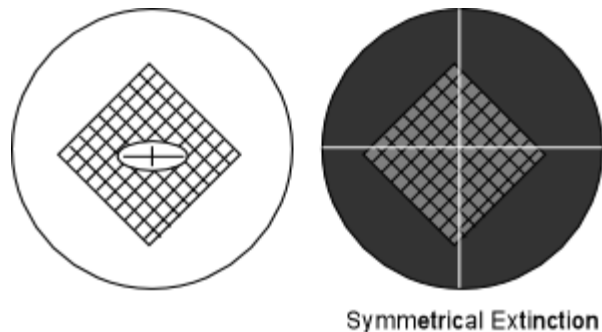
For the case of parallel extinction, the crystal will be at the extinction position when the cleavage is aligned parallel to the cross hairs.

Note that in this case if the crystal is rotated 90° from this extinction position, that it will again be extinct. But remember that all anisotropic crystals have two extinction positions that are 90° apart, and that the extinction angle is defined as the smallest angle (in this case 0°). Again, in these diagrams, the crystal is not shown to be completely black at the extinction position to aid in the clarity the presentation.


Parallel Extinction
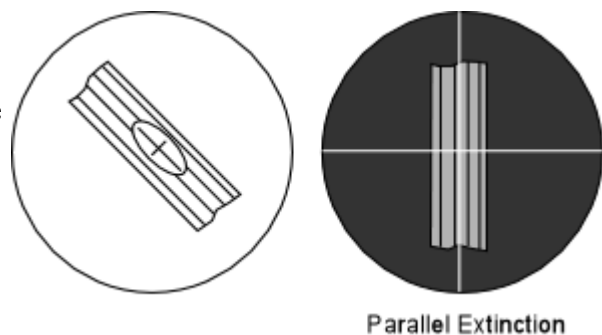
Sign of Elongation

Some crystals tend to grow in elongated habits. When this is the case, note that they can be elongated parallel to their slow vibration direction or parallel to their fast vibration direction.

- Crystals *elongated parallel to the slow direction* have a *positive sign of elongation* or are said to be *length slow.*

- Crystals that are elongated *parallel to their fast direction* have a *negative sign of elongation* or are said to be *length fast*.

To determine the sign of elongation, place the crystal so that it is in a position where the long direction of the crystal is parallel to the slow direction in the compensator.

Observe an area that shows a 1° gray interference color (usually along the thin edges of the crystal) with the analyzer inserted. If this 1° gray area turns to 2° blue, addition has occurred telling us that the slow direction in the crystal is aligned with the slow direction of the compensator. This crystal is length slow.
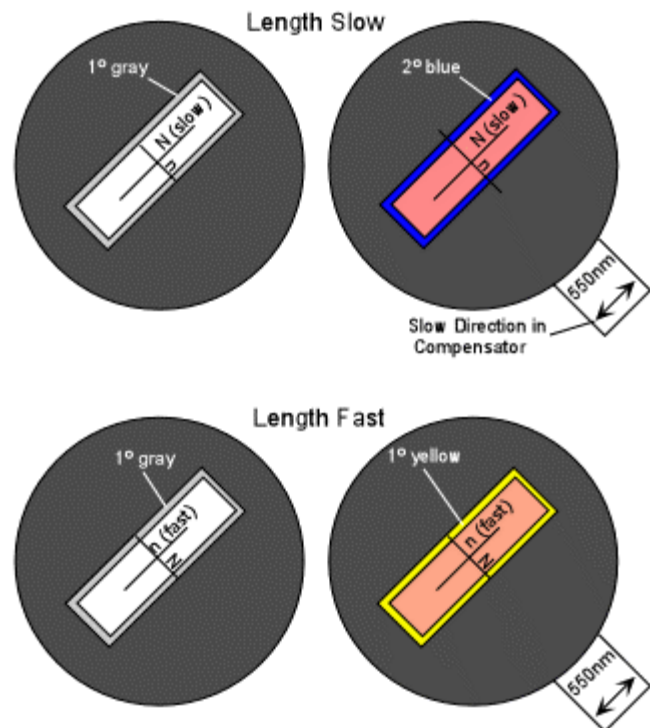
If, one the other hand, the 1° gray area turns yellow, it tells that subtraction has occurred, and the fast direction in the crystal is aligned with the slow direction in the compensator. The crystal is then said to be length fast.

Note again, that the length slow/fast property only applies to crystals that always show a habit with a preferred direction of elongation.

Absorption and Pleochroism

Recall that in isotropic substances preferential absorption of different wavelengths of light may occur upon passage through the crystal. This results in light of wavelengths that are not absorbed being transmitted and combining to produce a certain color known as the absorption color (observed with the analyzer **not** inserted). Some uniaxial crystals have more than one absorption color because the different wavelengths are absorbed to different extents depending on the direction of vibration of the light as it passes through the crystal. When a crystal exhibits more than one absorption color it is said to have *pleochroism*.

The relationship between the color of the crystal and the vibration direction for light is called the pleochroic formula. A uniaxial crystal that exhibits pleochroism will show this property

best if the C-axis, or optic axis is parallel to the microscope stage, so that both of its principle vibration directions can be observed.

In the example shown below, the *pleochroic formula* is ω = yellow, ε = blue. That means that when the ω direction is parallel to the polarizer only light vibrating the ω direction will pass through the crystal, and it will show a yellow color.
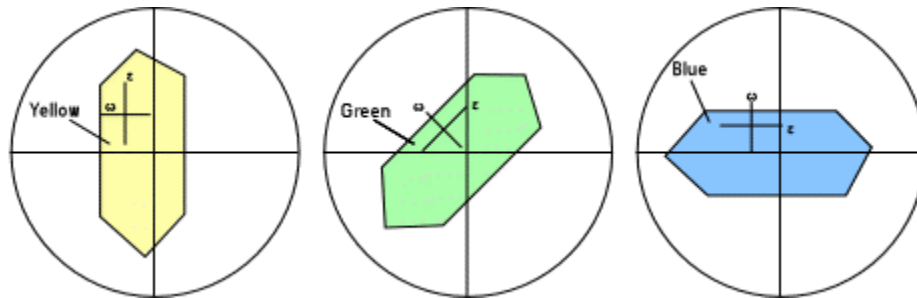
When the ε direction is parallel to the polarizer only light vibrating in the in the ε direction will pass through the crystal and it will show the blue absorption color in the case illustrated.

At intermediate positions the crystal will show a combination of the two colors, in this case green.

Note also that if the optic axis is oriented perpendicular to the microscope stage, light will see only the ω vibration direction, and will thus only show the absorption color associated with the ω direction.

This gives us another method for finding a grain oriented with its optic axis perpendicular to the microscope stage. **If the mineral is pleochroic, a grain that shows no change in color on rotation of the stage is one with the optic axis oriented perpendicular to the stage**. Such a grain should also give us a centered optic axis interference figure in conoscope mode.

Abnormal (Anomalous) Interference Colors

If a mineral has strong absorption of certain wavelengths of light, these same wavelengths will be absorbed by the crystal with the analyzer inserted, and thus the crystal may produce an abnormal or anomalous interference color, one that is not shown in the interference color chart. For example, imagine a crystal that shows strong absorption of all wavelengths of light except green. Thus, all other wavelengths are absorbed in the crystal and the only wavelengths present that can reach the analyzer are green. The crystal will thus show a green interference color that is not affected by the other wavelengths of light, and thus this green color will not appear in the interference color chart.

Examples of questions on this material that could be asked on an exam

1. Define the following: (a) retardation, (b) sign of elongation, (c) length slow, (d) length fast, (e) pleochroism, (f) extinction angle, (g) abonormal interference color.

2. Explain how you would use the interference color chart to determine the birefringence of a grain with a given thickness by knowing the interference color.

3. Explain how one would use the compensator plate to determine the directions associated with high refractive index vibration direction and low refractive index vibration direction in a mineral grain.

4. List as many ways as you can to locate a grain that will give you a centered or near centered optic axis interference figure.

5. Draw a centered optic axis interference figure and label all of the parts. Show the effect that would occur if you were to insert a 550 nm compensator plate if this grain was uniaxial positive. Be sure to show the compensator plate and its slow direction.

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