L6: Introduction to Optical mineralogy

Tuesday, August 18, 2020 7:21

Time on task: 2 hours (material posted on Sept 14th, Students hours: Monday Sept 28th and Wednesday Sept 30th)

Goals:

Upon completion of this lecture, you should be able to:

1. Define and describe the property of light
2. Describe the interaction of the lab with matter
3. Define refractometry and birefringence
4. Explain the concept of optical indicatrix

This lecture is complemented with your labs #5 to 8.

1. Properties of Light

What is light?

Light has several definitions:

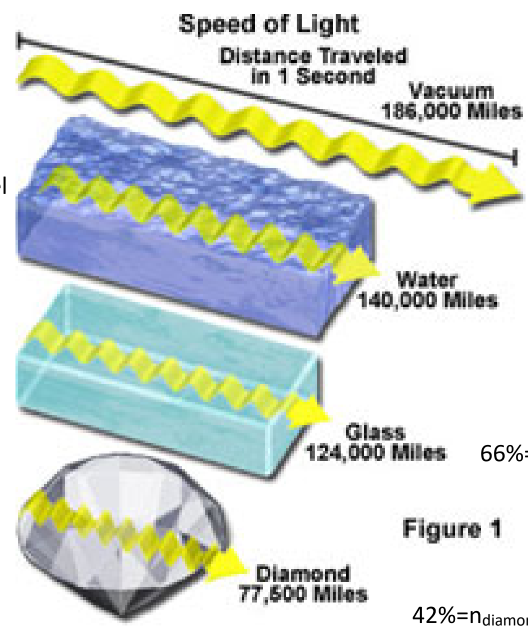
- Particles or quanta – photons
- Electromagnetic **wave**
- Both (particle-wave duality)

For our point of view, the important word is **wave**. And it's a wave that travel very fast through material. It's the fastest substance we know.

The velocity of light is constant as long as the media in which the light travel is the same, but it differs as function of the media.

Light travel faster into vacuum. And we used this speed as a **reference**:
***c* (for light celerity) = 2.988 * 10^8 m/s.**
c is one of the most important constant in physics.

It travel slower in water. At about 75% of the speed in vacuum, slower in glass and even slower in diamond and with other minerals, it drops off even slower.



100%= c/c

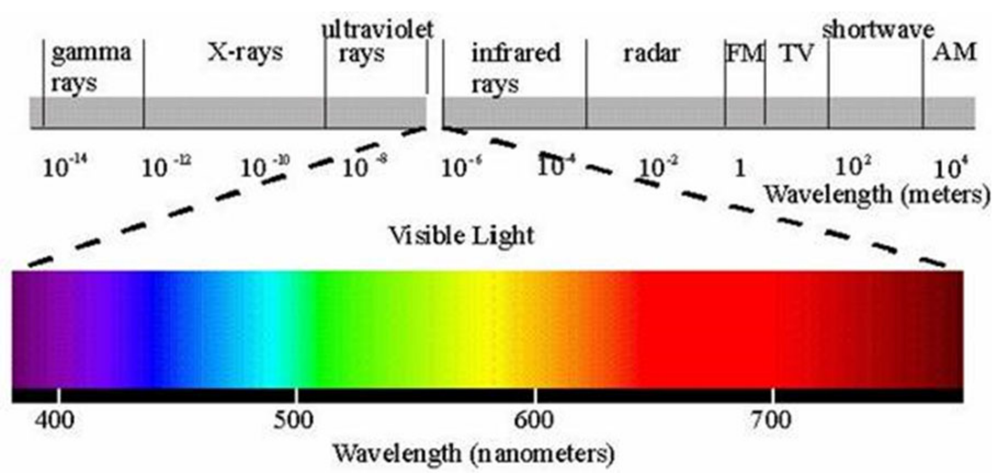
75%=n_{water}/c

66%=n_{glass}/c

Figure 1

42%=$n_{diamond}$/c

Light is also an **electromagnetic radiation.**



The electromagnetic spectrum can be divided into several bands based on the wavelength. Visible light represents a narrow group of wavelengths between about **380 nm and 730 nm.**

Our eyes interpret these wavelengths as different colors. If only a single wavelength or limited range of wavelengths are present and enter our eyes, they are interpreted as a certain color. If only a single wavelength is present, we say that it's a **monochromatic light**. If all wavelengths of visible light are present, our eyes interpret this as **white light**. If no wavelengths in the visible range are present, we interpret this as dark.

2. Interaction of light with matter

As we said previously, light **cannot** travel faster than *c*, but it can travel slower. This is where we introduce our first diagnostic property. **The index of refraction, noted n.** n is the ratio between the velocity of the light into vacuum, c, and the velocity of the light into the medium (i.e., the mineral).

n = c/v

You will see that minerals can have several n because crystals have different axes and the velocity of light is not necessarily the same in all directions of the crystal.

Going back to the first figure of this lecture, we can calculate the index of refraction of the different media:

- **The minimal index of refraction is 1**, it's the s**peed into vacuum**
- Light in water travel at 75% of its maximal speed. In other words, $n_{water} = c/v_{water} = 1/0.75 = 1.33$.
  Note that this is the index of refraction of water at **20°C**. If we change the temperature, we change n, because the density of the water will change.
  The index of refraction of **glass is 1.5.** It's important to know that when you use a petrographic microscope, you will see after why.
  And the index of refraction of diamond is 2.4.
- The index of refractions of minerals varies from 1.40 to 3.22, and **most of minerals fall into 1.4-2.0.** You can notice that some of the minerals have (n_o or $n\beta$).
  That's mean it is indicate a specific direction the crystal. You will learn more about this in your lab#8.

Mineral	n
Fluorite	~1.435
Leucite	~1.510
Quartz	~1.545
Apatite	~1.635 (n_0)
Augite	~1.71 (n_β)
Zircon	~1.95 (n_0)
Rutile	~2.6 (n_0)

1.2.1. Isotropy and anisotropy

Materials can be divided into 2 classes:

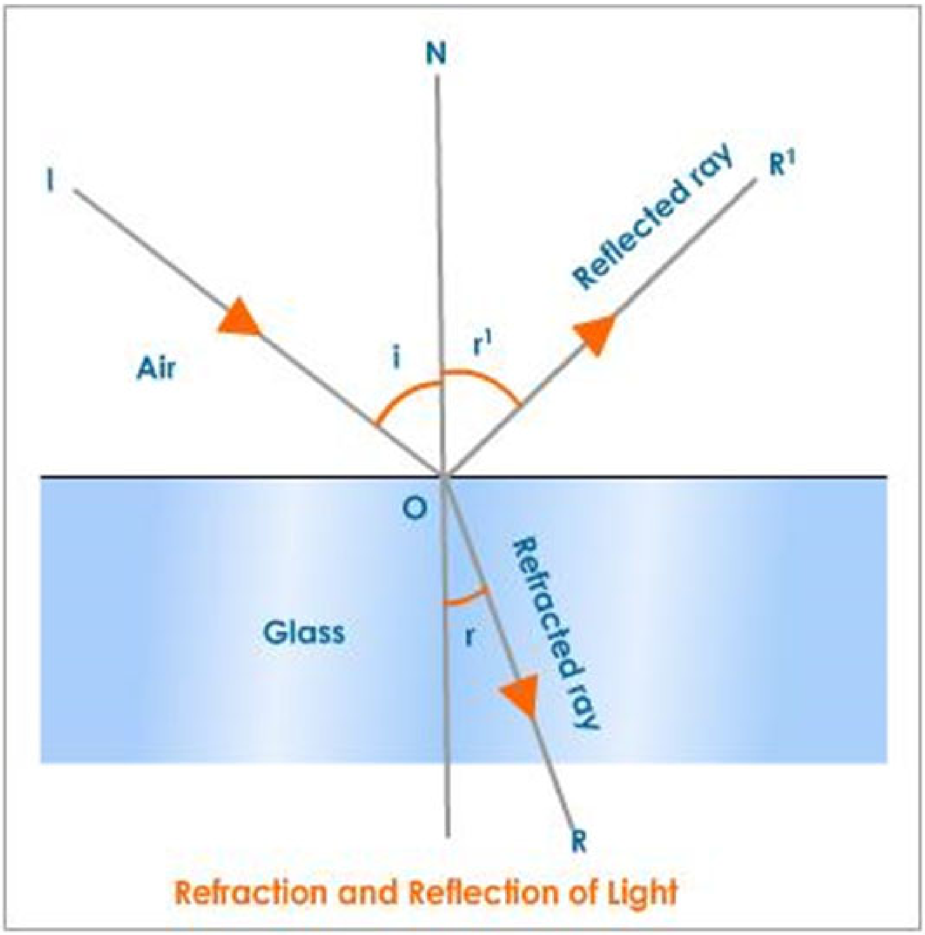
- Materials whose refractive index not depends on the direction that the light travels are called **isotropic materials**. In these materials the velocity of light is the same in all the directions. Isotropic materials have a single, constant refractive index for each wavelength. Glass, gases, most liquids and amorphous solids are isotropic. Minerals that crystallize in the isometric system, are also isotropic.
  e.g., diamond, fluorite
- Materials whose refractive index does depend on the direction that the light travels are called **anisotropic materials**. These types of materials will have a range of refractive indices between two extreme values for each wavelength:
  - Minerals that crystallize in the tetragonal, hexagonal and trigonal crystal systems (as well as some plastics) are **uniaxial** and are characterized by 2 extreme refractive indices for each wavelength.
    e.g., Quartz, Calcite
  - Minerals that crystallize in the triclinic, monoclinic, and orthorhombic crystal systems are **biaxial** and are characterized by 3 refractive indices.
    e.g., Feldspars, pyroxenes, amphiboles

1.2.2. Refraction

Why do we call this property "index of refraction"? Because it's due to the ability of light to refract in a media. If the angle between the incident light rays and the phase boundary (e.g., air/mineral) is different from 90˚, the light rays change their propagation direction; they are refracted.

As long as the medium is **isotropic**, the angle of refraction is link to the angle of the incident wave and to the refractive index through the **Snell's law**:

$$n_i \sin(i) = n_r \sin(r)$$



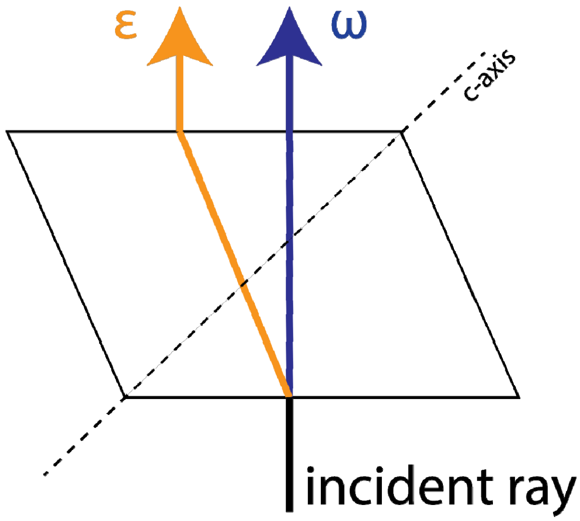
Note that if the light enter the transparent media with a 0° angle, that is perpendicularly to the media, then the refracted ray (or wave) is also perpendicular to the media:

$n_i \sin(0) = 0 = n_r \sin(r) \Rightarrow r = 0°$.

Light propagation in **anisotropic materials** (i.e., all the minerals that does not crystallize in the isometric system) is direction-dependent. Light entering an anisotropic crystal is "split" into two light waves that vibrate orthogonal to each other (with exceptions applying to specific directions in the crystal). The two light waves propagate through the crystal with different velocities. This phenomenon is called **double refraction.**

This property is well known in calcite because the double refraction is visible in clear hand sample (called optical calcite). Some of you might have a calcite specimen (M-34) in your kit that is clear enough to do the test.

For uniaxial minerals (i.e., crystallizing in the tetragonal, hexagonal and trigonal systems, such as calcite), the two refracted rays are called **ordinary** (ω) and **extraordinary** (ε) rays. The ordinary ray is the one that follows the Snell's Law.

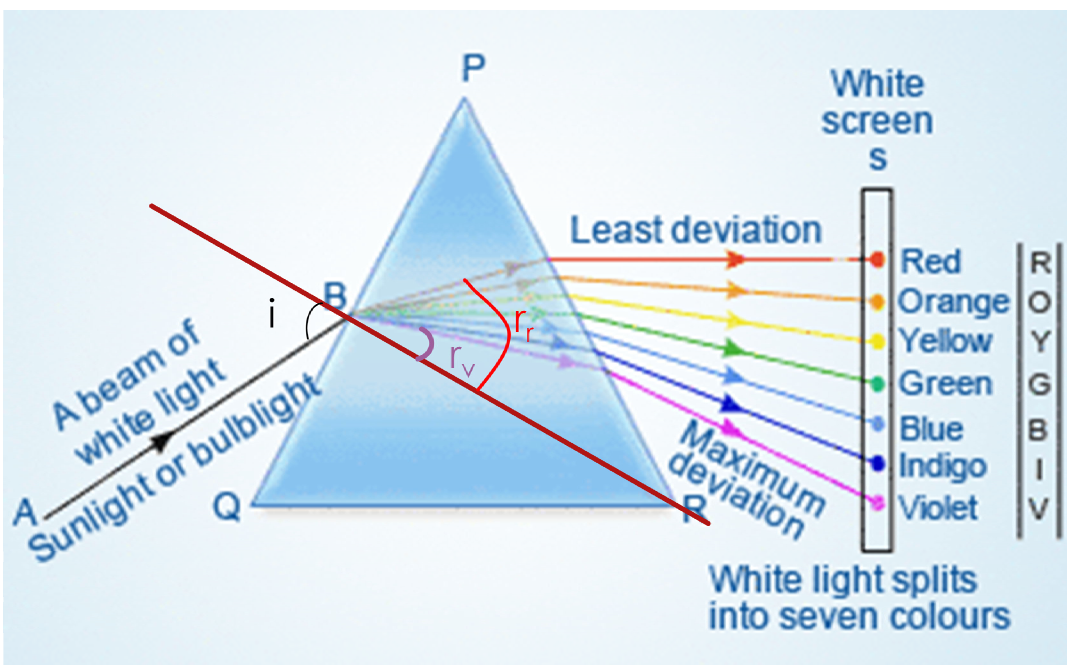


For biaxial minerals (i.e., crystallizing in the othorhombic, monoclinic and triclinic systems), both refracted rays are direction-dependent.

The difference of speed between the two rays is called **birefringence**. All **anisotropic** minerals are said **birefringent**. It's a very important property because it's the property that allow you to see all these awesome colors with the microscope (XPL mode). We will understand why in the second part of this lecture.

1.2.3. Dispersion

Definition: Dispersion is the prism effect that occurs when the white light is split into its component colors (i.e., different wavelength travel at different speeds). i.e., the "rainbow effect".



The White light entering such a prism is refracted in the prism by different angles that depend on the wavelength of the light.

The refractive index for longer wavelengths (800nm, red) are lower than those for shorter wavelengths (300nm, violet). This results in a greater angle of refraction for the longer wavelengths than for the shorter wavelengths.

There is a problem with this. In fact, if you want to use the index of refraction of a mineral as a diagnostic property, this needs to be a fixed value. If you used white light to illuminate your thin section, each ones of the different wavelengths will have a different refractive index. So normally, when we measure the index of refraction, we use what's called **monochromatic light**, i.e. a light with one frequency (or one wavelength).

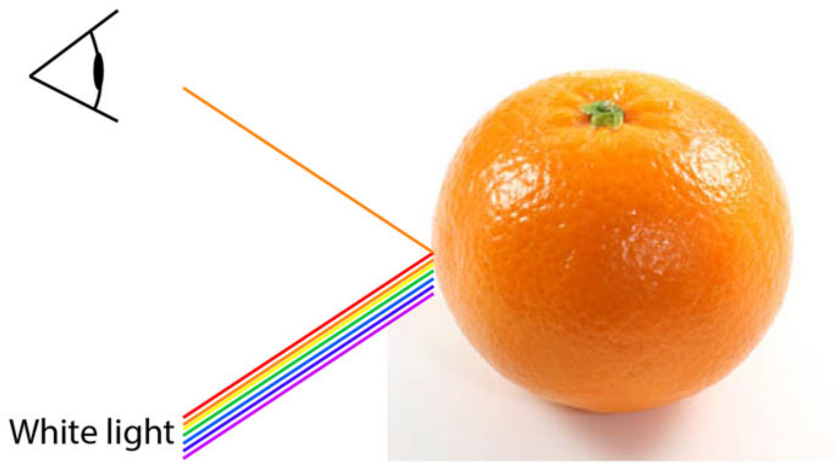
With the microscope, the light is "as monochromatic as possible". The way we do this is simply putting a blue filter. That's bring me to the 4^{th} definition: absorption.

1.2.4. Absorption

When light enters a transparent material some of its energy is dissipated as heat energy, and it thus loses some of its intensity. When this absorption of energy occurs selectively for different wavelengths of light, they light that gets transmitted through the material will show only the wavelengths of light that <u>are not absorbed</u>. **The color of a mineral or any other object is the color of light that <u>is not</u> absorbed on transmission of reflection.**

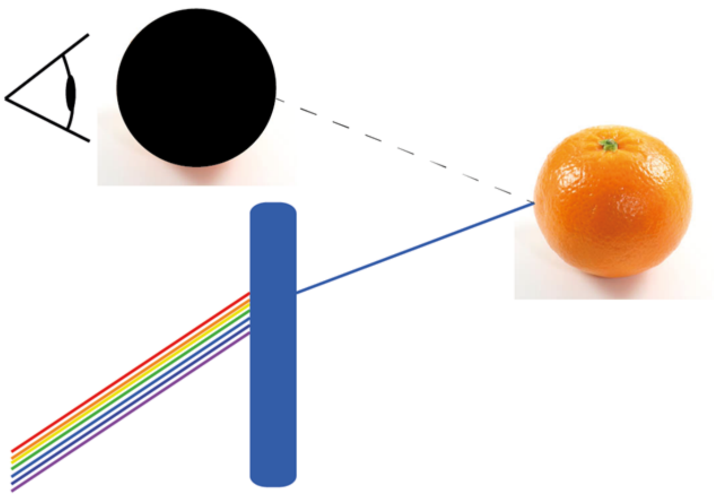
A white object is white because it reflects all the visible spectrum. Similarly, a clear mineral transmits essentially all the visible spectrum. A black object absorbs all the wavelengths of light.

Example: An orange lighted by a white light seems orange because this fruit is actually absorbing all the wavelength except orange.



Now, what would be the color of this orange is we place a blue filter in front of the white light?

We will see the orange black as the only colors passing through the filter would be blue and blue is absorbed by the orange.

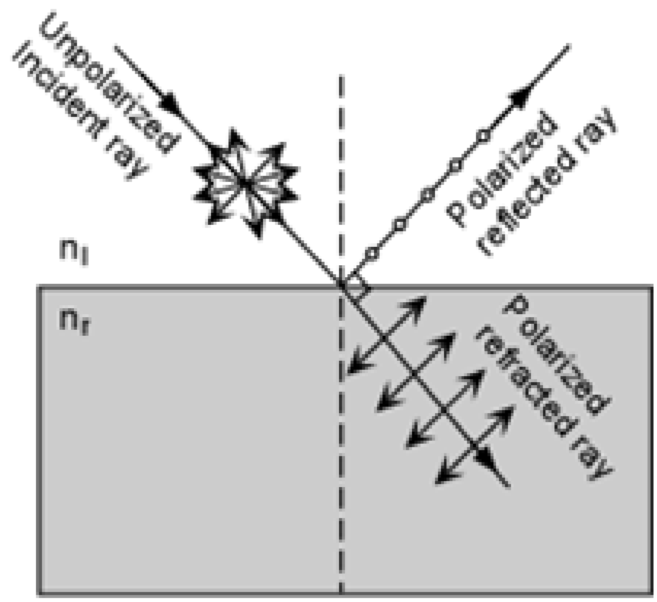


1.2.5. Polarization

Normal light vibrates equally in all directions perpendicular to its path of propagation. <u>If</u> the light is constrained to vibrate in only on plane, we say that it is plane **polarized light.** The direction that the light vibrates is called **the vibration direction**.

There are two common ways that light can become polarized.

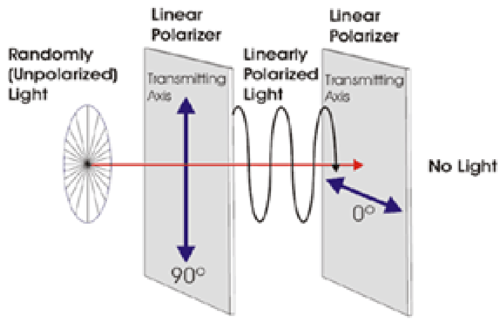
- The first involves reflection off of a non-metallic surface, such as glass or paint. An unpolarized beam of light, vibrating in all directions perpendicular to its path strikes such a surface and is reflected. The reflected beam will be polarized with <u>vibration directions parallel to the reflecting surface</u> (perpendicular to the screen as indicated by the open circles on the ray path).



If some of this light also enters the material and is refracted at an angle 90o to the path of the reflected ray, it will also become partially polarized, with vibration directions again perpendicular to the path of the refracted ray, but in the plane perpendicular to the direction of vibration in the reflected ray (the plane of the screen).

- Polarization can also be achieved by passing the light through a substance that absorbs light vibrating in all directions except one. Anisotropic crystals have this property in certain directions, **called privileged directions**.

Crystals were actually used to produce polarized light in microscopes built before ~1950. The device used to make polarized light in modern microscopes is a **Polaroid** (yes, same technology that in cameras that have the same name). A Polaroid consists of long-chain organic molecules that are aligned in one direction and placed in a plastic sheet. They are placed close enough to form a closely spaced linear grid, that allows the passage of light vibrating only in the same direction as the grid. Light vibrating in all other directions is absorbed.



In part because Polaroid's are now mostly associated with photographs, we call these "devices" **polarizers**. If another polarizer with its polarization direction oriented **perpendicular** to the first polarizer is placed in front of the beam of now polarized light, then no light will penetrate the second polarizer. In this case we say that the light has been **extinguished.**

On the petrographic microscope, we can look at a thin section in two different modes: **Plane Polarized Light (PPL)** when only **one polarizer** is placed between the light source (and its blue filter) and the thin section, or **Crossed Polar Light (XPL)** when **another polarizer** (also called analyser) is placed between the thin section and the ocular.

Question: If you buy polarized sunglasses, what is the direction of polarization? And why should you probably not wear polarized sunglasses when you drive in winter? (the answer is the end of the assessment)

L6: Refractometry and Birefringence

Tuesday, August 18, 2020 16:49

3. The polarizing microscope.

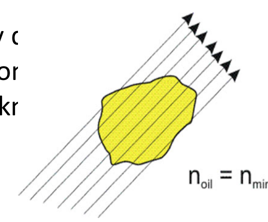
In optical mineralogy, we use a microscope that is equipped with two polarizers that are oriented so that their vibration directions are perpendicular to one another.

The light from the source (at the bottom of the microscope) is covered with a blue filter (to make it 'as monochromatic as possible') but is not polarized (the light is going in all directions). The light ray first passes through a lower polarizer (usually just called polarizer), where it becomes polarized. In Lab 5, you will determine the direction of polarization of the teaching microscopes. The light then passes through a hole in the rotational stage and enters a lower lens, called objective lens. Each of the G&G teaching microscopes has 3 objectives with different magnification.
You then have the possibility of insert a the second polarizer, called analyzer. The vibration direction of the second polarizer is perpendicular to the first polarizer. You can also use the accessory plate. On the G&G microscope, the accessory plate is a gypsum plate. You will learn more about this during your labs 7 and 8.

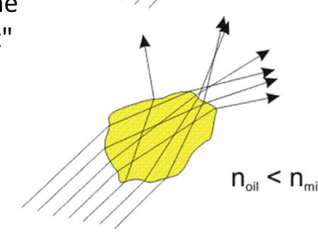
You can find a short video (petro.mp4) associated with this lecture where I present the G&G teaching microscope.

4. Refractometry

The first diagnostic property of minerals in thin section is their index of refraction. To precisely c the index of refraction of the mineral, we use a technique called refractometry. The method cor having immersion oils of known refractive index (or index of refraction) and comparing the unkr mineral to the oil.



If the indexes of refraction of the oil and the mineral are the same, light passes through the oil-mineral boundary without being refracted and the grain does not appear to "stand out" from the oil (i.e, if the grain is colorless, it is going to be very hard to locate it in the oil).



If the index of refraction of the oil and the mineral are NOT the same. Light is refracted at the grain-oil boundary and the grain appear with a relief.

The immersion method consist at testing various oil to find the one where the mineral does not stand out anymore. This method gives a quantitative (i.e, a numerical value) estimate of the index of refraction.

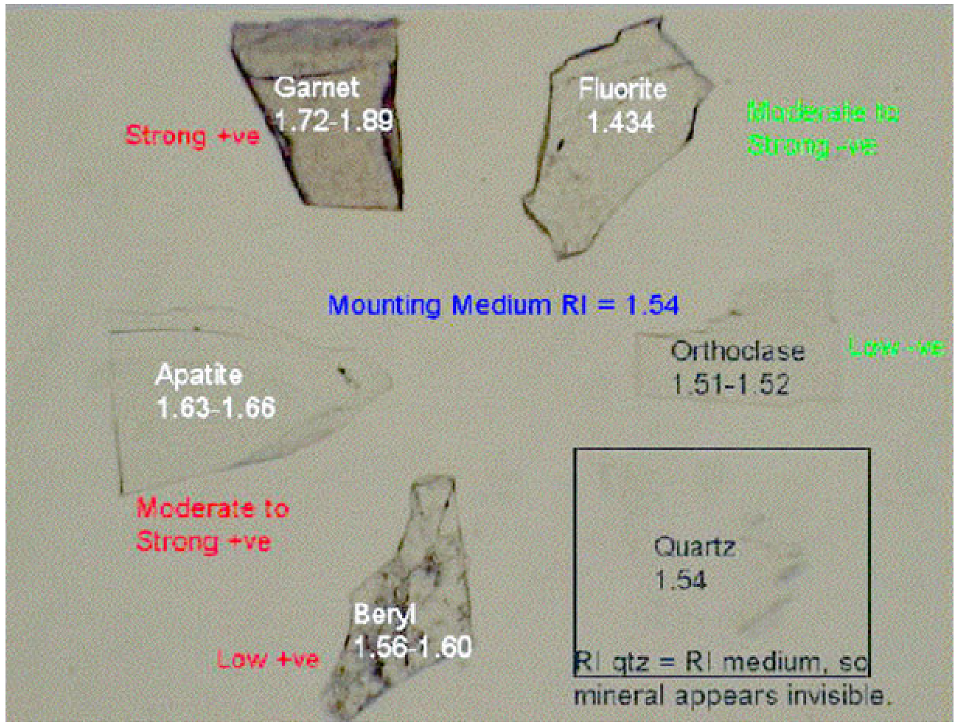
However, very often, we can't apply this method. Thin sections are often prepared from rocks, and not separate minerals, and mounted in epoxy, such as the thin sections you will study in labs. Hence, we used a qualitative (i.e., relative comparison) method by comparing the relief of the minerals with the mounting media (glass/epoxy) and the other grains.

4.1. Relief

The degree to which a mineral stand-outs from the mounting medium is called **relief**.
If the index of the mineral is higher than the index of the mounting medium (glass, epoxy), the mineral has a **positive relief.** Inversely, if the $n_{mineral}$ is lower than n_{glass}, the relief is **negative**. Higher is the difference of n between the mineral and the mounting media, more the mineral will seem to stand out of the thin section.

However, positive and negative relief looks the same in static conditions. So we need an additional method to distinguish between these two.

This figure shows some examples of the relief of minerals on glass. The index of refraction of "window glass" is 1.54. Quartz and orthoclase shows almost no relief (i.e., they are almost invisible) because they have index of refraction very close to 1.54. On the contrary, garnet and fluorite show strong relief (i.e., thick grain boundary - this will be an **important characteristic** to illustrate in your thin section sketches.), but when garnet a positive relief, fluorite has a negative relief.

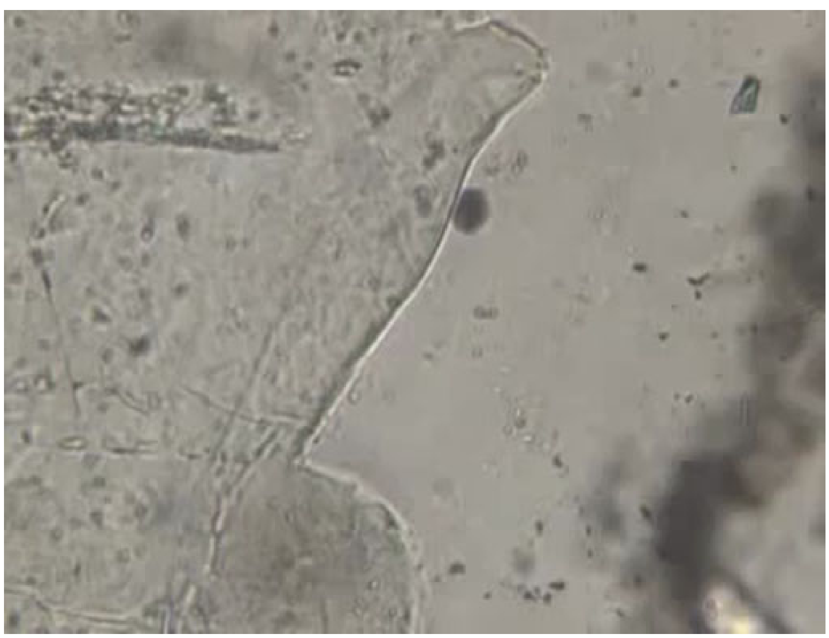


4.1.1 The Becke line method.

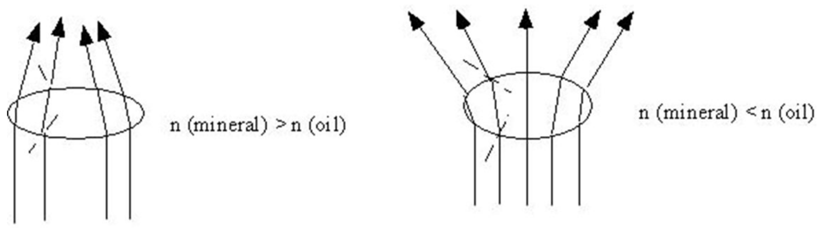
You will use this method in lab starting lab 6.

The Becke line is a band of light around the mineral grain when the grain is slightly out of focus. The becke line may lie inside or outside the grain depending on how the microscope is focused.

The best what to see the Becke line is to use the intermediate (*10) or the high magnification lens (*40) and to close the diaphragm (located just above the lower polarizer) 2/3 way.



When you increase the distance between the thin section and the objective (i.e, when you lower the stage), the becke line moves toward the mineral/medium with the highest index of refraction.



Formation of the Becke.

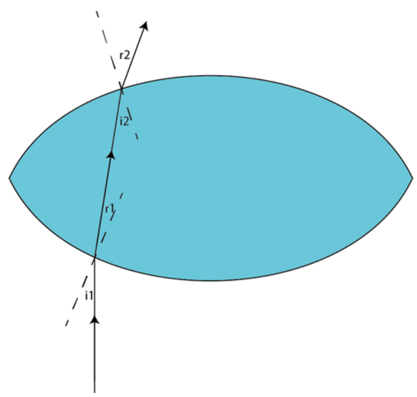
Look at this video that shows the boundary between two minerals. Can you tell which one has the highest relief? (keys at the end of the assessment). The video starts with both minerals on focus. Make sure to locate the Becke line. What happens when the user increases the distance between the objective and thin section and that the thin section is not on focus anymore?

You will study several examples of this phenomeona in Lab 6 and use this property in the following labs.

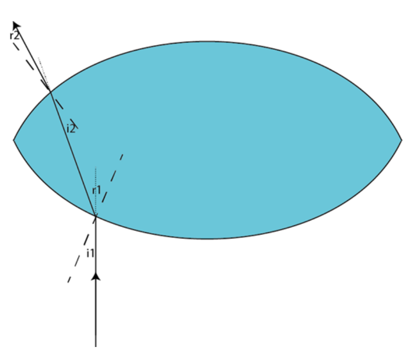
How that works?

This is due to the shape of the mineral. Most minerals are thinner on the edge than in the middle and have the shape of a lens.

If the **index of refraction is highe**r than the mounting medium, the mineral will act as a **converging lens**. This is in agreement with the Snell's law: if the index of reaction is larger, the refracted angle is smaller than the angle of the incident ray.



If the **index of refraction is lower**, the refracted angle is larger, and the mineral acts as a **diverging lens.**



5. Introduction to Optical Indicatrix

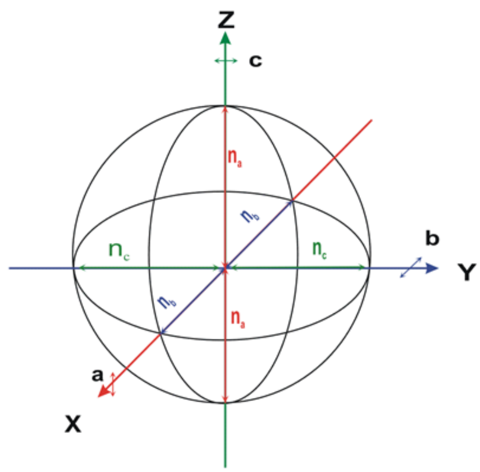
The concept of optical indicatrix is important because it gives a visualization of the way that the refractive index varies with direction in a substance (a mineral for this class). You will look at that more in detail in your lab 8 (note that you will need a lemon, a kiwi, 2 markers and some toothpicks to complete this lab.)

Definition. An **optical indicatrix** is a 3D representation (ellipsoidal) of the variations of the refractive index in a substance. The ellipsoidal is defined by three perpendicular vectors and each vector length is proportional to the index of refraction (n) in the same direction.

5.1 Isotropic substance.

Isotropic substances are those wherein the velocity of the light (or the refractive index - n= c/v) does not vary with the orientation of the substance. Minerals that crystallize in the **isometric crystal system** (=cubic system) are **isotropic**. Glass is also usually isotropic.

The optical indicatrix of an isotropic substance (e.g., an isometric mineral) is a **sphere**: the three vectors have the same length has the light speed/index of refraction is the same in all directions. (in other words, the light follow the Snell's law in isotropic substance).



5.2 Anisotropic minerals.

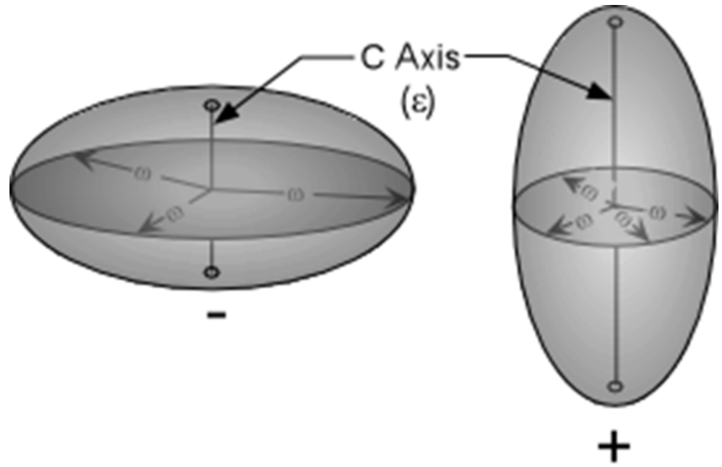
Anisotropic minerals are distinct from isotropic mineral by the fact that the velocity of light is not the same in all directions and by the fact they present double refraction and birefringence.

Between the anisotropic minerals, we distinguished between uniaxial and biaxial minerals:

- **Uniaxial mineral**s are mineral that growth in the hexagonal ($a \neq b \neq c$; $\alpha = \beta = 90°$; $\gamma = 120°$), trigonal ($a = b = c$; $\alpha = \gamma = \beta \neq 90°$) and the tetragonal ($a = b \neq c$; $\alpha = \beta = \gamma = 90°$) system. They are defined by **two** indexes of refraction.

Hence, the optical indicatrix of a **uniaxial mineral has two main vectors**: **n**ω (ω = ordinary) and **nƐ** (Ɛ = extraordinary) and present **one circular section**. The circular section is **defined by n**ω.

If **n**ω **< nƐ**, we says that the mineral is **uniaxial positive.** If **n**ω **> nƐ,** the mineral is **uniaxial negative**.

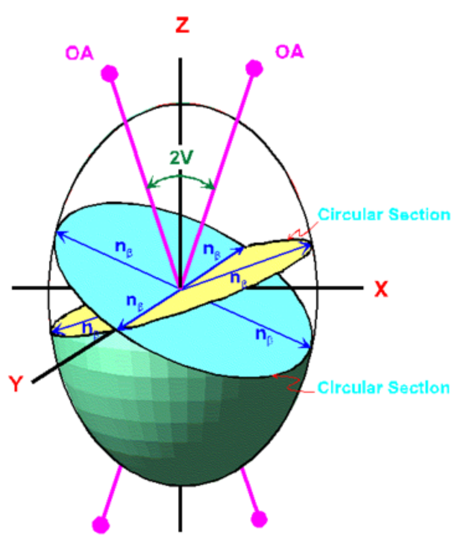


- **Biaxial minerals** are mineral that growth in the triclinic (a ≠ b ≠ c; α ≠ γ ≠ β ≠ 90°), monoclinic (a ≠ b ≠ c; α = γ = 90°≠ β), and orthorhombic systems (a ≠ b ≠ c; α = β = γ = 90°). They are defined by **three** indexes of refraction.

Hence, the optical indicatrix of a **biaxial mineral has three vector lengths**: **nα**< **nβ < nγ** and present **two circular sections defined by nβ**, none of them align with the vectors.

Biaxial minerals also have optic signs (biaxial positive: nα< nβ << nγ ; biaxial negative: nα<< nβ < nγ) but we won't discuss that in details in class.

The two axes perpendicular to the circular section are called ***optic axes***



6. Birefringence

As you probably noticed by now, inserting the analyzer (i.e., view in crossed polars), results in seeing a wide range of colors, called **interference colors**. Additionally, you might also have noticed that some grains stay completely black (we say they stay extinct) and others got extinct 4 times along a 360° rotation. The mineral goes extinct when the privileged directions are parallel to the lower polarizer. In fact, 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 and be completely be absorbed by the analyzer.
When the privileged directions are not parallel to the polarizer some light is transmitted by the analyzer and this light shows the color we name interference color.

6.1. Case of the extinct grains.

The plane polarized light is travelling perpendicular to the stage. In other words, the light source is vertical. Hence, the light is vibrating parallel to the stage, and the thin section just before it enters the thin section.

As we've discussed earlier, when light enters an isotropic substance with an incident ray angle equal to 0° (i.e., the ray is perpendicular to the substance), the light is not refracted and passes through the substance with same vibration direction (i.e., behaves following the Snell's low - ordinary ray).

Hence, for a substance to behave isotropically in thin section, the index of refraction must be the same in all directions parallel to the stage.

=> ALL GRAINS THAT ARE CUT PARALLEL TO A CIRCULAR SECTION OF THEIR INDICATRIX WILL APPEAR ALWAYS EXTINCT IN XPL.

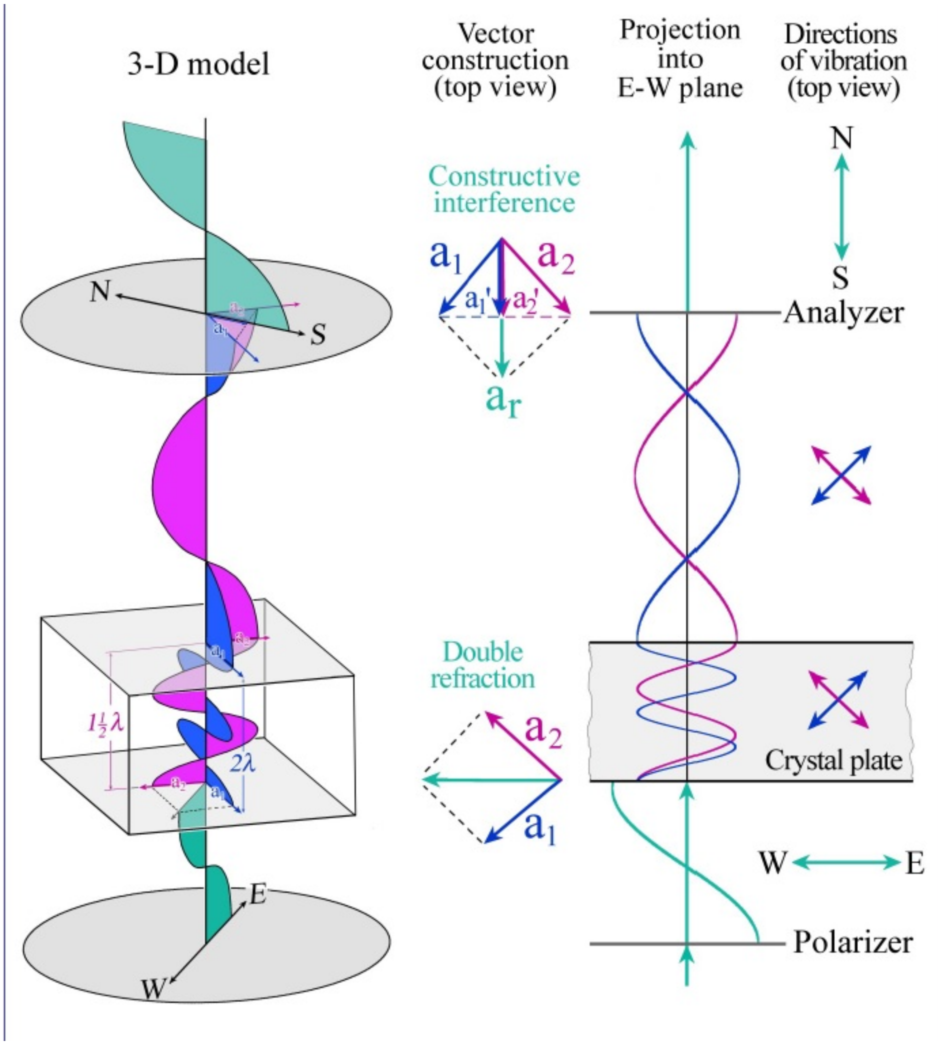
Hence, **isotropic minerals are always extinct** in crossed polars (XPL). (any section of a sphere is a circular section). But **anisotropic minerals can also appear extinct**. This is why you always need to check several grains in a thin section before doing a mineral identification.

6.2. Anisotropic minerals.

For any other cut that is not parallel to a circular section, anisotropic minerals won't stay extinct on the 360° rotation and will show interference color.

The reason for that is when light enters any section of an anisotropic mineral (except the circular section), the light is split into two rays (double refraction), represented on the figure below by a1 (pink) and a2 (blue) that do not travel at the same speed and are not (necessarily) parallel to the vibration direction of the polarizer. These two rays exit the crystal and finally arrive at the analyzer. If the projection of the two ray vibration direction on the analyzer direction is not equal to zero (represented by a_r here), the analyzer will let some light passes through. The color that we see is proportional to t**he difference of speeds between the two rays, called birefringence** (see below).

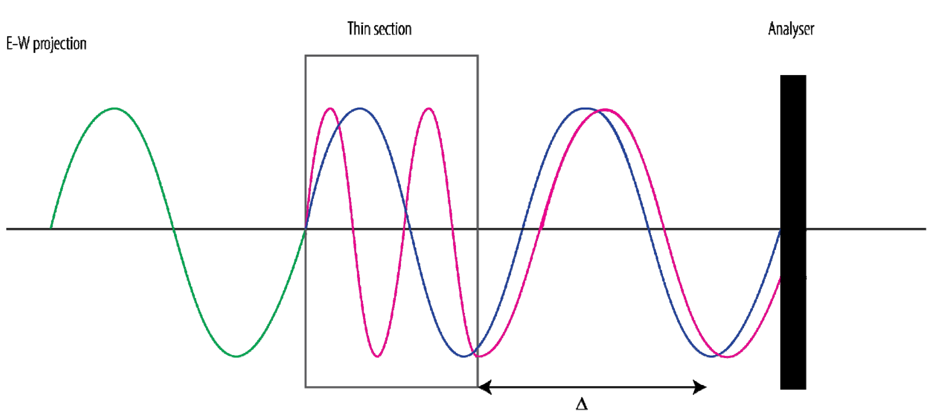
They are four positions, however, on a 360° stage rotation, where the mineral will go extinct.



Source: Guide for thin section microscopy - Fig. 4.25B (the PDF is in File → Additional resources)

6.3. Interference colors.

Definition: The **retardation (Δ)** is the distance that the fast ray (the ones that travel along the lowest direction) had traveled outside the mineral when the slow ray (high n) just emerges from the mineral. **Retardation** is a **wavelength** and corresponds to a certain **color** (that's where the colors in XPL come from). Retardation also depends on the thickness of the mineral (thickness of the thin section), d, as demonstrated below.



Vs: velocity of the slow ray (pink), vf: velocity of the fast ray (blue)

ts = d/Vs: time for the slow ray to travel through a thin section of thickness d.

During the same duration, the fast ray travel through the thin section and also to a distance equal to Δ.

ts = d/Vs = d/Vf + Δ/Vair

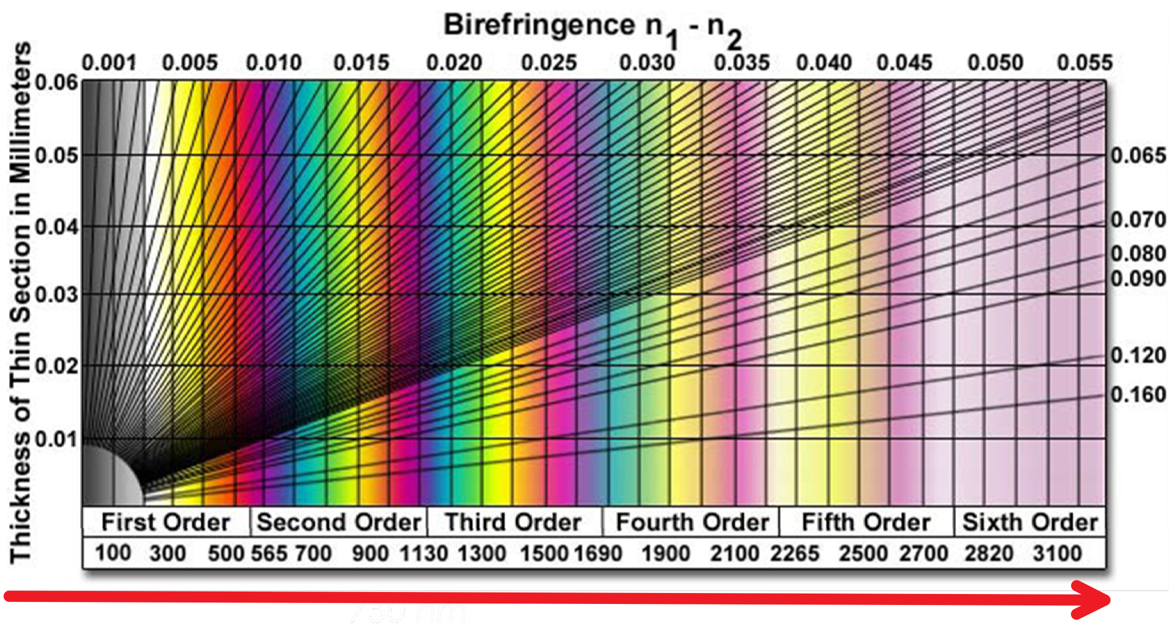
Assuming Vair = Vvacuum = c

Δ = d * (c/Vs - c/Vf)

Δ = d * (ns - nf)

Definition: birefringence: δ = ns - nf: difference between the indexes of refraction of the slow and the fast rays.

Only the **maximal birefringence** of a mineral is considered as a diagnostic property of the mineral and the maximal birefringence will result into the maximal retardation and consequently the highest order of interference color.



Retardation (Δ) in nm

The maximal birefringence is only going to be seen on certain sections of the mineral and for certain orientations. So it's important to look at several grains to determine this property.

After studying this material, can you guess for which section and which orientation you will be able to see the maximal interference colors? (keys at the end of the personnel assessment).

Once you found the grain with the highest order of interference colors, you can use the Michel-Levy chart above to find the corresponding maximal birefringence. Your will learn how to use this chart in Lab 7.

L6: Personal assessment.

Friday, August 21, 2020 16:46

After reviewing the lecture, you should be able to answer these questions:

****Multiple choices possible!****

1) **The index of refraction of a mineral**

A - is constant
B - is equal to the celerity divided by the speed of the light in the mineral
C - is quantified by the Becke line method.
D - can be determined with the Snell's law

2) **The reason an orange is orange is because**

A - only the orange wavelength is reflected by the fruit
B - only the orange wavelength is absorbed by the fruit

3) **The blue filter on the light source at the base of the petrographic microscope is there**

A - to transform the white light into plane polarized light
B - to transform the plane polarized light into a monochromatic light.
C - to transform the white light into monochromatic light.

4) **You are looking at a thin section, you see a colorless mineral in PPL. You insert the analyzer and now the grain appears black.**

A - it means that the mineral might be isotropic
B - it means that the mineral might be anisotropic
C - it means that the privileged direction of the crystal is parallel to the polarizer

5) **You look at a grain in thin section in XPL view and you see second order interference color** (you need to know how to read a Michel-Levy chart to answer this question)

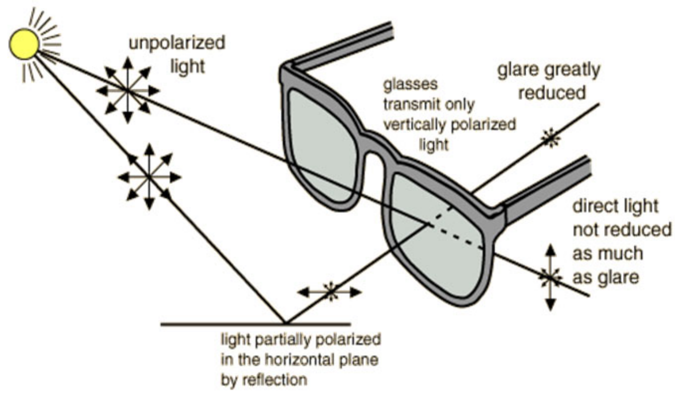
A - the minimal birefringence of the mineral is between 0.010 and 0.018
B - the maximal birefringence of the mineral is between 0.025 and 0.045
C - the birefringence of the mineral is, at least, between 0.025 and 0.045
D - We need to look at more grains to estimate the maximal birefringence

6) **You are looking at a crystal of quartz cut perpendicular to the c-axis**

A - the grain will look colorless in PPL
B - the grain will look extinct in XPL
C - the interference color will change with the rotation of the stage.
D -the grain will show 4 extinct positions in XPL

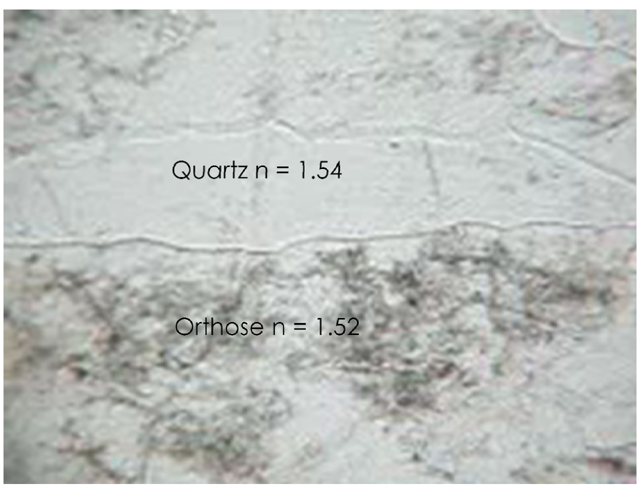
Keys for practices:

1) Polaroid sunglasses use these same principles. For example, incoming solar radiation is reflected off the surface of the ocean or the hood of your car. Reflected light coming off these surfaces will be polarized such that the vibration directions are parallel to the reflected surface, or approximately horizontal (see first method of polarization discussed in part 1). Polaroid sunglasses contain polarizers with the polarization direction oriented **vertically**. Wearing such glasses will cut out all of the horizontally polarized light reflecting off the water surface or hood of your car.



This is why it is important to <u>not drive with polarized sunglasses during winter</u> because, as you don't see the reflection, you might not see if the road is icy.

2)



3) uniaxial mineral: Section with nε and ω.; biaxial minerals: section with nα and γ.
For both, the maximal interreference colors are seen at 45° stage rotation from one of the four extinct positions in XPL