

Optical mineralogy

Primarily aims

- To learn the language (meaning and definition of the used terms) of optic and optical mineralogy
- To Learn some principle of optic such as property of light (polarization, interference, reflection, refraction, dispersion and wave length competent) the definition of the optic sign of uniaxial crystals
- To Learn the different effects minerals and materials on light under polarizer microscopes (these effects such as index of refraction, double refractions, polarization, interference color and figure)
- Get to learn what is the biaxial and uniaxial indicatrix, its various axes, planes, and the 2V angle.
- Learn to determine the. Indices of refraction, optic sign, and 2V angle of biaxial crystals in addition to sign of elongation.

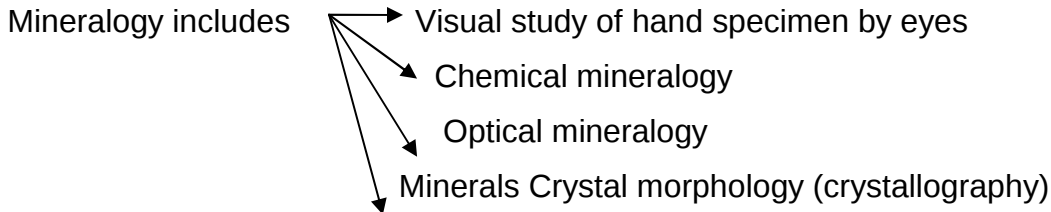
Final aim: to learn how to identify minerals and the rocks with differentiating their economic values

Method of the study

The study of mineral are done with thin section under polarized microscopes by and follow the below subdivision:

- 1- General aspects of minerals: Mineral composition, crystal symmetry, and optics
- 2- Orthoscopic mode of the mineral study / plane-polarized light: relief and refractive indices, form, cleavage, color
- 3-Orthoscopic mode of the mineral study / crossed polarizers: birefringence, sign of elongation, extinction, twinning
- 4- Conoscopic mode of the mineral study: optic character and optic sign, optic axial angle

Relation of the optical mineralogy with other branches of Mineralogy



Optical mineralogy: that branch of geological sciences that deal with optical properties of minerals. Optical mineralogy mainly deals with three things:

- 1- Polarizing microscope (petrographical microscope)
- 2- Visual light (white light)
- 3- Thin section

1-polarizing microscope

Polarized microscope is of possible interest to many sciences that are concerned with crystalline materials such as : geology, mineralogy, crystallography, materials science, biology, forensic science

Polarizing microscope has four differences as compared to ordinary microscope, they are:

- a) It has rotating circular stage which graduated in to 360 degrees
- b) It has Polarizer and analyzer plates: In modern microscopes polaroid sheets are used as polarized and analyzer but in old microscopes **Nicol** prism or Ahern prism are used the polarizer and analyzers used in our microscopes are made of Polaroid sheets which consist of a sheet of cellulose fed with crystals of quinine iodosulfate which is absorbing light in one direction but transmit in the other direction.
- c) It has Accessory plates : such as mica plate , gypsum plate and quartz wedge
- d) It has Bertrand lens: located between analyzer and ocular, which brings the image of interference figure in to the focal plane of the ocular.
- e) Objectives : they are used for magnification of the original object on the stage, two numbers are engraved on the tube of objective lenses:
 - 1- Magnification of the original object e.g: (1x, 3x, 10 x, 40 x and 100 x) the objective lens in the diagram has magnification power of (10) time more than original object on the stage.

- 2- Numerical apertures (N.A)

$$N.A = \sin u$$

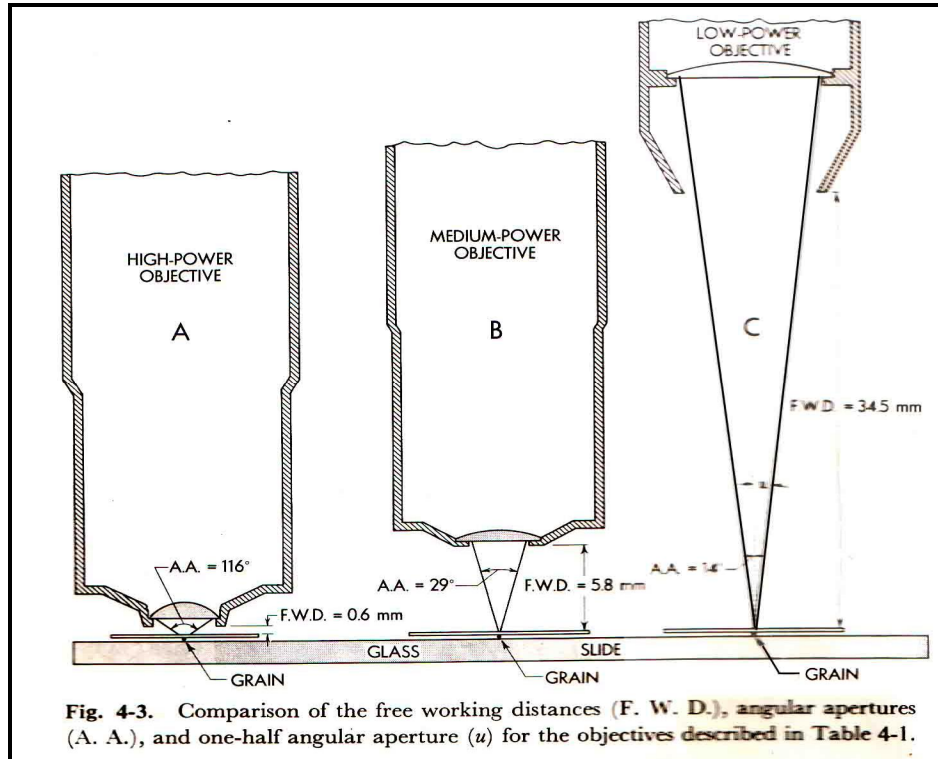
$U = \text{angular operator} / 2$

$100000 * N.A = \text{lines separated} / 1 \text{ square inch}$

So if $N.A = 0.25$ it means that 25000 lines can be separated in one square inch

Free working distance:

It is the distance between the objective and the top of the cover glass of the microscopic slide when the objective is focused



Comparison of the free working distance, angular apertures and one-half angular aperture (u) for the three types of objective lenses.

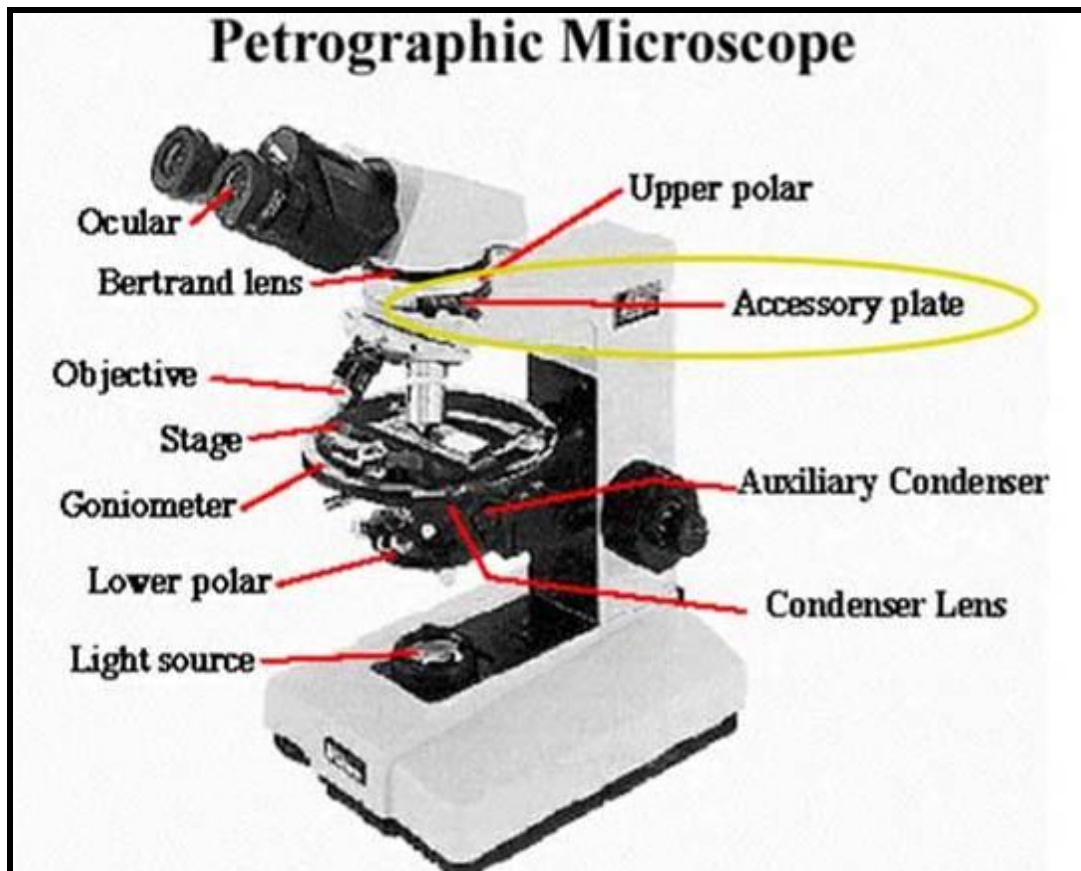
Ocular: (Huygenian type of ocular)

It is used for magnification of the image formed by objective and to bring the image to plane of exist pupil it is consist of field lens, eye lens and fixed diaphragm.

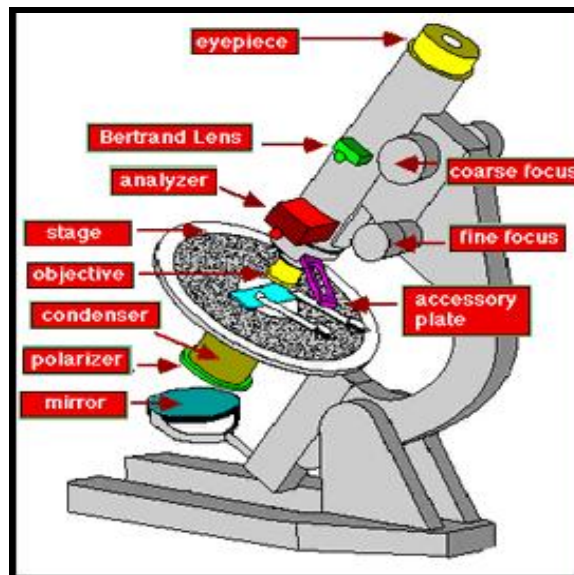
1-Parallel pollars

Ordinary light composed of various wave lengths

2- cross- polars



Modern students polarizer microscope (normally used after, 1970) on which the most important parts are indicated (Also called petrographic microscope)



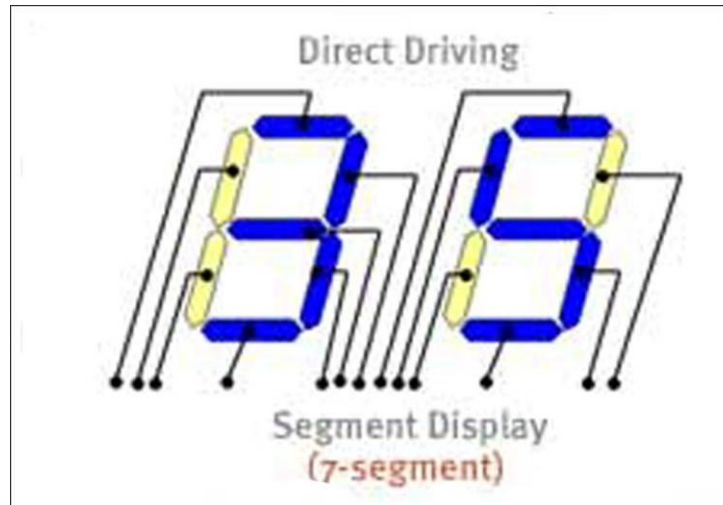
Simple polarizer microscope (normally used before, 1970) on which the most important parts are indicated

Some application of Polaroid sheets (plates) in human life:

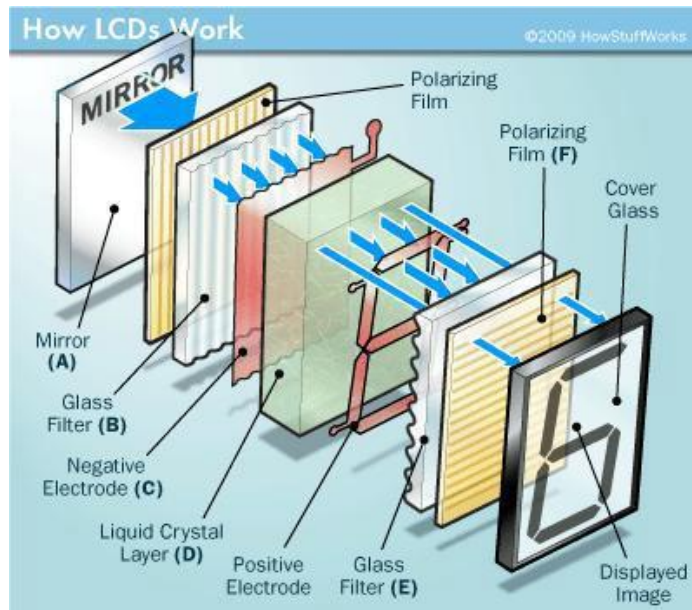
1- LCD watches (liquid crystal display watch)

Television, mobile, computer and digital watch screens consist of a two Polaroid sheets (one act as polarizer and other as analyzer) which are called LCD (liquid crystal display) sheets or pieces. These sheets are called Polaroid sheets which are first made by Polaroid Company in USA. The most common liquid-crystal displays (LCDs) in use today rely on picture elements, or pixels, formed by liquid-crystal (LC) cells that change the polarization direction of light passing through them in response to an electrical voltage.

As the polarization direction changes, more or less of the light is able to pass through a polarizing layer on the face of the display. Change the voltage, and the amount of light is changed. The sheets are consisting of small crystal embedded in certain liquid. as shown in the cross-section diagram in the diagram. when there is no battery in the watch, the watch screen appear clear (bright 1) but when battery used some area of the liquid crystals became dark because the crystals of these area acts as analyzer and absorb light as shown in position.



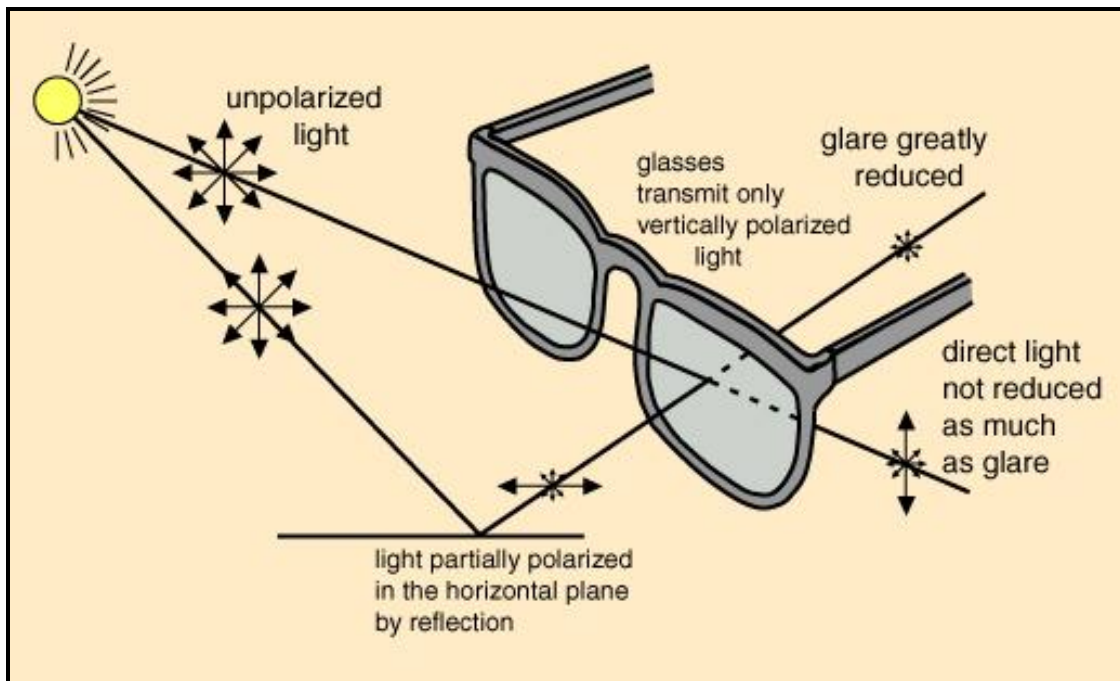
Digital LCD watches work by polarizer and analyzer, the blue (grey) segments are those through which voltage or current is applied changing direction of the polarization of the crystals and black which is visible.



LCD or Plasma Screens contain two polaroid sheets that act as polarizer and analyzer

2- Sun glass

When sun light strike a polished surface (water surface) a part of this light polarized by reflection and when reaches the glass on the eye, the polarized part absorbed by the glass which made of Polaroid sheet and decrease its effect on the eye.



Adjustment of polarizing microscope:

- 1- Centering the objective with the microscope field of view.
- 2- Crossing the polars (or Nicols)
- 3- Testing the cross hairs
- 4- Determination of the vibration plane of the lower polar (polarizer)

1- Centering the objective:

The objective is (centered) when its lens axis coincide with the vertical axis about which the microscope stage is rotating

For centering the objectives a simple procedure is followed:

1- Find an easily recognized point and then rotate the stage. The point must have a concentric circle of rotation about the intersection of the cross hair but it has no concentric circle of rotation, the following procedure is followed:-

- 1-rotate the stage until the point is farthest from the intersection of the cross-hairs
- 2-bring it in half way by means of centering screws
- 3-then bring it to the center of the cross hairs to the center of the field of view) by actually moving the slide by hand
- 4-rotate the stage and repeat the operation if the centering has not been completed in the first time

2-Crossing the polars (polarizer and analyzer)

Every time before putting the slide on the stage, the polars must be crossed as shown on the page (1 and 2) (cross polars diagram) the polarizer located below the stage which has N-S polarization direction the analyzer located between objective lenses and the ocular which has E.W vibration direction. When both polarizer and analyzer are inserted in the light path of microscope the field of view becomes dark this means that both polars are at right angle to each other

2- Testing the cross hairs: the cross hairs are lines engraved on a glass plate in the ocular.

It is important that the hair lines be parallel to the planes of the vibration of the two polars. This is done by the manufacturer company, but some time necessary to test the setting of the cross hairs with planes of the polars. This done by natrolite crystal with elongate and rectangular section. The natrolite crystal becomes dark between crossed polars when the edges of the crystals are parallel to the vibration direction –A slide containing a small **natrolite** crystal may be placed up on the stage between crossed polars.

If the cross hairs are in adjustment, the hair lines should be parallel or at right angles to the straight lines of the crystal boundary (crystal of face)

3- Determination of the vibration plane of the lower polar (polarizer) :-

After the other adjustments have been made, the vibration direction of the polarizer can be determined with either fibrous tourmaline fragments or a rock section containing biotite showing cleavage. Biotite is used because of availability of biotite. Biotite is brown under polarized light and has maximum dark color when the cleavage is parallel to the vibration of the polarizer. So the stage

is the rotated until biotite attains maximum dark brown cooler, in this case the direction of the biotite cleavage is direction of polarizer vibration.

2- Visual light (traverse wave motion)

The vibration light represent limited band of wave length with in electromagnetic spectrum, ranging from 3900 to 7700 Å (angstrom). If light of all wave length simultaneously reach the human eyes, the light is interpreted by the brain as white light.

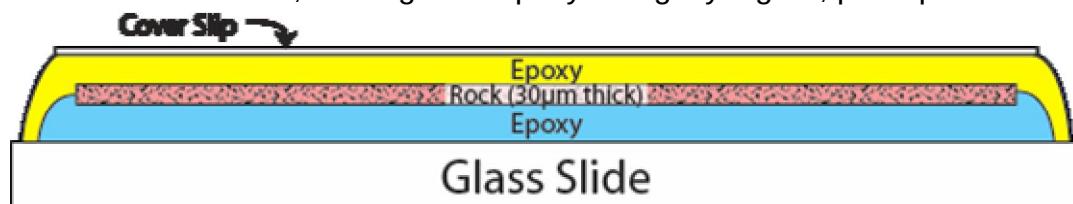
But light with one wave length called mono chromatic light, for example, sodium vapor lamp is a source of mono chromatic light with wave length of 5890 Å but the tungsten lamp is a source of white light (ordinary light). Traverse wave terminology and shape in which polarization and interference occur. Only sound wave is longitudinal which means that the vibration direction is parallel to direction of propagation in which polarization and interference do not occur

3- Thin section

It is a fragment of rock or mineral mechanically reduced to thickness of (0.03mm) by grinding and polishing of thickness makes most rocks and minerals transparent which finally ready for optical study.

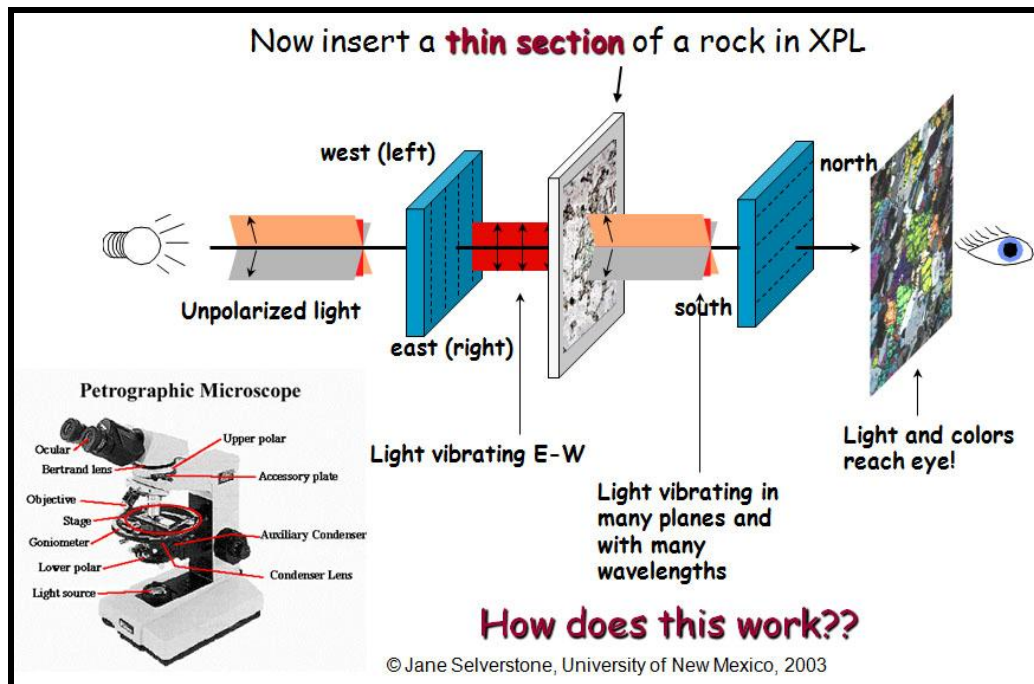
Procedure for making thin section

A thin section is a 30 µm (= 0.03 mm) thick slice of rock attached to a glass slide with epoxy. Typical thin section slides are 26 mm x 46 mm, although larger ones can be produced. They are generally covered by another glass slide, a cover slip also attached to the rock with epoxy. The epoxy ideally has an index of refraction of 1.54, although our epoxy is slightly higher, perhaps 1.56.



The sections may be left uncovered for chemical analysis on the SEM or electron microprobe. If so, temporary cover slips may be weakly attached with glycerin.

- 1- Sawing a hand specimen to get a flat chip which has 4 square cm in area.
- 2- Polishing one of the two surfaces and then mounting on glass slide using Canada balsam.
- 3- Grinding of the chip, which is mounted on the glass slide, to a thickness close to 0.03mm with (1000) grade carborundum.
- 4- Then the slide covered with thin cover slide by liquid Canada balsam.
- 5- During polishing the chip must be examined several times under polarizer microscope to determine the standard thickness of the thin section (0.03mm). This done by the interference color of the quartz or feldspar which they give first order grey when the thickness reaches (0.03mm).



Position (location) of the thin section in the light ray pass from its radiation from the bulb to the eyes of human
 Position (location) of the thin section in the light ray pass from its radiation from the bulb to the eyes of human

PROPERTIES AND NATURE OF LIGHT

The study of the following properties of light are necessary for

- 1- Light represents a relatively limited band of wave lengths within the electromagnetic spectrum , this band ranging from 3900 to 7700 A
- 2- Light is traversal wave which can undergo 1) interference 2) polarization
- 3) Reflection 4) refraction

3- Reflection and refraction:-

When light passes from air in to a denser medium, such as glass, part of it is reflected from the surface back in to the air and other part enters the glass. The reflected ray obeys the law of reflection which says that:

- 1- The angle of incident (i) equals the angle of reflection (r), when both angles are measured from the surface normal
- 2- The incident and reflected rays lie in the same plane.
- 3- That part of light that passes in to the glass travels with lesser velocity than in air and no longer follows the path of the incident ray but is bent or refracted. The amount of bending depends on the 1) obliquity of the incident ray 2) the relative velocity of light in the two media. The greater the angle of incident, the refraction (small angle of refract angle and the greater the velocity difference, the greater refraction.

Speed of light = 3×10^8 m

- 4- Index of refraction:

Index of refraction of material can expressed as the ratio between the velocity of light in the air and it is velocity in the denser material $n = \text{velocity in air} / \text{velocity in material}$

The velocity of light in air is considered here as equal to the reciprocal of the velocity

$N = 1/v = 1/\text{velocity of light in materials}$

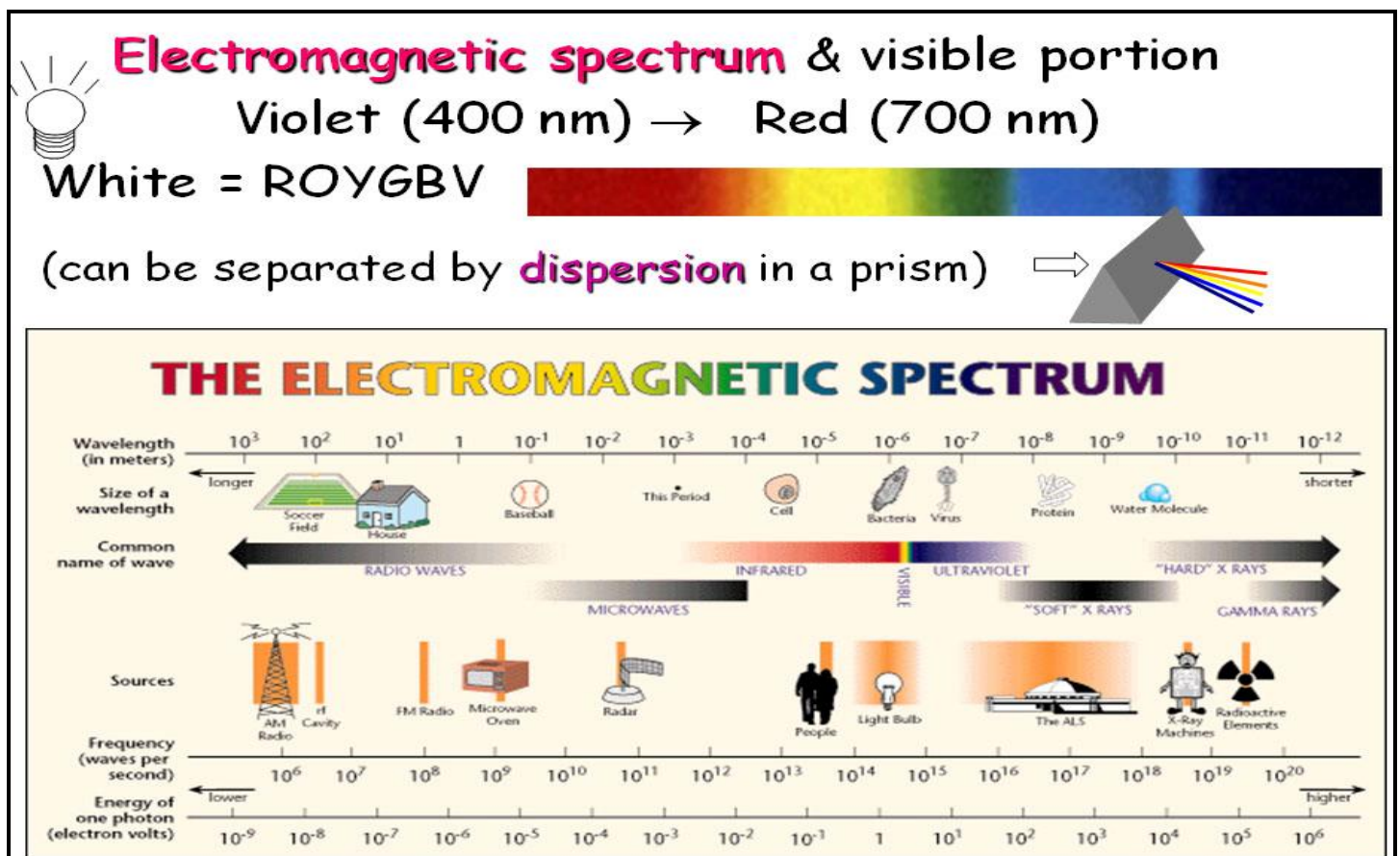
Generally index of refraction of two substances in contact with each other are

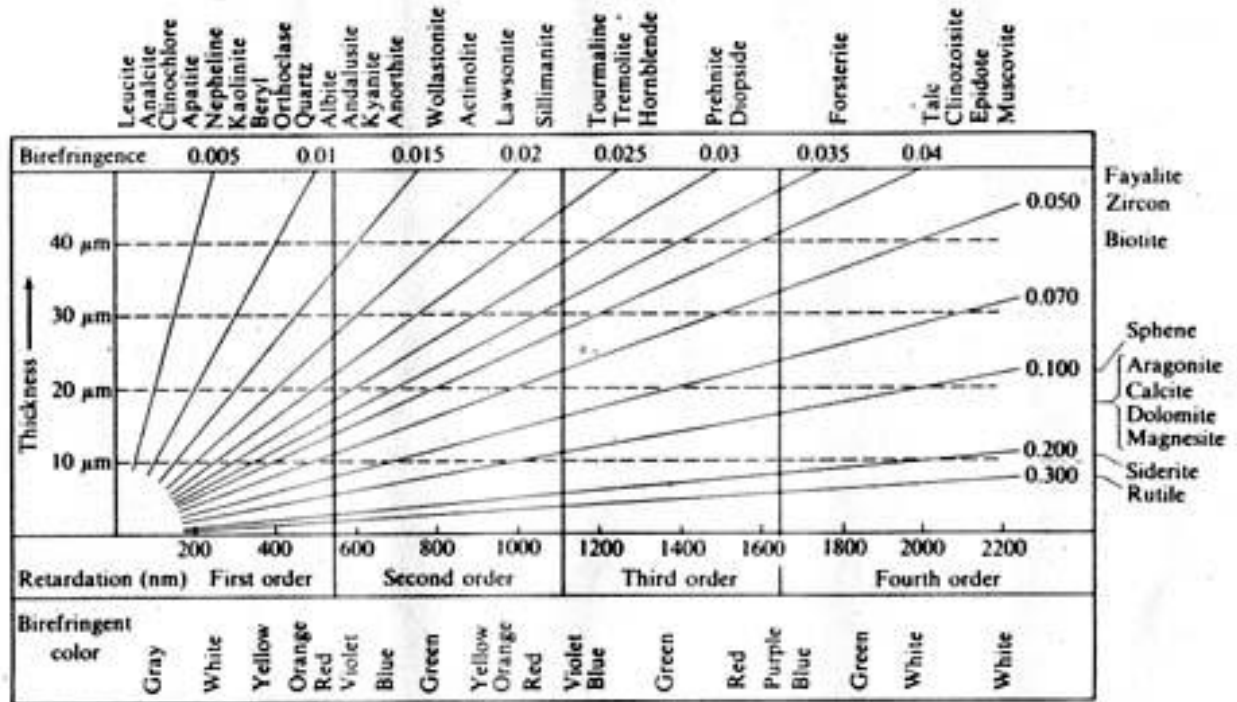
$n_1/n_2 = v_2/v_1$

The precise relationship of the angle of incident (i) to the angle of reflection (r) is given by Snells law: which state that ratio of $\sin i / \sin r = \text{constant}$ and this constant is index of refraction (n). $\{ \sin i / \sin r = n \}$

Which is regarded as constant property for each transparent material.

$N_1/N_2 = 1/v_1 / 1/v_2 \longrightarrow n_1/n_2 = v_1^{-1} / v_2^{-1} \longrightarrow v_2/v_1$

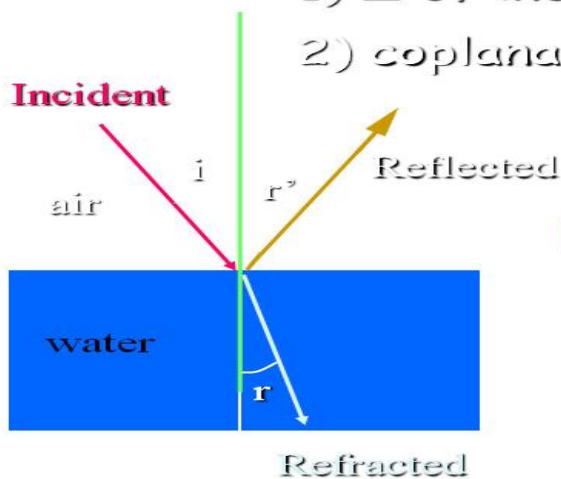




Refraction

Incident ray and reflected rays:

- 1) $\angle$ of incidence $i = \angle$ of reflection r'
- 2) coplanar "plane of incidence"
($\perp$ plane of interface)



Refracted rays:

- 1) Slower in water (or glass)
- 2) $\angle r \neq \angle i$
Depends on Δ velocity

5- Dispersion:

It is difference in indices of refraction of a given mineral for different wave lengths of the spectrum of white light. The velocity of light in glass is equal to frequency multiplied by wave length, or $v = f \times \lambda$ and if we supposed that if (f) is fixed, then the longer (λ) the greater velocity (as for red light) and violet has smaller (λ) so has less velocity in the glass. because of reciprocal relation between velocity (v) and refractive index (n) , $n = 1/v$, so n for red light is less than n for violet light as shown in the diagram above, this is known as dispersion of the indices, and because of it, monochromatic light is used for accurate determination of the refractive index. Dispersion of the minerals = $nv - n_r$. The least dispersive mineral is fluorite and the mineral with the highest value of dispersion is diamond

Material dispersion can be a desirable or undesirable effect in optical applications. The dispersion of light by glass prisms is used to construct spectrometers and spectroradiometers. Holographic gratings are also used, as they allow more accurate discrimination of wavelengths. However, in lenses, dispersion causes chromatic aberration, an undesired effect that may degrade images in microscopes, telescopes and photographic objectives.

The phase velocity, v , of a wave in a given uniform medium is given by

$$v = \frac{c}{n}$$

Where c is the speed of light in a vacuum and n is the refractive index of the medium.

In general, the refractive index is some function of the frequency f of the light, thus $n = n(f)$, or alternatively, with respect to the wave's wavelength $n = n(\lambda)$. The wavelength dependence of a material's refractive index is usually quantified by an empirical formula, the Cauchy or Sellmeier equations.

Total reflection and the critical angle

The index of refraction is a fundamental property of a substance, and its determination may provide valuable diagnostic information about minerals and crystals. Over a period of four centuries, widely varying devices and experimental arrangements for measuring indices of refraction have been developed. These instruments are generally called refractometers, or-if the physical phenomenon of total reflection is used--also total reflectometers. These range from the precursor of Kepler's refractometer (1611) to the primitive but ingenious instrument of Wollaston (1802) to modern.

When light pass from a lower (n) medium, it refracted away from the surface normal (as shown below)

The greater obliquity of incident ray, the greater angle of refraction until the angle reached which the refracted ray is parallel to the surface (E and E') in this case the angle of refraction is 90 degree, and the angle of incident, is in this case, called critical angle.

So the critical angle is the incident angle at which the refracted angle is 90 degree (the angle between ray- 3-and surface normal ray-1) and at any angle greater than critical angle total reflection will occurs

Q1/ why mono chromatic light used for measurement of refractive indices.

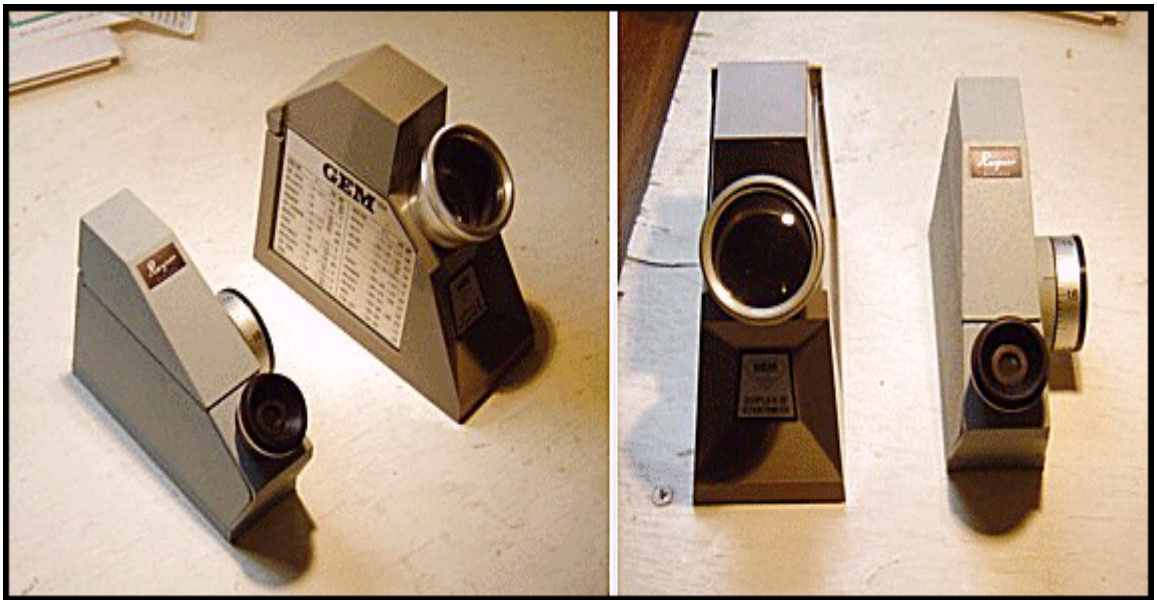
Measurement of refractive index of minerals

Refractometer

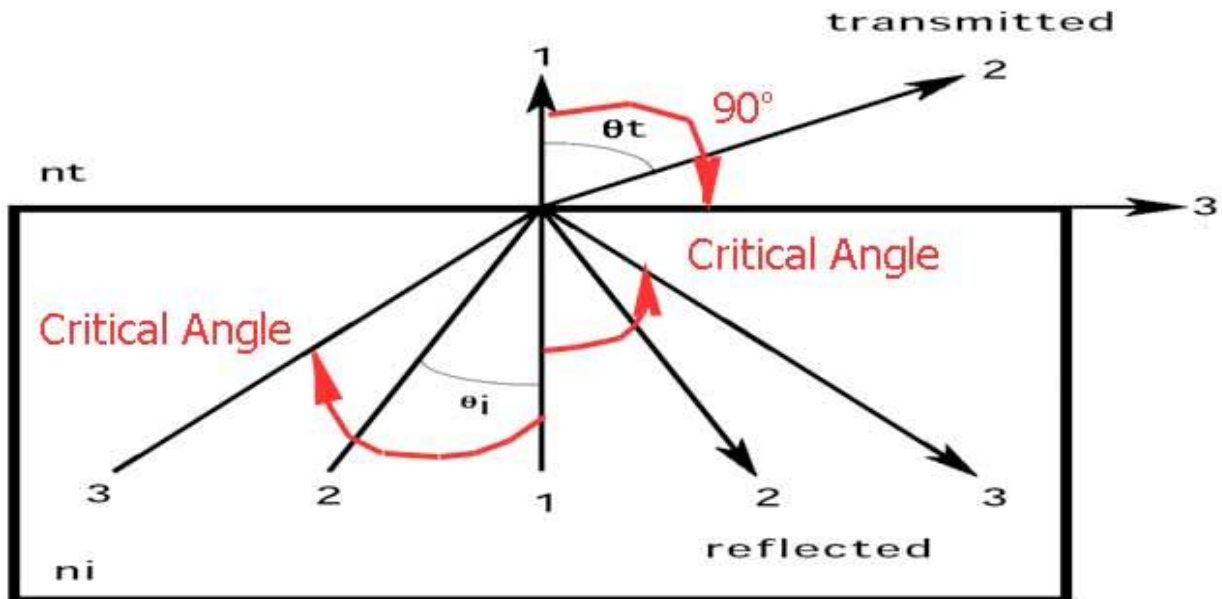
A refractometer is an absolute necessity for gem identification. It measures the refractive index of your gems. Besides the RI, a refractometer will also give you the birefringence and optic sign. When possible, it is easier to obtain the optic sign from a polariscope. However, that can't always be done, so you need the refractometer as an alternate means to determine the optic sign when necessary.

Refractometers costs in the neighborhood of \$500 to \$1000. In North America the primary source is the Gemological Institute of America. In Europe the primary supplier is Kneuss Instruments. Used refractometers occasionally come available on eBay.

Inexpensive models are now available from China for under \$200. Their reliability varies, so if you purchase one of these make sure it is from a reliable company that will exchange it. For instructions on how to check the accuracy, see Gem Lab Refractometer.



Two photos of two jeweler's refractometers as seen from different directions (see the diagram below for parts) showing light reflected at the critical angle (C.A) for mineral spinel



Ray path illustrating reflection and refraction, Rays 1, 2, 3, are incident from the lower left and each ray has reflected and refracted portion. The angle of the reflection is equal to the angle incidence (θ_i) can be found by application of the Snells Law. Ray 3 shows the case of the total reflection when $\theta_t = 90^\circ$

1- By refractometer

Finding of critical angle is a quick and easy method for determining the refractive index of minerals and liquids. The instrument used is refractometer which consists of a polished hemisphere of high refractive index glass. a crystal face or a polished surface of the mineral is placed on the equilateral plane of the hemisphere but separated from it by a film of a liquid . The liquid must has a refractive index higher than that of hemisphere slightly convergent light is directed up ward through the hemisphere and depending on the angle of incident, is either partly refracted through the unknown mineral or totally reflected back through the hemisphere. If a telescope is placed in a position to receive the reflected ray, we can observe a sharp boundary between the portion of the field intensely illuminated by the totally reflected light and the remainder of the field, when the telescope is moved so that its cross hairs are precisely on the contact, the critical angle C.A is red on the scale on the hemisphere. By knowing this angle and the index of refraction of the hemisphere (n) we can calculate the index of the mineral

(n) of the mineral = $\sin \text{critical angle} \times (n) \text{ hemisphere}$

Index of mineral = $\sin \text{critical angle} \times \text{index of hemisphere}$

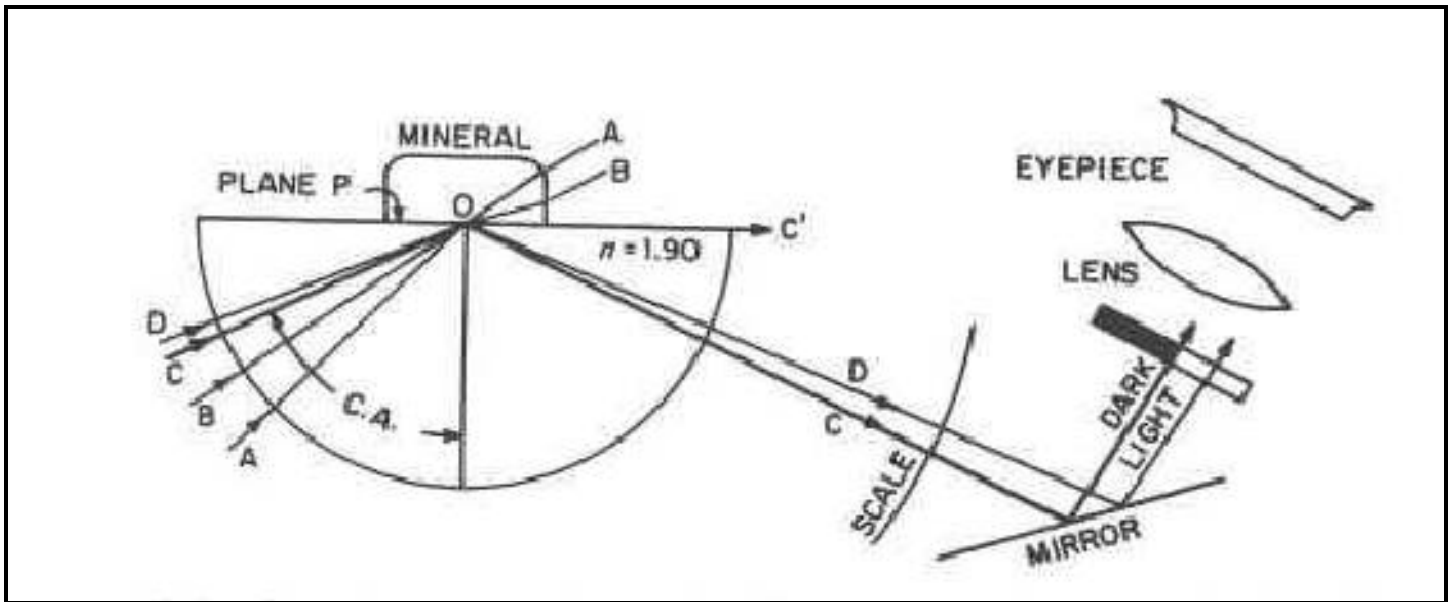
$n = N \times \text{critical angle}$

The hemisphere must be made of high index glass of known index.

$n_r/n_i = \sin i / \sin r$

Q1 / why the refractometer does made in the form of hemisphere

Q2/ how can you prove that (f) not change when light pass through high density (high n) material.



Longitudinal section through jeweler's refractometer (see the photo above) showing light reflected at the critical angle (C.A) for mineral spinel

2- By using polarizer microscope

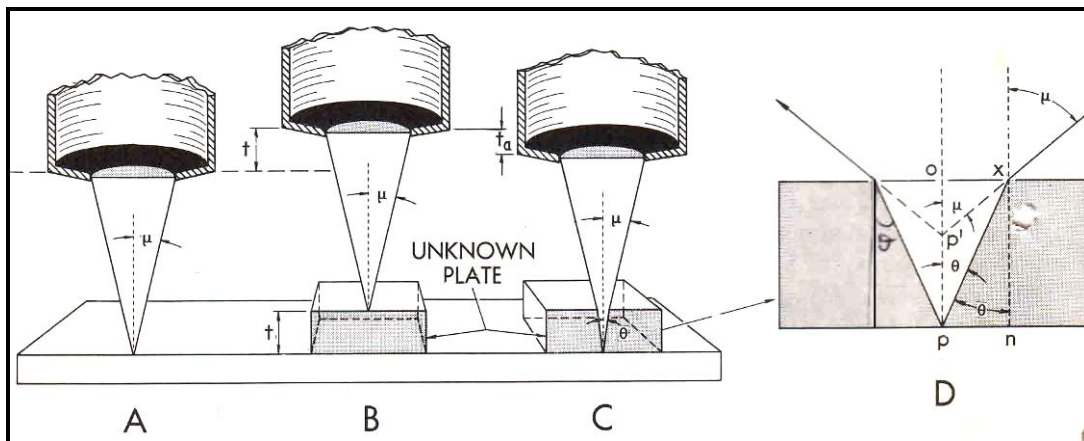
This method is called De chaulnes method which permits measurement of refractive index of transparent plates (grains) with only fair accuracy (not as accurate as refractometer method). This method depends on the value of true thickness and value of apparent thickness which can be measured by polarizing microscope. the a apparent thickness represents the apparent depth of the plates bottom surface below its top surface as viewed looking down through the plate and the apparent thickness inversely proportional to refractive index $n \propto 1/\text{app. Thickness}$

The diagram above shows the three steps in the chaulness method by microscope. They are:

1-Focus a medium- power objective (N.A 0.25) on the upper surface of a glass slide placed on the microscope stage.

2-Carefully place the plate of unknown index on this glass slide then rack upward (by using the fine-adjustment drum only) until the upper surface of the unknown plate is in sharp focus(see fig.2) , then indicate (t) which quall the difference between this second reading on the fine- adjustment drum and that obtained in step (1)

3-Now carefully focus downward through the unknown plate until the upper surface of the supporting glass slide is in sharp focus (see fig -3) and indicate apparent thickness (ta) which equals the difference between this fine-drum reading and that obtained in step 1 . Then the index of refraction of the unknown plate is $n = \text{drum difference in 2} / \text{drum difference in step 3}$



Three steps of the de Chaulness method for measuring the refractive index of unknown mineral.

The differential reading of drum obtained in step 1 and 3 are respectively proportional to t and ta , so these two values can be substituted directly in the above equation as below

$N = t/ta$ this equation can be derived from the fig (4)

$\tan u = ox/op^-$ and $\tan \theta = ox/op$ and $op^- = ta$ so $op = t$

$\tan u / \tan \theta = op/op^- = t / ta$ since rays px and xz obey Snell's law,

so $n = \sin u / \sin \theta$ for small angles the ratio of their sines approximately equals that of their tangents, so

$$n = \sin u / \sin \theta \approx \tan u / \sin \theta = t / ta$$

3-Finding refractive index by immersion methods

This method is one of the most convenient methods of measuring the refractive index of a transparent solid (mineral fragments). This is done by immersing fragments of mineral (or any substance) in a series of liquids of known refractive index. The immersion liquids used should at least span (include) the refractive index range between 1.430 and 1.740 at intervals of 0.005. Such sets of immersion liquids are obtainable commercially or can be prepared in the laboratory. This method depends on the observing the relief of the grains (fragment) in the liquids. Several grains of unknown (n) of the minerals are prepared and all put on a glass plate. Then each grain is immersed in a drop of the known liquid (known index) when the grain cannot be distinguished in the liquid, this means that the index of grain is equal to that of the liquid.

Q1/ why immersion method is more convenient than other method

The observation of mineral and liquid is done by microscope if the grains are very small but when the grains are large the observation can be done by eye or hand lens.

When a grain is immersed in liquid (or oil) there are two possibilities

- 1- The index of mineral is more than the liquid
- 2- The index of mineral is less than the liquid.

In this case how can we know the right relation between the mineral and liquid?

This is done by the Beck line method

Beck line: It is a bright line which separate substances (minerals) of different refractive index and this line can be visible under microscope

Beck line method:

Beck Line method is done under polarizing microscope for comparing the refraction index of two substances in contact with each other. The two substances may be:

- 1- Two mineral with common boundary.
- 2- A mineral and immersion oil or liquid
- 3- Mineral and Canada balsam which surrounds the mineral in thin section. If these substances have different refractive indices, they are separated by a beck line which moves toward the center of high refractive substance when this stage lowered. But moves away from the substance when the refractive index is less.

When the mineral can be seen in the oil it means that two substances have different relief.

Relief: it is visibility of outline (boundary), cleavage and surface feature of the mineral in the field of the microscope under (ppl) which depends on the index of refraction.

- 1- **Low relief:** has smooth surface and boundary cannot be seen but when analyzer used boundary can be seen. $I.R = C.B$ or $IR = OIL$

e.g: quartz and Canada balsam

- 2- **Moderate relief:** boundary and surface can be seen

$I.R$ of mineral $>$ $I.R$ of C.B

e.g.: Muscovite and Canada balsam

- 3- **High or very high relief:** the boundary and cleavage of the Mineral can be seen clearly and the surface of the mineral is Rough. e.g: olivine and C.B or olivine and nepheline.

Refractive indices and relief of some common minerals

minerals	Indices of refraction	relief
C.B	1.537	
Fluorite	$N = 1.434$	Low relief
Quartz	$N_e = 1.553$, $n_w = 1.544$	Low relief
Calcite	$N_w = 1.658$, $n_e = 1.641$	High relief (twinkling)
Apatite	$N_w = 1.646$, N_e	High
Grossularite (garnet)	$N = 1.771$	Very high relief
Sphalerite	$N = 2.369$	Very high relief
Aragonite	$N = 1.530$, $n_B = 1.681$ $N = 1.686$	High relief (twinkling)
Opal	1.40	
diamond	2.46	

Twinkling: it is changing of relief when the stage (with the mineral) is rotated under (ppl) because of changing of refractive index according to crystallographic axis this is seen clearly in calcite and aragonite.

Relief: relief is dependent on refractive index of material.

Now we are at the position to complete the immersion method of finding the refractive index of unknown mineral or substance.

When the mineral immersed in known I.R, then we must observe the boundary of the mineral if boundary can be seen, this means the I.R are not equal, then the Beck line is used to see whether I.R of the mineral is higher or lower than the oil (or liquid) if higher, then another oil is used for immersion with higher I.R until the mineral cannot be seen in the oil, this means oil I.R = Min. I.R

But if lower than that of the mineral then oil of lower I.R is used until the grain cannot be seen

I.C = interference color

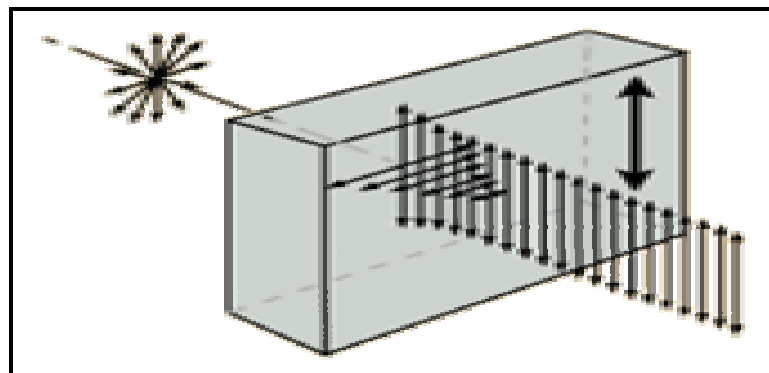
I.R = index of refraction

6- Polarization of light

One of the main properties of light is polarization. It is modification of light so that its vibration directions are restricted to a single plane or in a circular or elliptical pattern. Polarized light is used in polarized microscope for optical analysis of minerals or rocks in thin section.

1- Polarizing by absorption

Certain material such as tourmaline crystal and Polaroid sheets permit light to vibrate only in one direction (called polarization direction) and absorb light in direction at right angle to direction of polarization.



Polarization by Absorption by Polaroid sheet

Q1/ why does rough surface not make light polarized.

2- Polarization by double refraction:

Before discussion of polarization by double refraction it is necessary to discuss the isotropic and anisotropic crystal and substances.

All transparent substances can be divided into two groups:

A-Isotropic group: includes 1- noncrystalline substances such as gases, liquids, and glass these are called (amorphous materials)

2-crystals that belong to the isometric (cubic) system. In these material light moves in all directions with equal velocity and hence each isotropic substance has single refractive index (n)

A- Anisotropic substance:

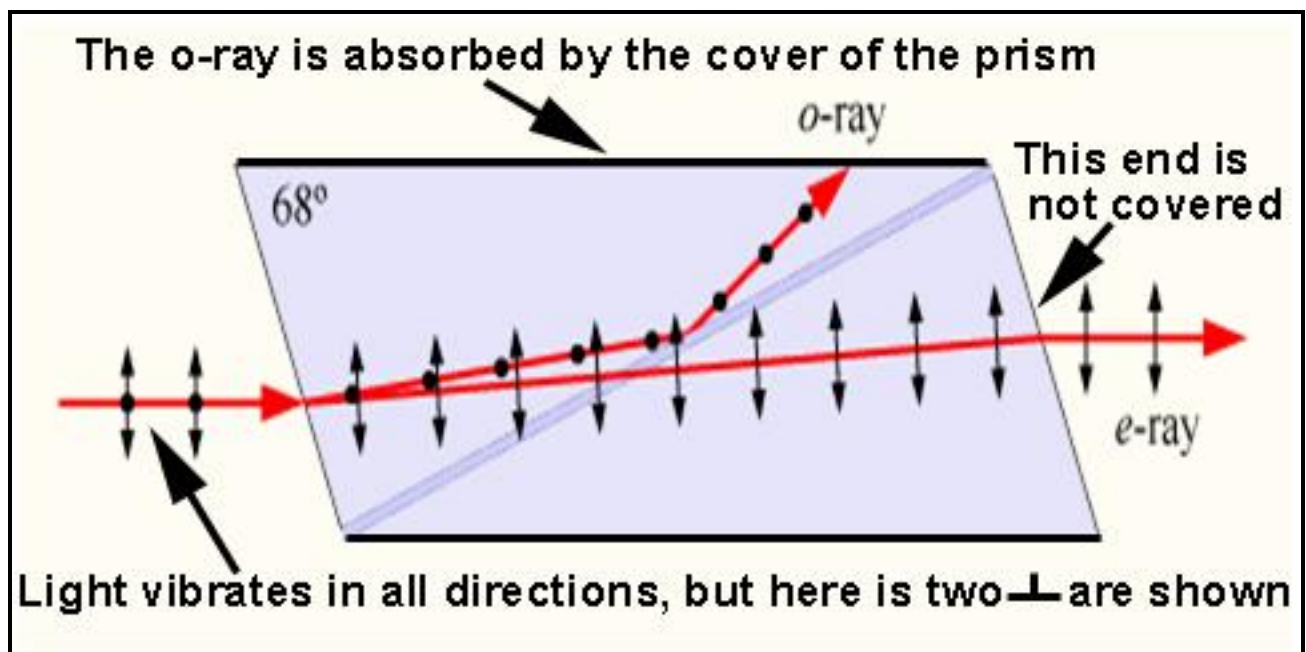
Which include all crystals, except those of isometric system, the anisotropic crystals are belonging to one of these systems:-

1- Orthorhombic 2- tetragonal, 3- hexagonal 4- trigonal 5- monoclinic and 6- triclinic system. In these crystals velocity of light varies with crystallographic direction and thus there is a range of refractive index.

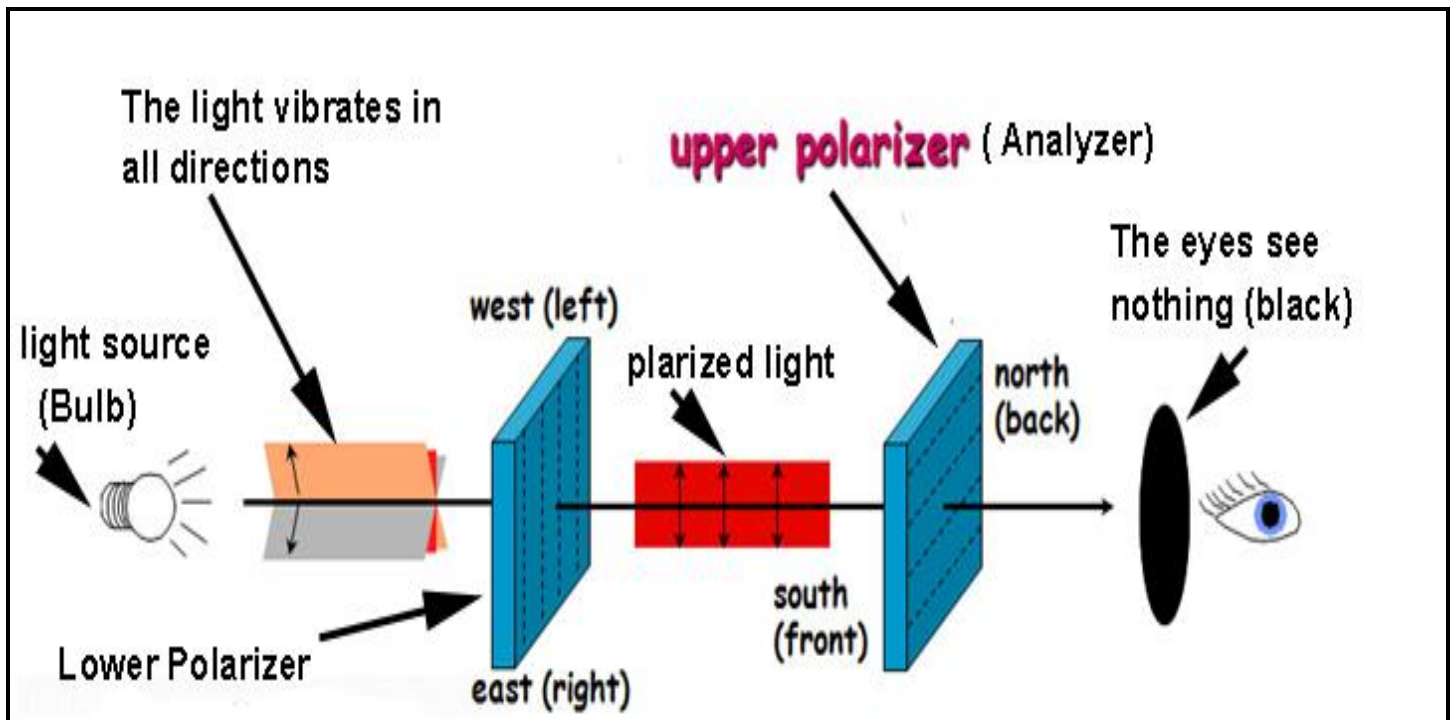
In general, light passing through anisotropic crystal is broken into two polarized rays vibrating in mutually perpendicular planes. Thus for a given orientation, a crystal has two indices of refraction, one associated with each polarized ray.

Now we are in position to discuss polarization by double refraction.

Polarization by double refraction was the method by which the first efficient polarizer is made by William Nicol, and this polarizer called Nicol prism, as shown in the diagram, which made of clear calcite crystal called Iceland spar. An elongate rhombohedral crystal cut at a certain angle and then the halves are rejoined by Canada balsam. When light enters the prism from below, it resolved into two rays: o-ray (ordinary ray) and e-ray (extraordinary ray). Because of the greater refraction of the o-ray it is totally reflected at the Canada balsam surface. The e-ray with refractive index (n) close to that of the Canada balsam continues to pass the prism and emerges as a plane polarized light (PPL). Nicol prism was the only polarizing device in the old microscope but now Polaroid sheets are used.



Nicol prism used as polarizer and Analyzer device in old microscopes (before, 1970).



3-polarization by reflection:

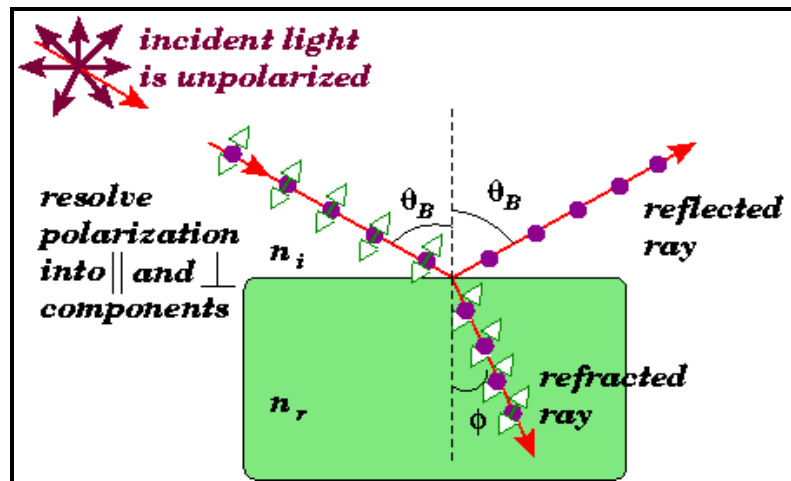
Light reflected from a smooth, non metallic surface is partially polarized with vibration direction parallel to the reflecting surface is the degree of polarization depends on the 1- angle of incident, 2- index of refraction of the reflecting surface.

The maximum polarization happens

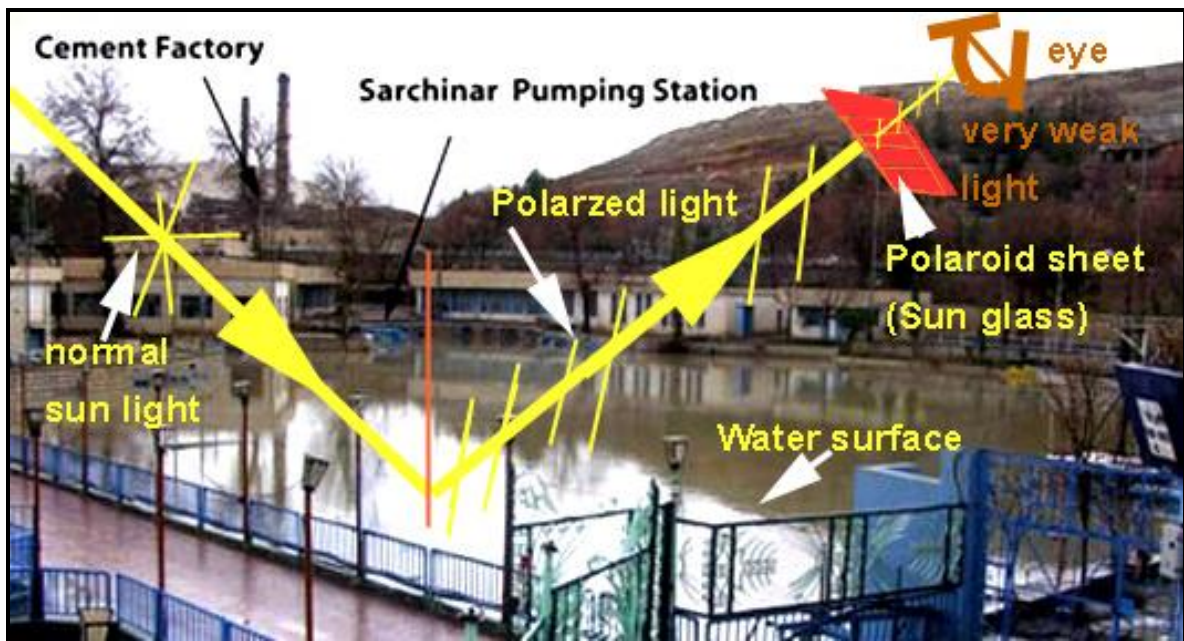
When the angle between the reflected and refracted ray is (90) degree this is called (Brewsters law). The fact that the reflected light is polarized can be easily shown by viewing it through a polarizing sheet. When the vibration direction of the sheet is parallel to the reflecting surface the light pass through the sheet with only slight reduction in intensity but when the sheet is turned 90 only small percentage of light reach the eye and all absorbed.

Brewster's angle (also known as the polarization angle)

is an angle of incidence at which light with a particular polarization is perfectly transmitted through a surface, with no reflection. When unpolarized light is incident at this angle, the light that is reflected from the surface is therefore perfectly polarized. This special angle of incidence is named after the Scottish physicist, Sir David Brewster (1781–1868).



Polarization by reflection from polished surface



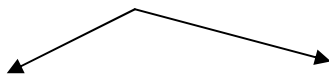
Polarization by reflection from polished surface (in this case surface of water of Sarchinar pond is used)

Q1/ how do you can know that reflected light from smooth surface is polarized.

Procedure for optical study of minerals using polarizing microscope in progressive steps

A- Under plane polarized light (PPL)

1- Transparency : the ability (by percent) of minerals to transmit light



Transparent Mineral
Under PPL and X.P

b- opaque minerals (when transparency is zero and black
e.g: hematite, pyrite

When transparency is more than zero and admit light to pass through.

e.g: Quartz, garnet, tourmaline

2- color: it is the color showed by mineral under (PPL). Some time called body color

a- Colorless (e.g : quartz , orthoclase, olivine)

b- Colored

1- Nonpleochroic { it means that mineral has body color but non pleochroic e.g:spinel green

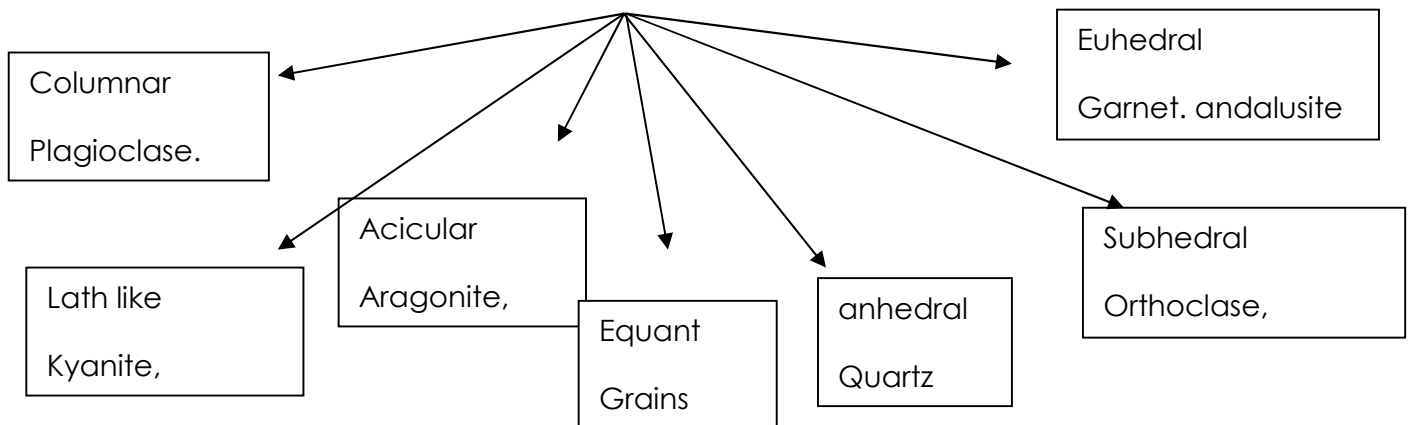
2- Pleochroic $\longrightarrow$ It means that the color of the mineral changes when the stage is rotated. e.g:

Biotite $\longrightarrow$ pleochroic from brown to pale brown

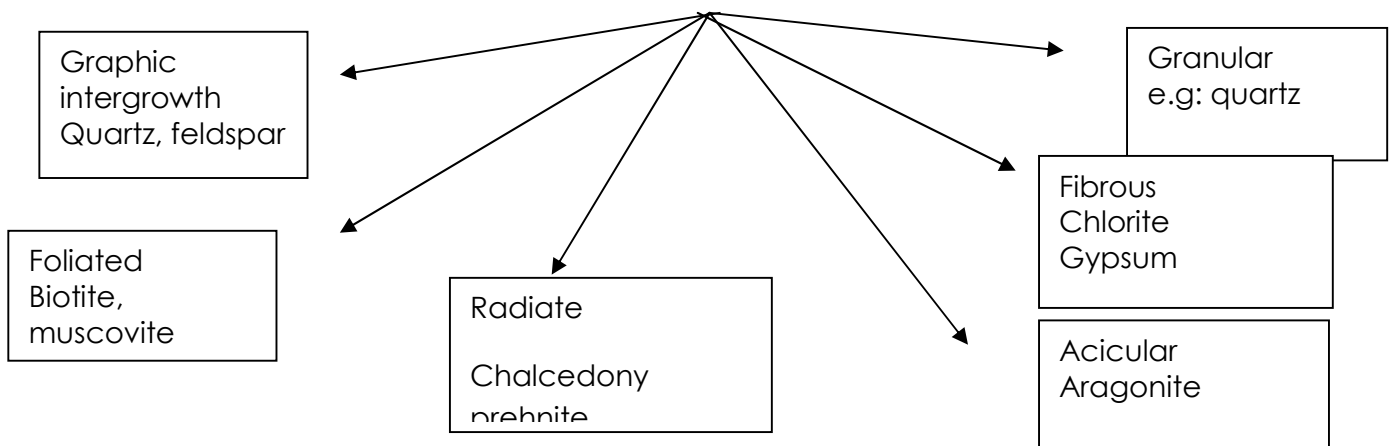
Hornblende $\longrightarrow$ pleochroic from green to colorless

3-Form (or shape)

a) Form of crystals



B-Form of crystals or grains aggregates!



C-Form of structure formed by grains and crystals

4-index of refraction (n):- it is the ratio of velocity of light in air to the velocity of light in contain medium. in thin section study ,index of refraction of minerals are compared to index of Canada balsam (C.B) or by comparing two minerals which are in contact with each other and one of the two it is index is known. The comparing is done by focusing the microscope on certain grain bounded by C.B then the stage is lowered (or the tube is raised) to see the movement of the bright line which called Becke line, when (x10)or (x25) objective is used the line can be seen better than with (x3) or (x6)

a)

$n_m < n_{C.B}$

When the stage lowered the Becke line move to out of the grain, it means that

$n_m < n_{C.B}$

b) $n_m > n_{C.B}$

When the stage lowered the B.L moves to center of the grain, it means that

$n_m > n_{C.B}$

C – $n_m = n_{C.B}$:- the grain boundary cannot be seen under polarizer because relief of the two substance are equal. To see the grain boundary use analyzer

Index C.B = 1.537

Index of quartz = 1.544

5-Relief (contrast): it is the visibility of outline (boundary) and surface of grains of minerals in the field of microscope under (ppl) which depends on the difference between the n_m and $n_{C.B}$ or between two minerals with common boundary.

a- Low relief: when the mineral has smooth surface and boundary cannot be seen. (to see use analyzer) e.g : quartz , sanidine $n_m = n_{C.B}$

b- Moderate relief : boundary and surface can be seen

e.g: muscovite, sillimanite $n_m > n_{C.B}$

C- High or very high relief: the mineral grain or (crystal) has dark boundary and rough surface e.g: olivine, garnet $n_m \gg n_{C.B}$

D-Negative relief: boundary can be seen clearly but the mineral has smooth surface. in this case the mineral seen as a hole in the surrounding mineral e.g: quartz in biolite

Quartz in calcite

Quartz in garnet

6-Surface nature:

a- Smooth surface as quartz (low relief)

b- Moderate rough as feldspar(moderate)

c- Very rough surface (high relief) as olivine garnet

How we can able to see cleavage clearly:

- 1- The illumination (light) must be lowered
- 2- The stage must be rotated because cleavage may be visible in one position of the stage and not in others this property of minerals called twinkling as seen in calcite
- 3- In some case the cleavage may be seen better if the focus is changed (to make out of focus)

8- fracture: it is random and irregular breakage of crystals and grains.

Properties of minerals under (X.P) of parallel light (now analyzer is used)

9- Anisotropism

a) Isotropic minerals: are those minerals which appear dark (black) under (X.P) and remain black when the stage is rotated. e.g: garnet ,leucite , Canada balsam also isotropic which can be identified by it is darkness under (X.P) and show no granular nature and has low relief

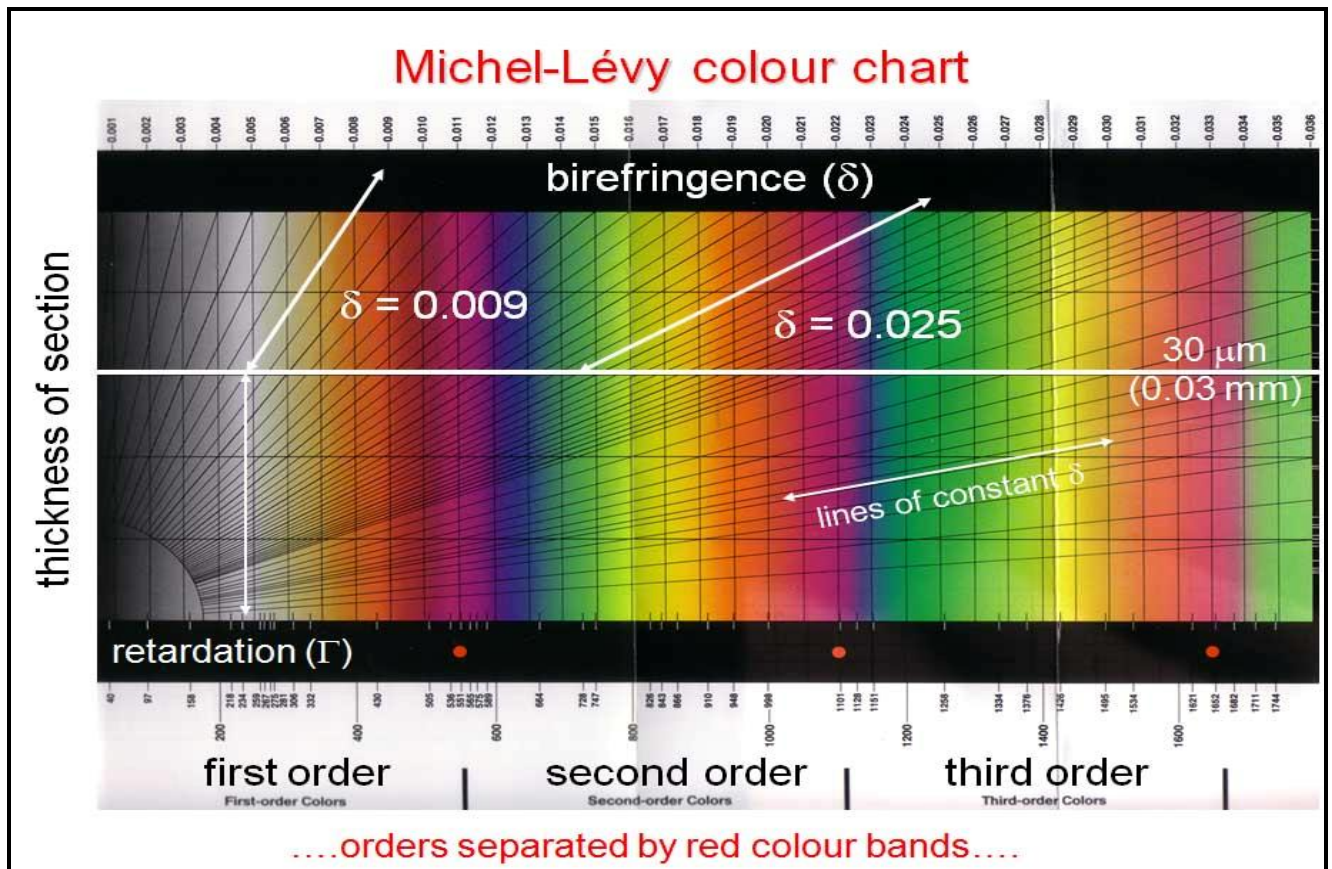
b) Anisotropic minerals: are those minerals, some of which are dark and others are bright under (X.P), and when the stage is rotated successive brightness and darkness (extinction) occurs.

10- Interference color (normal interference color)

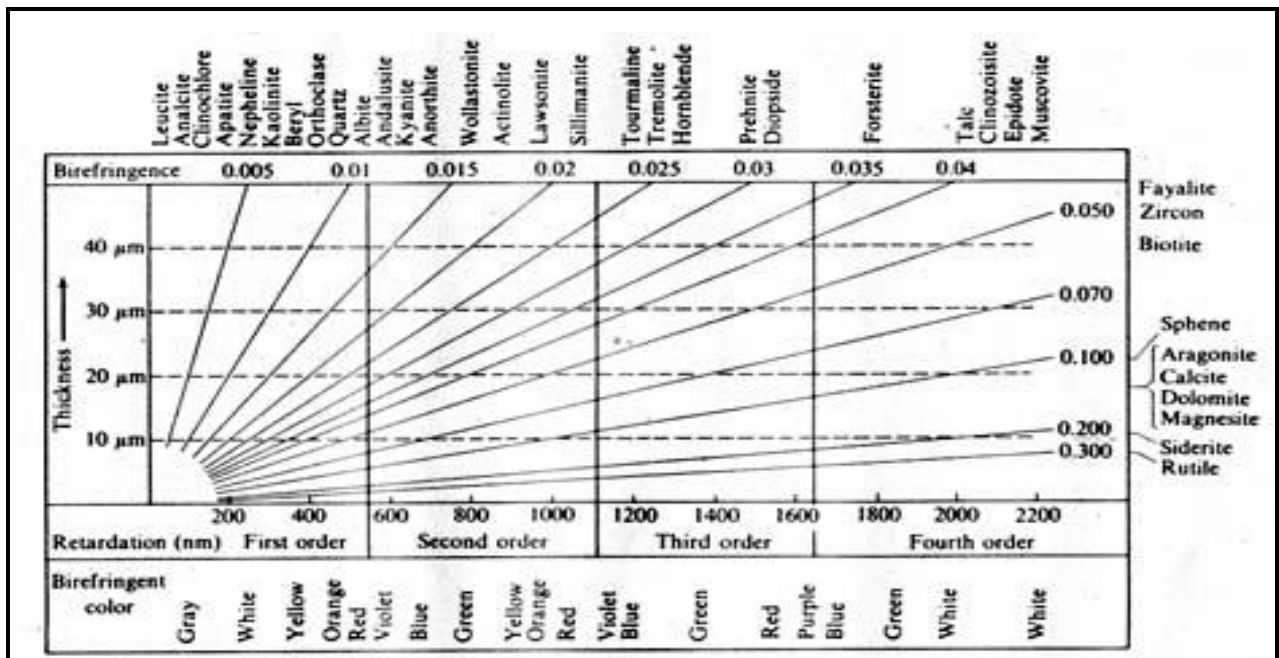
It is the color displayed by an isotropic crystals under (X.P) light, which formed by retardation of the mineral and absorption by analyzer. The type of color depend on

- | | |
|-----------------------------|-------------------------------|
| 1- Thickness of the mineral | 2- orientation of the crystal |
| 3- Nature of light used | 4- type of minerals |

The normal interference colors are divided in to several orders according to repetition of the certain colors such as: 1st order, 2nd order, 3rd order and 4th orderetc. and these order arranged according to retardation as one axis and thickness as the other axis, in the form of a chart called interference color chart on which most of the anisotropic mineral are plotted on it



Mitchel Lievy color chart shows how interference color changes with thickness and with type of mineral



Mitchel Lievy color chart shows how interference color changes with thickness and with type of mineral

Interference color chart of the transparent minerals

$n_2 - n_1$ = birefringence , therefore the retardation $\Delta = t (n_2 - n_1)$

Δ = Retardation n_2 = greatest index

T = thickness of a thin section n_1 = least index

The interference color chart is the graphical representation of equation $\Delta = t (n_2 - n_1)$ and the light used is white light. Because the maximum value of birefringence ($n_2 - n_1$) is a constant for each mineral $\Delta = t \times 0.009$ for quartz, $\Delta = t \times 0.172$ for calcite thus for each mineral there can be plotted a straight line that relates birefringence to thickness of the crystals. By showing retardation (Δ) and type of I.C and its order.

Anomalous interference color: it is abnormal production of (I.C) which do not follow the color chart or do not follow the equation $\Delta = t (n_2 - n_1)$. This type of interference colors (I.C) result from

- 1- Strong selective absorption of particular wave length during its passage through the crystal
- 2- Large variation in the value of the (ϵ and w) for different wave length of light e.g: a mineral has 200 μ retardation gives first order white I.C but for a mineral with an anomalous I.C gives other color.

Vesuvianite $\longrightarrow$ gray - green

Zoisite $\longrightarrow$ greenish blue

Melielite $\longrightarrow$ Berlin blue

Masked I.C: it is a mixture of color of mineral (body color) and i.c. In some case the color of mineral covers (masks) the I.C. e.g : staurolite has pale brown under (X.P) which is mixture of pale yellow + first order red .

Hornblende $\longrightarrow$ masked i.c. glauconite $\longrightarrow$ mask i.c

Extinction angle: it is the angle through which a crystal (grain) of an isotropic mineral must be rotated from a known cleavage direction (or known crystal face) to the position at which gives maximum extinction (darkness) under (X.P). But if a mineral grain remains in darkness for complete rotation, it means that the section is cut at right angle to optic axis.

a) Parallel extinction :

It is a type of extinction of birefringent mineral which become dark when direction of cleavages or (crystal face) is parallel to direction of polarizer or analyzer e.g: sillimanite, biolite

b) Oblique extinction : in this case the mineral become dark (extinct) when the cleavage make an angle with polarizer or analyzer

e.g: amphibole minerals, and pyroxene minerals.

Measurement of angle of extinction

1-Find a crystal which has clear cleavage or has crystal boundary.

2-Bring the cleavage direction to be parallel to polarizer vibration direction by rotating the stage. Record the reading value on the stage.

3-Now again rotate the stage until maximum darkness reached for the crystal. Then again record the value of the angle on the stage. The subtraction of the two values is equal to angle of extinction

Second reading – first reading = angle of extinction

- The stage rotated to the left and right and we must take the nearer side

c) Symmetrical extinction: this type of the extinction appears in a number of minerals with rhombic cross-section of the crystals. These crystals become dark under (X.P) when the vibration direction of polarizer are parallel to diagonal of the rhombic crystal

d) Wavy extinction: this type of extinction occurs when the crystals extinguish successively in adjacent area as the stage is rotated. This type of extinction formed because of pressure which causes the change of optic axis direction.

Sign of elongation

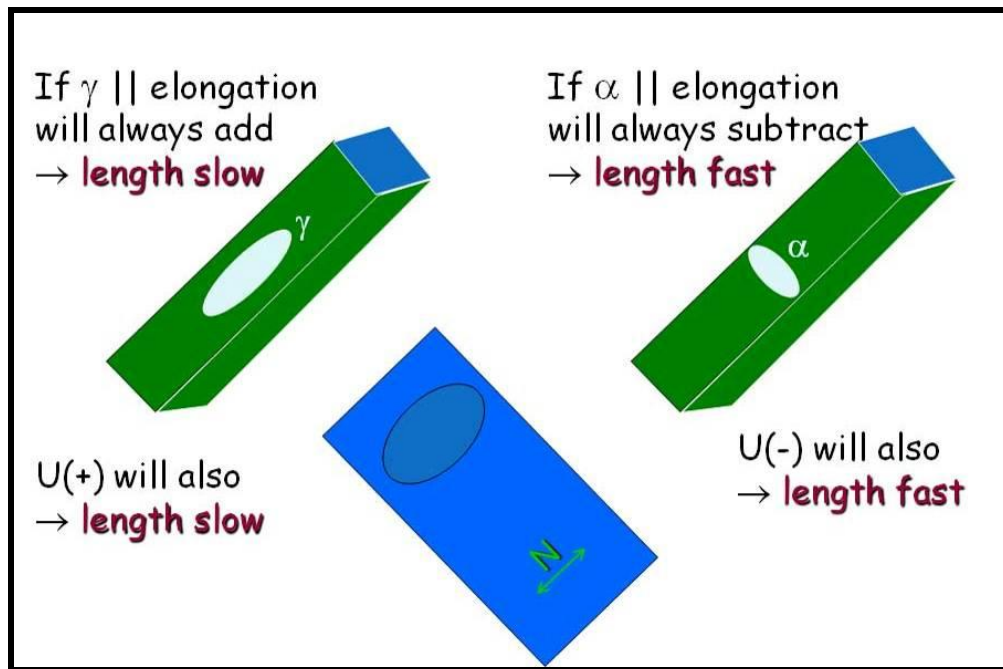
it is indication of vibration direction of elongated crystals (lath like, columnar & needle like crystals). When the vibration direction of slow ray of the crystal is parallel to long direction of crystal, the mineral has positive elongation or length – slow but when the vibration direction of slow ray lies across the crystal in the short direction the mineral has negative elongation or length – fast this properties is determined by using accessory plate called gypsum plate which marked with vibration direction of slow ray & fast ray . Finding of the sign of elongation is as following:

1- Find elongate crystal

2- Bring the crystal to 4 quadrant and align it to be parallel to direction of inserting the gypsum plate and to has maximum (I.C)

3- Insert the gypsum plate and see whether the (i.c) of the mineral increase or decrease. Because vibration direction of slow and fast ray are indicated on the gypsum plate so we can make comparison between that of the mineral and that of gypsum plate

4- When the i.c. increase it means that slow direction of gypsum plate coincide (or parallel) to that of the mineral so the mineral has length fast or negative sign of on positive sign of elongation twining : twining is recognized under (x . p) by rotating the stage shows grains made up of two or more parts united (joined) along straight line . and when the stage rotated apart extinguish while the other part shows interference color (by light position) and this is called simple twin which consist of two equal part united along straight line eg : sanidine



The figure shows the indication of the sign of elongation of crystals by gypsum plate

Lamellar twin (poly synthetic twin)

This type of twin consists of two alternate bands (lamellae). The first band is in extinction, the second will be in bright position (i.e.) and when the stage is rotated the two bands reverse in extinction. e.g: plagioclase, calcite

How we can measure the angle of extinction of lamellar twin:

By measuring of angle of extinction of this type of twin we can know the minerals of plagioclase group by plotting the value on the curve of Mitchell Levy as following:

Only nearer side is taken

1-Bring the grain that shows lamellar twin to position to be parallel to pol. Vibration direction (uniform illumination position) and record the value

2-Rotate the stage to the right until one band become totally dark (extinction position) and record the value

3-The subtraction of the two value will be right side twin extinction angle.

4-Then again bring the grain to the position to be parallel to pol. Vibration direction again.

5-Rotate the stage to the left until the other band of the twin become totally dark then record the value on the stage. The subtraction of the two values will be the angle of left side twin then the two angles divided by (2) which gives us extinction angle of plagioclase then plotted on the curve to know the mineral.

Indicatrix (which means indices indicator)

Definition: it is geometric figure that represent the refractive indices of a crystal. it is formed by drawing, from central point representing the center of the crystal, lines in all directions whose lengths represent the refractive indices for those vibration directions. indicatrix is useful for

1- Interpretation of optical phenomena

2- Remembering and predicting of these optical properties, especially for anisotropic minerals.

How indicatrix is made by using PPL light

1- Finding refractive indices of the crystal from all direction with indication of value of the angle

2- Plotting of the value of refractive indices on the graph paper with proper scale provided that the angle of plotting is at right angle to angle of measurement. and all the value represented as a straight line drawn from a common point which coincides with the center of the indicatrix. (center of crystals)

3- Connecting the end of all the lines will give us the indicatrix of the mineral

1- Isotropic indicatrix: the isotropic substance which mentioned before, their indices of refraction do not change with the vibration direction of the light. Consequently, all the vectors relating index of refraction to vibration direction is of equal length, so all isotropic indicatrix are perfect spheres:

Radius $r_1 = r_2 = r_3 = r_4 = r_5$ are equal in length

2- An isotropic indicatrix: in an isotropic media the index of refraction actually varies according to the vibration of the light in the crystal, so the indicatrix for anisotropic minerals is divided into two types;

Uniaxial and biaxial optical indicatrix.

a- Uniaxial indicatrix: Type equation here.

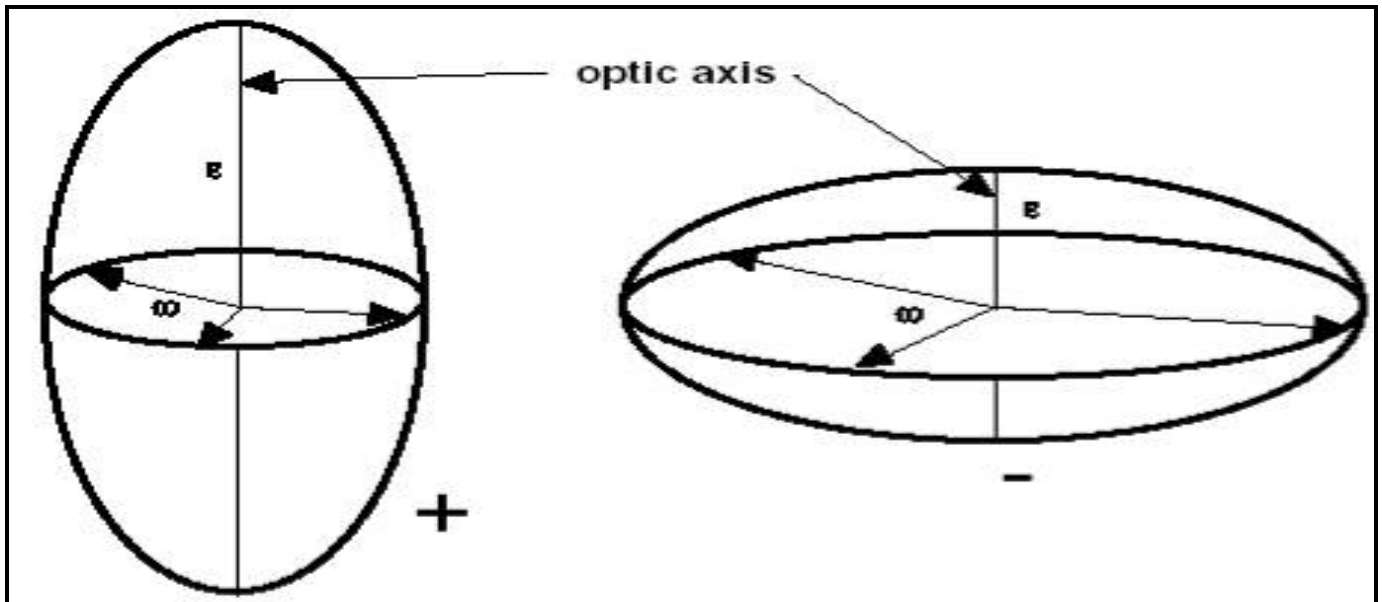
The mineral of the trigonal, hexagonal and tetragonal have the uniaxial indicatrix which is not a sphere but an ellipsoid of rotation. This means that the light vibrates parallel to optic axis has an index called (n_e) (epsilon). But for all vibration direction at 90 degree to the optic axis (coincides with c-axis) the crystal has other index which symbolized (n_w) (omega). all value of (n) between n_e and n_w are intermediate in value between the two and symbolized n_e' (epsilon dash) and its value change with the angle θ which can be calculated by this equation when

(n_e) and (n_w) are known

$$n_e' = n_w \sqrt{1 + \left(\frac{n_w^2}{n_e^2} - 1\right) \cos^2 \theta} \quad \text{Type equation here.}$$

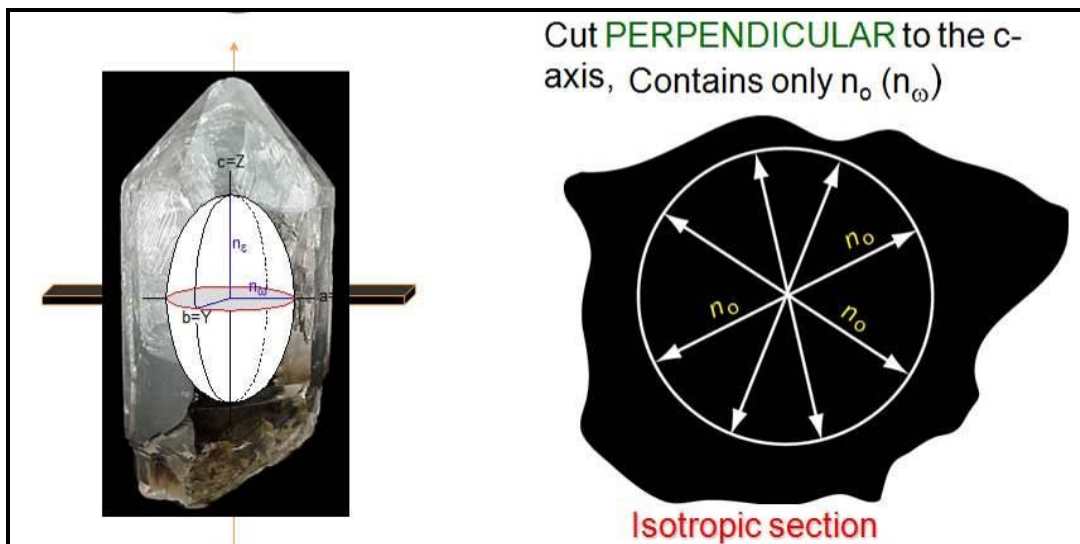
When the value of n_e is greater than n_w the crystal is positive? (uniaxial positive) $n_e - n_w = \text{positive}$ e.g: quartz

But when n_w is greater than n_e the crystal has negative sign or (uniaxial negative) $n_e - n_w = \text{negative}$ e.g: calcite optical

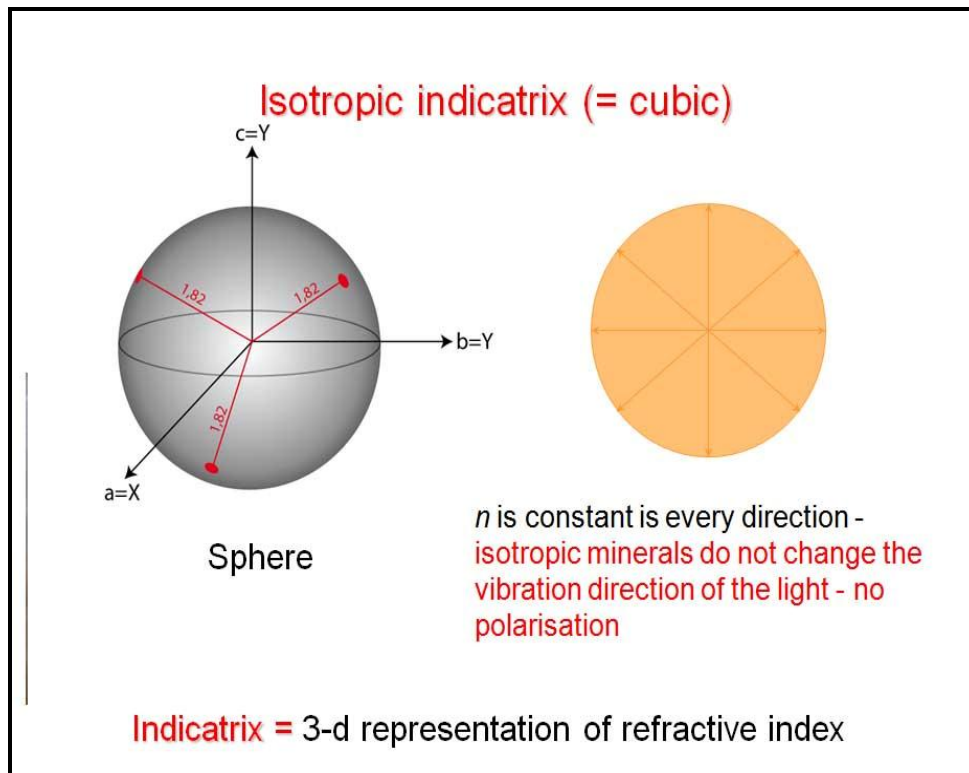


Left: Indicatrix of a positive uniaxial mineral $n_\epsilon > n_\omega$ which has only two indices (they are called Omega ω (smaller) and Epsilon ϵ (larger)). Right: Indicatrix of a negative uniaxial mineral ($n_\epsilon < n_\omega$) which has only two indices (they are called Omega ω (larger) and Epsilon ϵ (smaller)).

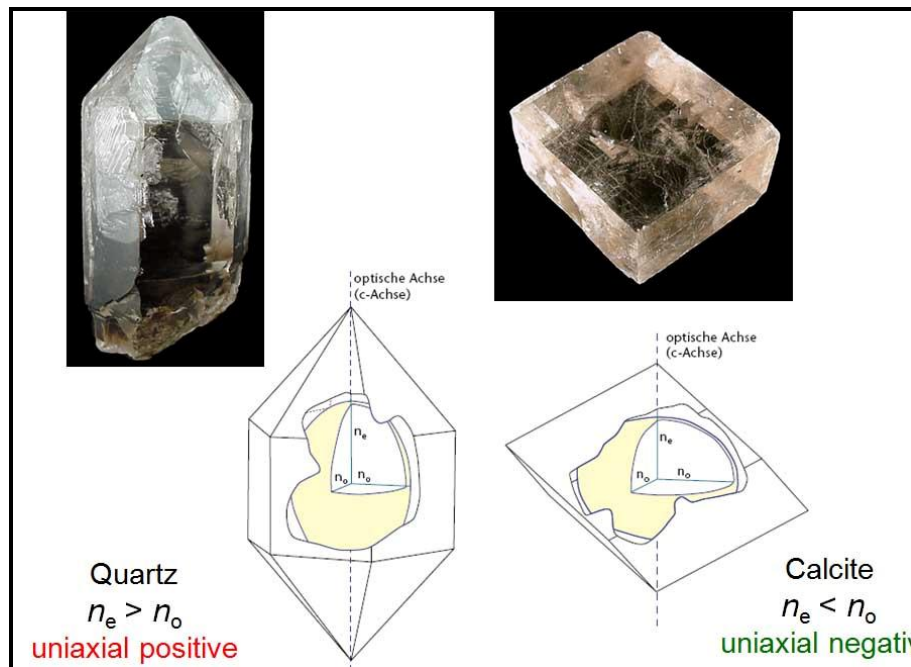
Q/ why uniaxial crystals have two indices (two axes)?



Left: A quartz crystal (optically uniaxial crystal) in which its Indicatrix is drawn inside it can be seen that it has two refractive indices. Right: optically isotropical mineral (appear dark under XP light) it can be seen that it has only one index (such as garnet or glass)

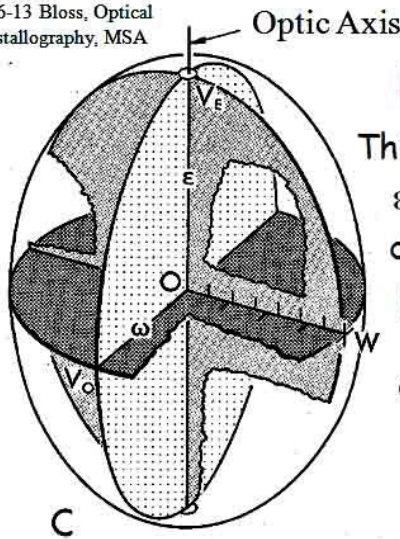


Indicatrix of isotropic mineral, is perfect sphere which means that indices don't change according to direction



Two uniaxial crystals and their indicatrix

Fig 6-13 Bloss, Optical Crystallography, MSA



Principal section:

This is essentially the same as random, but here ϵ' is really true ϵ . In this case both rays really do vibrate $\perp$ propagation & follow same path (as we have simplified the random case)

We shall consider random and principal as alike, only the value of ϵ varies.

Biaxial indicatrix:

Orthorhombic, monoclinic and triclinic crystals are called optically because they have two directions in which light travels with zero birefringence (has no double refraction) but in uniaxial crystals there is only one such direction. Light moving through a biaxial crystal (except along the optic axes) travels as two rays with mutually perpendicular vibrations. The velocities of the rays differ from each other and change with changing crystallographic direction

The vibration direction of the fast ray is X,

= = = = slowest ray is Z,

This two vibration direction are at right angle to each other. The direction perpendicular to the plane defined by X and Z is designated as Y. For biaxial crystals there are thus three indices of refraction resulting from rays vibrating in each of these principal optical direction. The numerical difference between the greatest and least refractive indices is the birefringence = $n_2 - n_1$. The following letters and symbols have been used to designate the refractive indices,

Index

direction

ray velocity

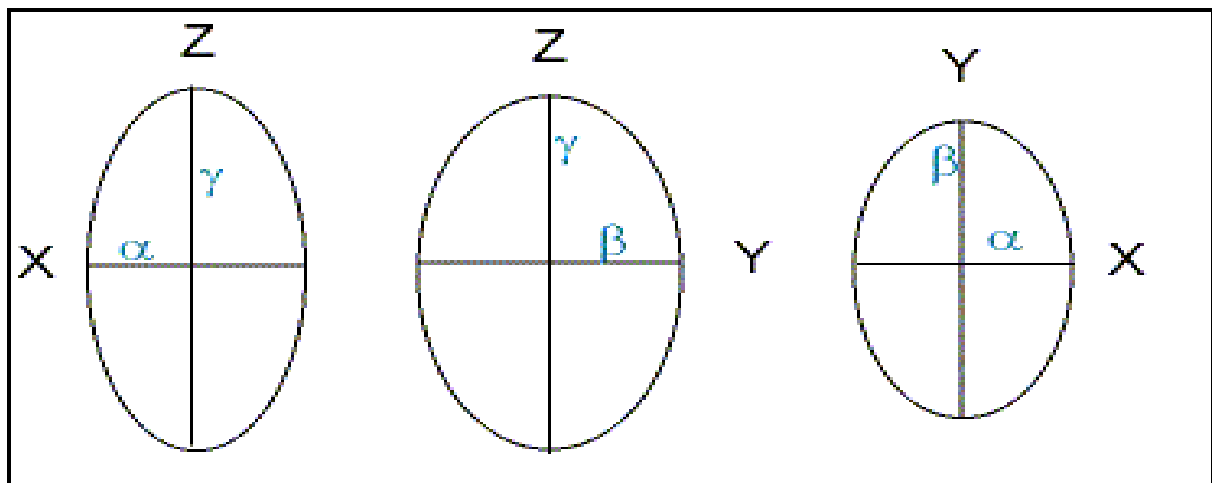
(alpha) n_α	X	highest
(Beta) n_β	Y	Intermediate
(Gama) n_γ	Z	Lowest

The biaxial indicatrix is a triaxial ellipsoid with three axes X, Y and Z are optical directions and they are mutually perpendicular. The lengths of the semiaxes are proportional to the refractive indices n_α along X, n_β along Y and n_γ along Z. The figure at right shows the three principal sections through the indicatrix, these are the planes XY, YZ, and XZ.

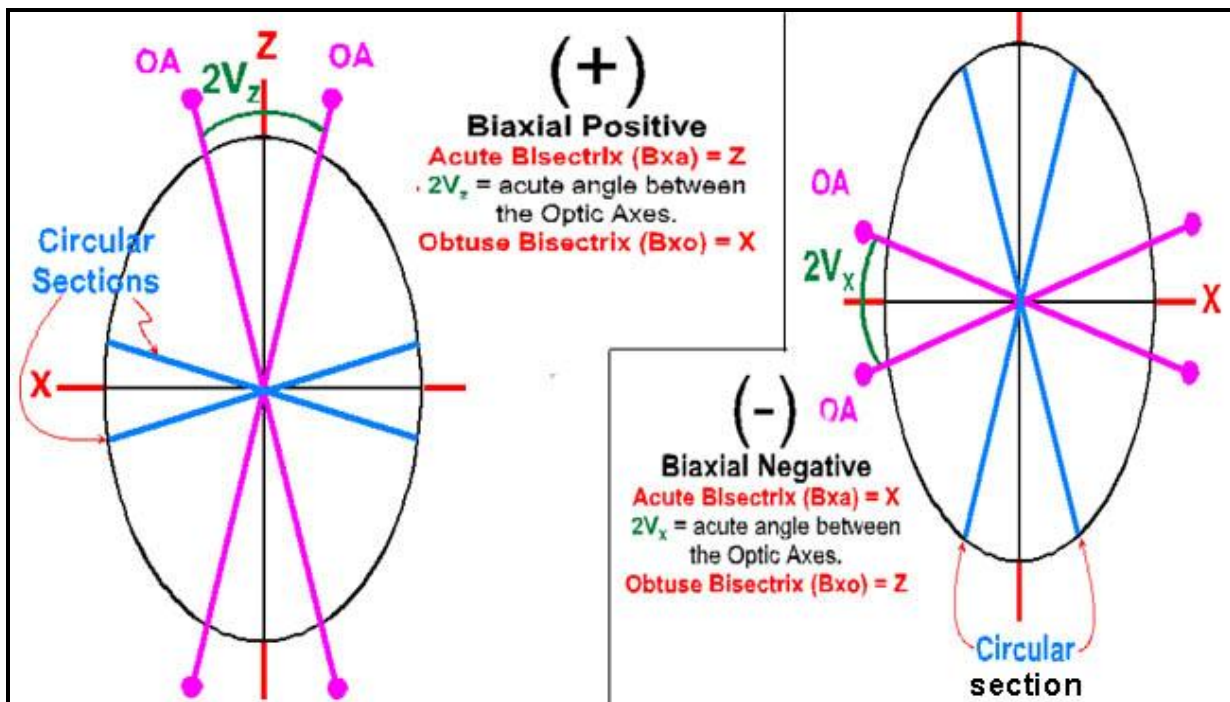
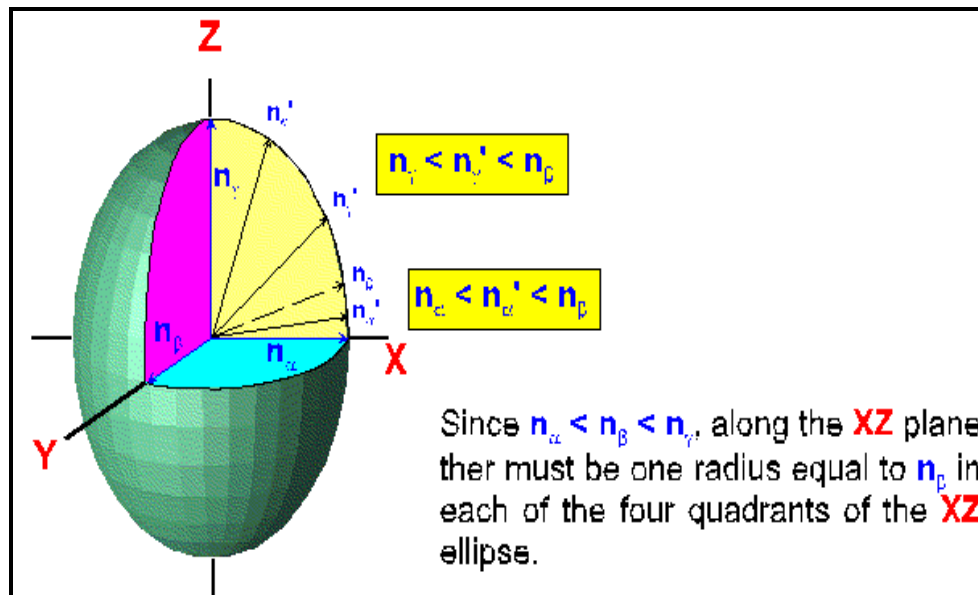
They are all ellipses and each has the length of it is semimajor and semiminor axes proportional to refractive indices as shown. The most important section is the XZ section. with it is semimajor axes proportional to n_γ and it is semiminor axis proportional to n_α , there must be points on the ellipse between these extremes where the radius is proportional to the intermediate index, n_β . With two exceptions is circular section of which S is the radius.

The two directions normal to these sections are the optic axis, and the XZ plane in which they lie is called the optic plane. The Y direction perpendicular to this plane is the optic normal. Light moving along the optic axis and vibrating in the circular sections shows no constant refractive index.

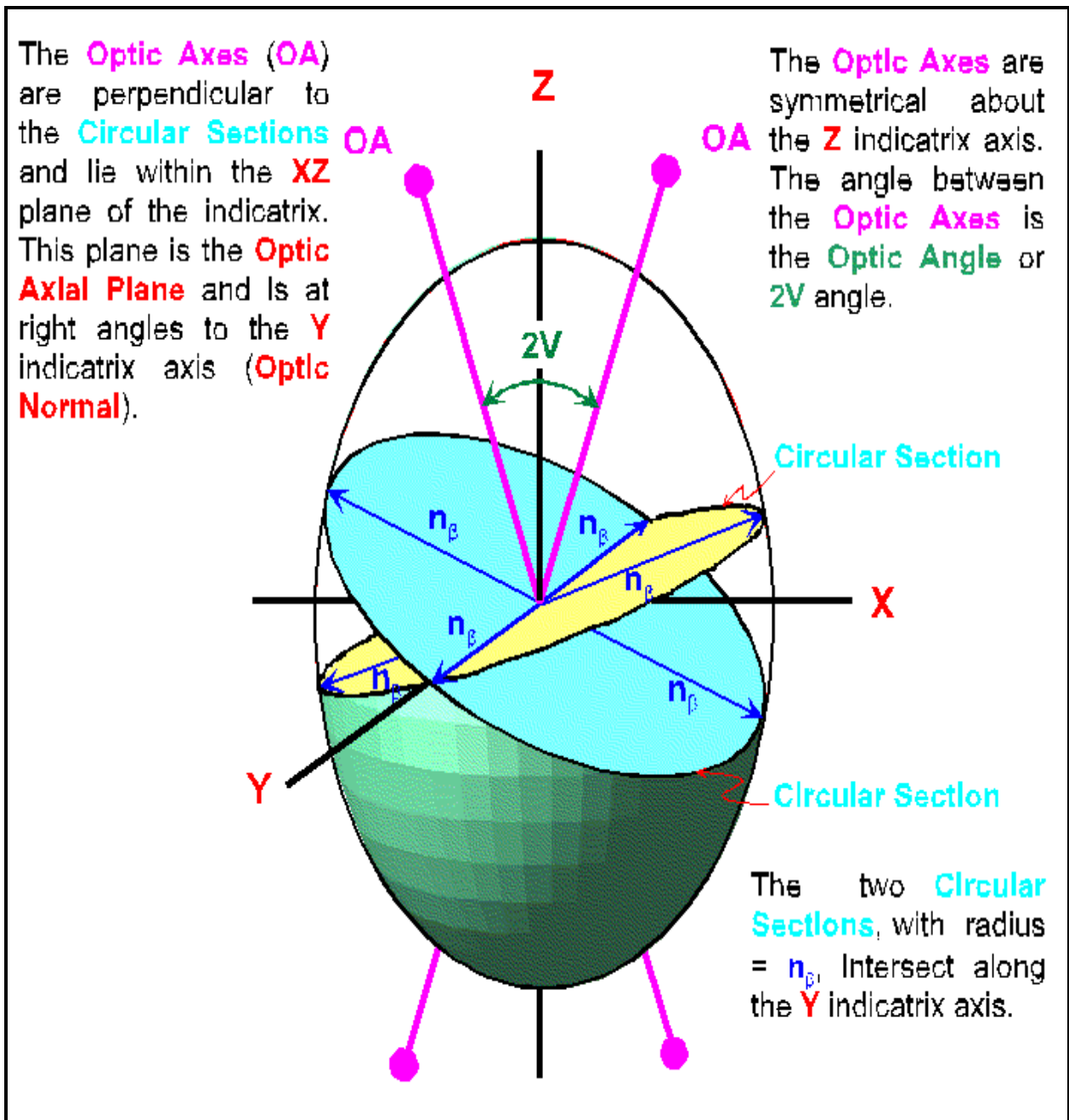
When n_β (beta) is close to n_α (alpha), the circular sections make only a small angle with the XY plane (section) and the optic axes make the same angle with the Z direction. The angle between the two optic axes, known as optic angle and is equal to $(2v)$. The optic angle is always acute and when bisected by Z, Z is acute bisectrix (Bxa), and X is obtuse bisectrix (BXO) because it bisects the obtuse angle between the optic axes when Z is the Bxa the crystal is optically positive. If n_β (beta) is closer to n_δ than to n_α (alpha) the acute angle between the optic angle between the optic axes is bisected by X and the obtuse angle bisected by Z. In this case X is acute bisectrix Bxa, and the crystal is negative when the n_β lies exactly half way between α and δ , the optic axis is 90 degree



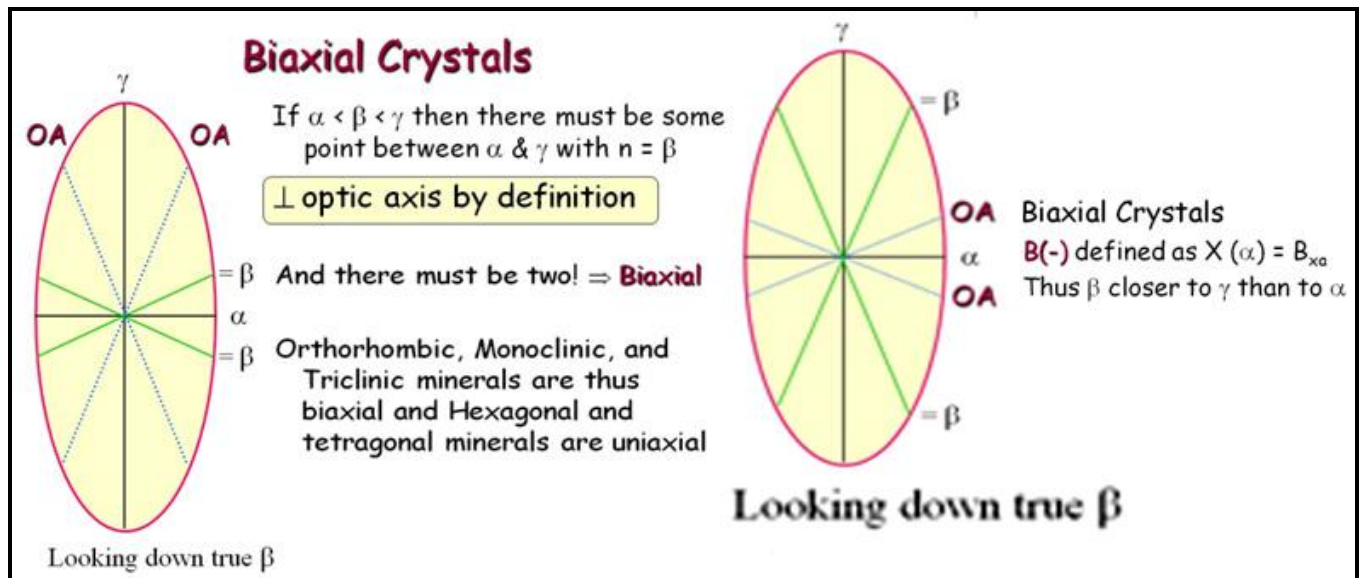
The principal sections of the biaxial indicatrix: XZ section, YZ section, YX section. The space axes (X, Y and Z) are important as references axes for learning indicatrix and optical mineralogy because they are fixed so the maximum, intermediate and minimum indices of biaxial minerals are measured along the axes). See that that n_α (alpha), n_β (beta) and n_δ (Gamma) are measured along X, Y and Z in biaxial minerals.



Different important components of the positive and negative biaxial indicatrix, each of the two circular sections (blue) are perpendicular to one of the optic axis. The two $2V$ is the smallest angle between the two optic axes in biaxial crystals. In positive indicatrix Z is BXa and X BXo while in negative is BXa is X and BXo is Z.



Different important components of the positive biaxial indicatrix, each of the two circular sections (yellow and blue) are perpendicular to one of the optic axis. The two $2V$ is the smallest angle between the two optic axes in biaxial crystals.



Same sections as shown above but we called it looking down through $n\beta$ (beta) of the biaxial indicatrix and you see the two optic axes (OA) in blue color and the trace of the circular section is in green.

INTERFERENCE OF LIGHT

Two light interfere when the following conditions are available:

- 1- Must have one source
- 2- Must have the same λ (wave length) or must be monochromatic
- 3- Must have the same line phase (retardation) must be $(\lambda, 2\lambda, 3\lambda, \text{etc.})$

Destructive interference between two waves with phase difference of

$$\frac{2n+1}{2} \lambda$$

$\frac{1}{2} \lambda, \frac{3}{2} \lambda, \frac{5}{2} \lambda, \text{etc.})$

Constructive interference

Interference of two waves with phase difference of $n\lambda$ ($1\lambda, 2\lambda, 3\lambda$)

The figure below shows interference of light from two slit illuminated by one source of light , interference occurs when the phase difference is equal to whole number of wave length

Interference color:

a) Interference color formed by reflection from a thin layer of oil floating on water. This formed by interference of two light waves reflected at opposite surfaces of the thin films of oil. In case of thin film (layer) interference occurs if phase difference is whole number (1λ , 2λ , 3λ etc) but the path difference of the light enter the layer must be $(1/2\lambda)$ or $2\text{ ray} + 3\text{ ray} = 1/2\lambda$ and the light reflected from the upper surface (ray 1) undergo reversal of phase of $1/2\lambda$ so the phase difference of ray (4) is 1λ , 2λ , 3λ etc as compared to ray (1)

Phase difference (P) = $1/2\lambda$ by reversal of ray (1) + $1/2\lambda$ by path difference = 1λ

In the case of this layer the conditions for constructive interference are available .why?

- 1- The light has one source
 - 2- The thickness make the light to be similar to mono chromatic light because permit certain wave length to interfere only depending on the thickness of the layer.
 - 3- The phase difference is the whole number (λ , 2λ , 3λ)
- Interference color formed under polarized microscope by isotropic minerals.

Condition for this type of interference color

- 1- The polars must be crossed(analyzer is used)
 - 2- The mineral crystal must be at 45 degree from extinction
 - 3- The phase difference must be $1/2\lambda$, or $(\frac{2n+1}{2}\lambda)$. $N=0, 1, 2, 3....etc.$
 - 4- When ordinary light leaves the polarizer and vibrate perpendicular to the paper (see the figure), and when strike the lower surface of the mineral section, the ray broken in to two rays. Both rays are polarized , but at right angle and the two ray travel at different velocities in the mineral along each plane ,as a result,
- When the two rays emerge on the upper surface of the mineral, one has travel farther than the other. Both continue along a straight line to the analyzer and vibrate at a right angle to each other. When they reach analyzer the two rays are resolved to a single plane as indicated in the figure. Thus the two rays come out from upper surface of the analyzer vibrate in the same plane which they are in the same phase caused by the mineral. So when the phase difference is $1/2\lambda$ interference color between the two rays and certain color can be seen which called interference color Caused by constructive interference.

Destructive interference:

Destructive interference occurs for those wave lengths which have $n\lambda$ retardation during moving through mineral grain and the resultant (R) is equal to zero but other wavelengths will undergo retardation of $1/2\lambda$ and constructive interference will occur. Retardation (Δ): for one mineral (Δ) may be changed through wide range by:

- 1- Varying the thickness (t) of the mineral
- 2- Changing orientation of the mineral section in such away as to change the indices of refraction n_1 and n_2 of the two rays emerging from the mineral. this relationship may be expressed the equation

$\Delta = t (n_2 - n_1)$ where t represent the thickness of the mineral converted to millimicrons ($1\mu = 10^{-6}$ mm)

N_2 is the greater index of refraction, and n_1 is the lesser index of refraction for a particular orientation.

This equation is similar to equation of straight lines passing through zero point (0)

Phase difference: the two rays emerging from the mineral have a phase difference equal to the retardation divided by the wave length:

$$P = \frac{\Delta}{\lambda} \text{ and } \Delta = t (n_2 - n_1)$$

$$\text{So } P = \frac{t(n_2 - n_1)}{\lambda}$$

When retardation is some whole multiple of a wavelength ($n \lambda$) the wave emerging from upper surface of the analyzer become equal and opposite in phase. The resultant is then equal to zero (see page 36). And produce dark field. But when retardation is $\frac{2n+1}{2} \lambda$ e.g: $\frac{1}{2} \lambda$, $\frac{3}{2} \lambda$, $\frac{5}{2} \lambda$...etc.

The two ray resolved in the analyzer on the same side of the line of transmission, and the resultant wave is equal to the sum of the two component (see page 36 constructive interference)

Example 1:

A mineral in thin section has birefringence of 0.009, what is the retardation

How interference color can be fined in thin section

We must find only the maximum interference color observed in the thin section. That is done by comparing between color chart and maximum interference color is characteristic of the mineral for a given thickness. we can observed maximum interference color in crystals section when cut parallel to optic axis , and the section parallel to optic axis is always dark under (X.P) because acts as isotropic minerals.

This figure shows change of i.c according to direction of section (all can be seen in one slide) when ($t = 0.035$)

Finding order of interference colors of a mineral plate

A plate (section) of mineral under the microscope behaves to light as an imperfect convex lens because usually thicker in the central part and thinner at the margins it is thus wedge...shaped in an irregular way, from the boundary (margins) it is thin, and thicker at the center. This type of grain is similar to quartz –wedge.

So we can see low order of i.c. at the boundary but toward the center we can see high order of I.C.

So if we can recognize order of one color in the mineral other colors can be recognized because there is always gradational contact between colors of order .and when the variation of thickness is high (as seen at right side of the figure) colors bands are formed because separation of colors is not perfect. This can be see when high magnification is used (X10, X16, X25) as wedge angle is here greater than in quartz...wedge the bands are extremely close together and mostly some dark color bands only can be seen these are the red- blue regions' in the quartz-wedges color. If only one of such dark band be seen on a plate the colors in wards (center) in the mineral belong to the 2nd order, if two exist the color at the thickest part belong to the 3rd order, and so on.

Thus, any interference color shown by any individual mineral plate (i.e, section or grain) can readily be recognized it is order by comparing with quartz-wedge scale or by comparison with interference-color chart

How interference colors change with thickness

The interference color of the same mineral changes when the thickness change because retardation change with change in thickness (t), when (t) increase

Also retardation increase so interference color change toward higher orders. The best thing to illustrate this interference color change is quartz-wedge which is an elongate wedge of clear quartz cut parallel to optic axis and fixed in a holder this quartz wedge , if gradually inserted, thin end first , in to the accessory slot, produces increasingly higher retardation as it is thicker portions successively move in to the light path

1- Here interference color caused by white light when passed through quartz-wedge

2- Here i.c. caused by monochromatic light only dark bands and one type of color formed.

1 st order	2 nd order	3 rd order	4 th order
Blue-gray	Violet-blue	Blue-green	Pink
White	Blue-green	Green	Pale-green
Pale yellow	Green	Yellow	Pale green
Orange	Yellow	Orange	pale-orange
red	red	red	pale-orange

△
100
500
1000
1500
2000

Change of interference color with change of type of light

When monochromatic light used in polarizer microscope, only one color can be seen. for example if muscovite seen under (X.P) and green color (550mu) is used for illumination only we can see green color for some grain but other grains are dark. When quartz-wedge is used instead of thin section, in this case bright bands of green color and dark bands are formed (see point (2) p.39). The bright bands are corresponding to the retardation of $\frac{2n+1}{2} \lambda$ but the dark bands are corresponding to retardation of $(n \lambda)$. The bright bands are only containing green color.

Accessory plates and wedges

Three accessories are used in optical mineralogy they are

1- Quartz wedge (discussed previously in page 39)

2- First –order red or gypsum plate

3- A quarter wave mica plate. These accessories are called comparators which mean that they are used for comparing between known interference color and unknown ones, and sometimes called compensators, because they compensate their retardation by means of change in interference color

of the mineral. Each accessory is designed to fit in to the accessory slot of microscope that intercept and transmit all light rays.

Like all anisotropic plates, each of these accessories has two mutually perpendicular vibration directions which called privileged direction. One of the two corresponds to the slower ray or Z-direction (or larger index n_δ) but the other corresponds to the faster ray or X-direction (or smaller index n_α)

These two directions are indicated on the plate, the X-vibration direction is along the length of the plates, light waves that vibrate parallel to Z direction while passing through the accessory plate travel move slowly than do those that vibrate parallel to X-direction during their transmission, so after emergence from the accessory, the slow wave is retarded with respect to the fast wave.

The gypsum plate or (first order red) is of constant thickness throughout. It is birefringence ($n_2 - n_1$) and thickness are such that it produce a retardation (Δ) of 550 μ . Consider two mutually perpendicular waves which are at phase. But after insertion of gypsum plate the wave that vibrates parallel to the Z-direction of the plate undergo retardation of 550 μ during its passage through the plate. And when reach analyzer 1st order red i.c is can be seen.

After passing through the plate they are no longer in phase and the one which vibrate to z-direction longer will be 550 μ behind the fast ray which vibrate parallel to x-direction of the gypsum plate.

The quarter-wave mica plate is a thin plate of sufficient thicken and birefringence ($n_2 - n_1$) to produce a retardation (Δ) of about 150 μ (which equal one quarter of the wavelength of sodium lump.590

The works of accessory are as following according to increase or decrease of retardation of the mineral plate (section):

Addition

Suppose that an isotropic crystal viewed at 45 degree off extinction between cross polars, shows first order gray i.c. ($\Delta = 100\mu$). Insertion of the gypsum plate so that its Z direction is parallel to that of the crystal changes the observed retardation color (i.c) to 2nd – order blue ($\Delta = 650\mu$). When insertion of an accessory increases the order of interference color by a value comparable to the retardation of the accessory, the process is called addition of interference color. The explanation as follows:

After emergence from the crystal, the wave that had vibrated parallel to z-direction of the mineral is 100 μ behind that had vibrated parallel to x-direction of the mineral. On entering the gypsum plate, this already retarded wave, since it vibrates parallel to z-direction of gypsum so it retarded an additional 550 μ , finally delayed 650 μ behind the fast ray. If viewed between crossed polars an interference color corresponding to 650 μ (that is, second-order blue) is observed.

Subtraction : assume the previous crystal to has been rotated 90 degree so that its X and Z direction have exchanged positions the retarded wave that vibrated within the crystal parallel to Z of the crystal (slow direction) would be as before 100 μ behind the fast wave up on emergence from the crystal . now when it enters the gypsum plate, this formerly slow wave vibrates parallel to the fast

direction but the formerly fast wave vibrate parallel to the slow direction of gypsum plate, consequently, although the fast ray (white wave) fig (2) was 100 μ a head prior to entering the gypsum plate, the dark wave slow ray gained 550 μ to overtake it while traveling through the gypsum plate. Thus on emergence from the gypsum plate, the black wave is a head by 450 μ (550 μ – 100 μ). The refraction color corresponding to 450 μ (1st order orange) can be seen. Such process produced because the fast wave in the crystal becomes the slow wave in the gypsum plate, is called subtraction, the resultant retardation equals the difference between the individual retardation values of the two plates involved.

General rules for addition and subtraction:

Addition occurs when the Z- direction ($n\delta$ – direction) of the crystal and that of the compensator (accessory) plate most nearly coincide. Subtraction occurs when the Z- direction (δ -direction) of the crystal and that of the compensator are at right angles. We can state this conversely: if addition occurs, then Z of the crystal and of the compensator must be parallel or nearly parallel. If subtraction occurs, they must be perpendicular to each other or nearly so.

If, after insertion of first order red plate or quarter – wave plate interference colors of higher order are observed to displace those of lower order, addition has occurred.

If, lower order colors displace those of higher order, subtraction has occurred.

Uses of accessory plates

The gypsum plate is useful when used with minerals with high order of interference color gypsum plate used for the following:

- 1- For finding sign of elongation
- 2- For finding optic sign of uniaxial and biaxial minerals
- 3- For finding order of interference color.

But mica plate used when the minerals have low order of interference color. (And have effect of crystal sections on behavior of polarized light and ordinary light)

Here we study the effect of crystal sections on behavior of polarized light and ordinary light, especially when the mineral sections rotated from one extinction position to another.

As a rule: each section of anisotropic minerals has two certain direction of vibration which permits the light to pass through.

But each mineral grains and crystals has more than two of these vibration directions.

Properties of these two directions in crystal section

- 1- They are perpendicular to each other
- 2- They are fixed according to crystallographic axis and optic axes.
- 3- These two directions are called privileged vibration direction or ease vibration direction
- 4- When polarized light strike this two direction obliquely the polarized light resolved in to the two privileged vibration direction , this process called double refraction
- 5- One of the components is slow ray and its vibration direction called Z- in biaxial crystals. The other component is fast ray and its vibration direction called X

To explain the five points above, effect of quartz crystal on the polarized light is shown below (quartz crystals are anhedral in igneous and metamorphic rocks but may be euhedral in sedimentary rocks) quartz is uniaxial (optically)

The figures on page 44, figure no .1 has two privileged directions one parallel to length of the crystal e-ray direction (n_e) the other is at right angle to the length of crystal which coincide with O-ray direction or (n_w) index, when polarized light strikes the crystal from below perpendicularly, it passes through the crystal without double refraction as e-ray and in this case the crystal is at parallel extinction.

Figure (2) shows the crystal at extinction and the polarized light passes through the crystal as O-ray (w) = fast ray

But in the figure no. (3) Both e-ray & o-ray pass through the crystal because they strike the two privileged directions obliquely and so resolve into e-ray and o-ray here we can see interference colour

Calcite is another example: which is uniaxial (optically)

Orthoscopic and conoscopic study of minerals by observation of interference effects

Definition of orthoscopic study of minerals:

It is using of polarizing microscope, for studying minerals, in which light transmitted by the crystal (or thin section) is parallel to the microscope axis.

All the properties of the mineral studied previously are done by using parallel polarized light (orthoscopic study)

This type of arrangement of microscope is regarded as normal arrangement in which polarizer and analyzer are used.

Conoscopic study of minerals:

It is using of polarizing microscope, for studying minerals, in which light transmitted by the crystal section is condensed to pass through the minerals as a cone of light this is done by condenser lens (as seen in the figure) which is located below the stage.

In addition to 1- condenser lens, 2- Bertrand lens must be used. 3- High-power objectives (X 40, X25) must be used.

Orthoscopic study	Conoscopic study
1- The mineral illuminated by bundle of parallel rays	1- Illuminated by cone of rays only the central ray normally incident the mineral.
2- All the rays travel along the same crystallographic direction	1- Travel along different crystallographic direction.
3- Polarizer & analyzer are used	2- In addition to polarizer & analyzer, Bertrand lens are used.
4- Higher power & low power objectives are used	3- Only high power objective is used
5- Used for study of I.C, extinction and sign of elongation and twinning	4- Used for study of 1- figure & optic sign

Convergent light = light in form of cone

The conosopic arrangement is used for studying interference figure:

It is figure that is displayed by a birefringent crystals (an isotropic crystals) under (X.P) when convergent light, bertland lens, condenser lens and (X 40, X25) objective are used. It is combination of the isogyre and isochromatic curves which used for distinguish 1- uniaxial from biaxial crystals and to 2- determine optical sign. 3- Type of section or optic analysis

Interference figures of minerals

They are seen under XP and consist Black cross of isogyres, Circular isochromes (Middle of isogyres called melatope), Isochromes increase in order of color outward

Definition of isogyre:

It is a block part of an interference figure which is produced by extinction and indicates the area of parallel vibration direction of the rays to direction of polarizer and analyzer

1- Uniaxial interference figure: it is consist of two arm crossing at the intersection of the cross hairs with concentric color rings.

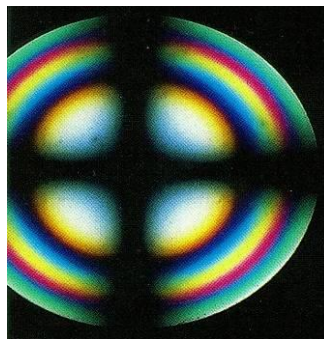


Figure consist of isogyres and isochromes, Isochromes: patterns of interference colors
Isogyres: dark bands (extinction). Nature of interference figure and patterns as stage rotated determines optical property. Types of figures controlled by cut of the grain

Flash figure

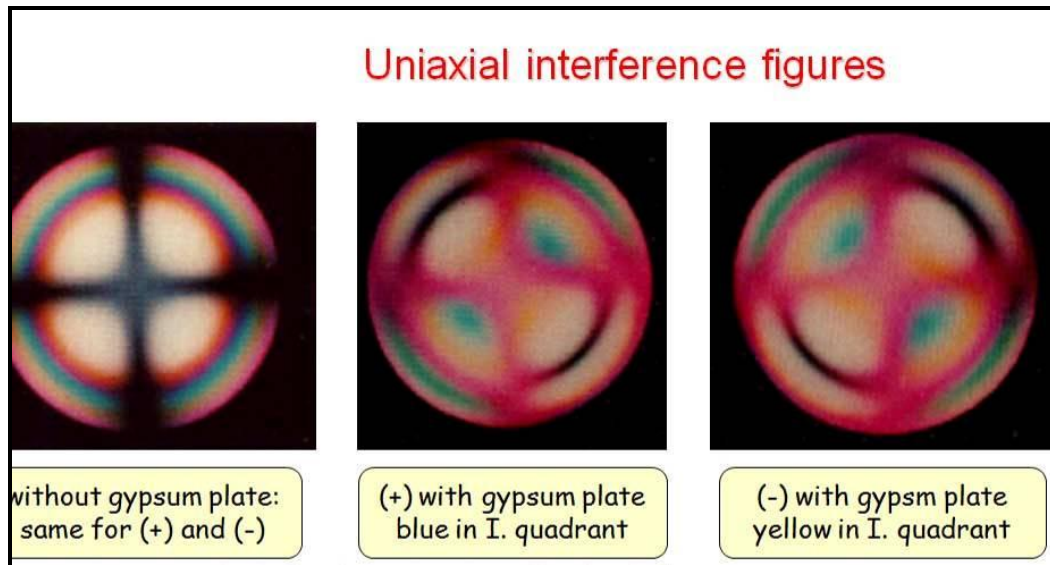
it is an interference figure which obtained from a sections parallel to optic axis in uniaxial crystals and obtained from sections perpendicular to optic normal ?(a line normal to optic plane) in biaxial crystals.

This figure consist of poorly defined black cross that almost completely fills the field of view, but with small rotation of the stage causes the cross to break up in to two hyperbolas that rapidly leave the field of view.

Centered uniaxial interference figure

This type of I.F is formed when the section is normal to optic axis and consist of two intersecting black bars (arms) which are forming a cross. The cross is concentric with series circles of

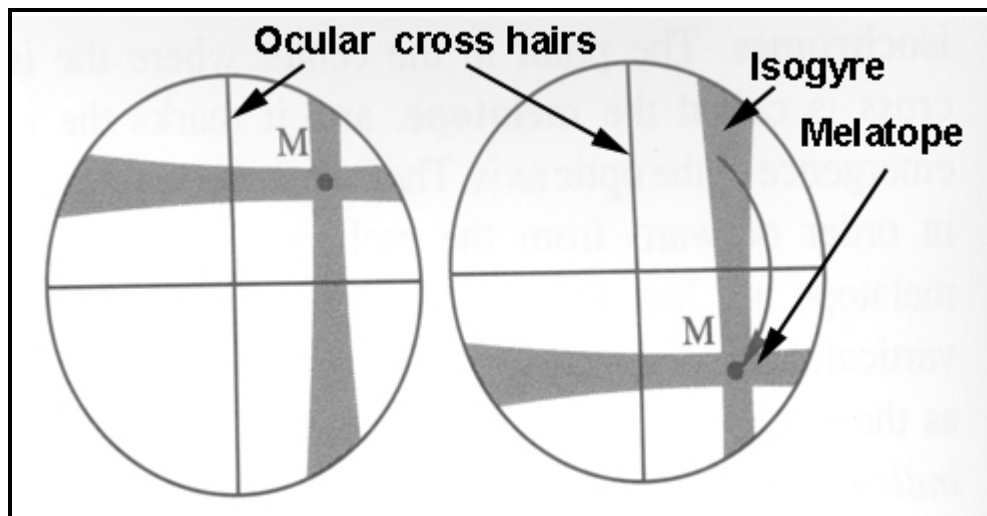
interference colors, the inner circles represent lower order colors but outer circles represent higher order colors.



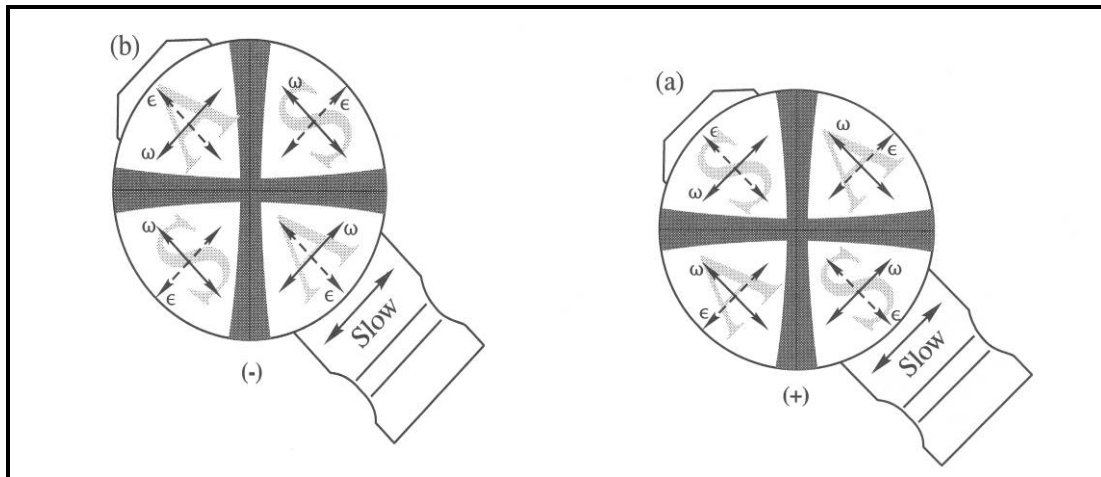
Positive and negative centered uniaxial interference, they Form when optic axis perpendicular to stage

Off centered interference figures

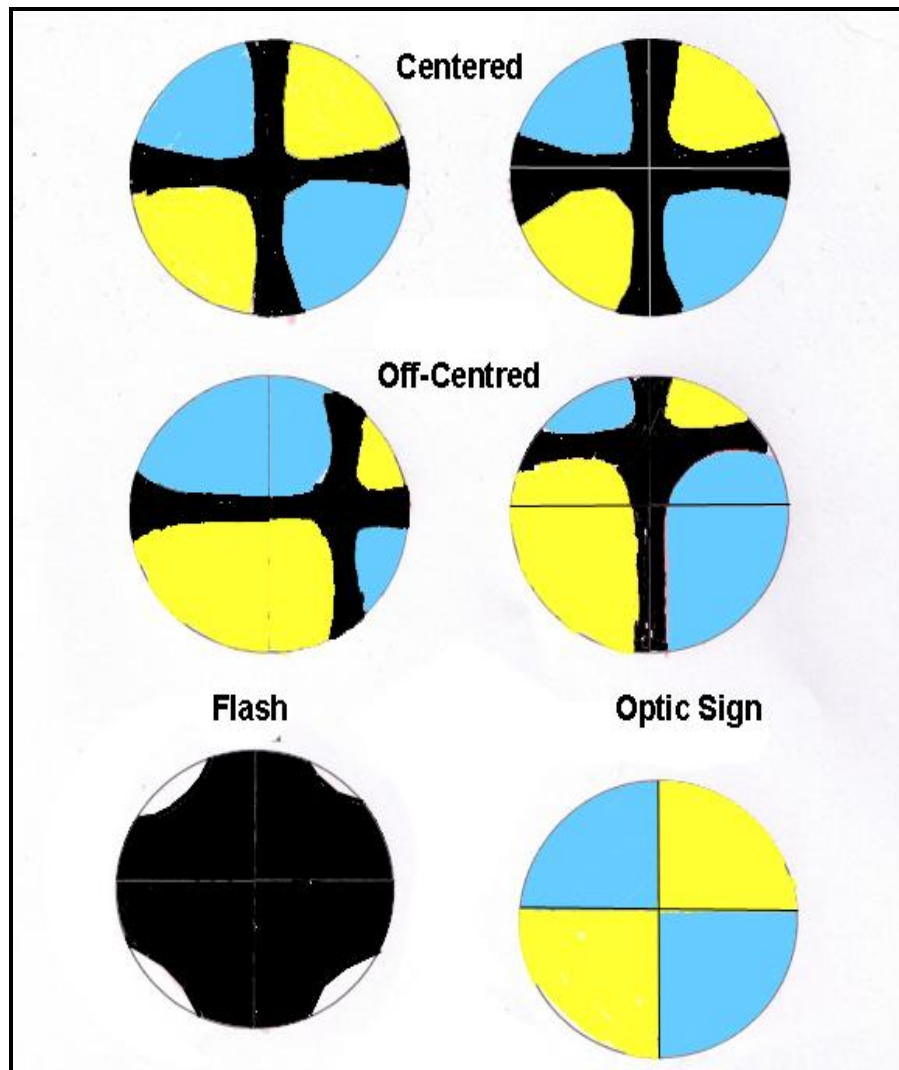
These figures are produced when the direction of section is no longer perpendicular to optic axis, it consist only of one arm, with concentric isochrome arcs. These color rings are produced by equal retardation when the light passes through the crystal obliquely in all direction as a cone of light.



Off-center (Optic Axis) OA, melatope (M) in field of view and inside field of view



Coincidence of the slow ray of both mineral and gypsum plate cause addition and Subtraction of color Increase and decrease of retardation)



Different interference figure of negative uniaxial crystal when gypsum is used, the flush figure cannot be used for determination of optic sign

Biaxial interference figure (Or Optic Axis Figure)

Biaxial interference figures are obtained and observed on a crystal plate when has been cut normal to acute bisectrix (BXa). When the trace of optic plane is parallel or normal to polarizer direction, it gives a figure resembles the uniaxial interference figure, but one of the arms (bars) thicker than the other, the thicker indicate the plane containing the acute bisectrix (BXa) and the optic normal.

The thinner one indicate the trace of optic plane and the two thinnest point (vertices) of the arm indicate emergence point of the two optic axis (melatopes), and the isochromatic curves(rings) have oval shape in biaxial I.F, the separation of the two melatopes indicate the value of $2v$.

When the stage rotated 45 degree to either side (left or right), the I.F at the left changes it is forms as following:

The black cross (isogyre) breaks in to two hyperbolas which has maximum separation at a 45 degree of rotation and color bands takes the oval form

2- Optic axis – centered interference figure (2)

3- This type of I.F can be seen under microscope when conoscopy arrangement is used and when the section cut perpendicular to the one of the two optic axes. In this case the I.F consists of only one black hyperbola.

The optic axis will emerge at center of the field of view, but the second optic axis will emerge at a distances out ward from the center of the field depending on $2E$ for the mineral.

The bisectrix and the other hyperbola located at the convex side of the observed hyperbola (isogyre)

3-obtuse bisectrix figure:

Biaxial crystal cut perpendicular to an obtuse bisectrix yield an interference figure at center of which the obtuse bisectrix (X or Z) emerges.

Such figure resembles the acute bisectrix figures but the $2V$ is larger. And the isogyres located at the out of the field of the view

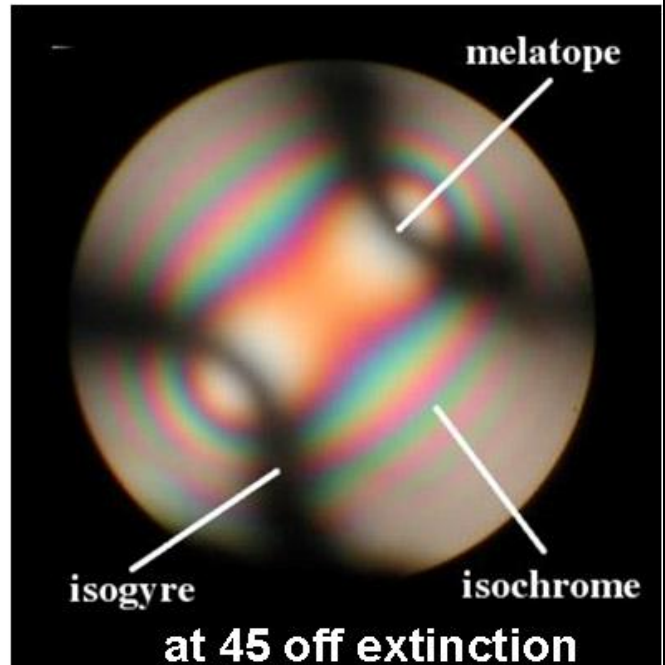
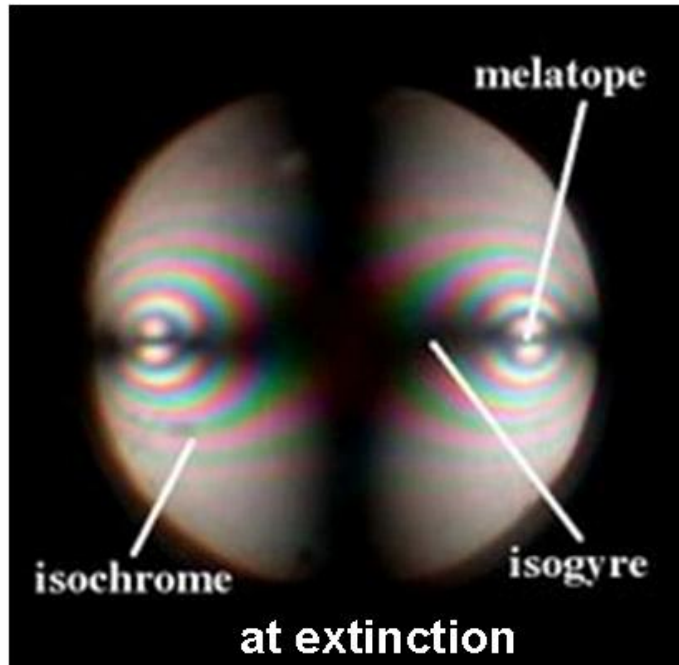
4- Optic normal figure :

When the crystal is cut perpendicular to optic normal forms flash figure (see p.48 for definition)

5- acute bisectrix figure

This figure consists (at extinction position of stage) of two unequal intersecting black bars (arms) one is thin and the other is thick and which are forming a cross. At the 45 degrees the two isogyre is separate into two curves and its maximum separation is called $2V$.

Acute bisectrix figure



Biaxial interference figure of acute bisectrix section at zero and 45 degrees of the stage rotation

Determination of optic sign by accessory plates:

(1) Uniaxial crystals : to obtained centered interference figure we must follow these points:

- 1- We must find a grain which is dark under (x.p) when the stage is rotated
- 2- We must use X40 objective, Bertrand lens and condenser lens.
- 3- Now we can see uniaxial centered Interference figure.
- 4- We must use gypsum plate or mica plate to fined optic sign by which we can know vibration of slow and fast ray
- 5- If e-ray is slow the crystal is positive and if fast is negative.
- 6- When gypsum plate is used the 2nd and forth quadrant become yellow. This is happen when the crystal is optically negative (see the figure below).
- 7- For positive crystal the interference color of the quadrants are exchange (as can be seen for fig. (3))
- 8- The e-ray (it is under n_e) is always vibrate radially according to optic axis but the o-ray vibrate tangentially according to circular boundary of the interference figure
- 9- For optically negative crystal subtraction occurs in the quadrants 1 and 3 when gypsum plate used and I.E become yellow but for 2 and 4 addition occurs and the I.C become blue this means that e-ray is fast but o-ray is slow

10- For optically positive crystal all the things are opposite to the negative crystals (as can be seen fig-)

For off centered interference figure, the determination of the optic sign is the same as for centered interference figure as can be seen below

When mica plate (one quarter wave length plate) is used the same subtraction and addition will happen in the quadrants but the amount of subtraction and addition will be less than the gypsum plate.

For example when mica plate used for determination of optic sign of uniaxial negative, addition occur in the second and forth quadrants, causing them to shift slightly toward the center. At the same time subtraction causes the colors in the first and third quadrants to shift slightly away from the center.

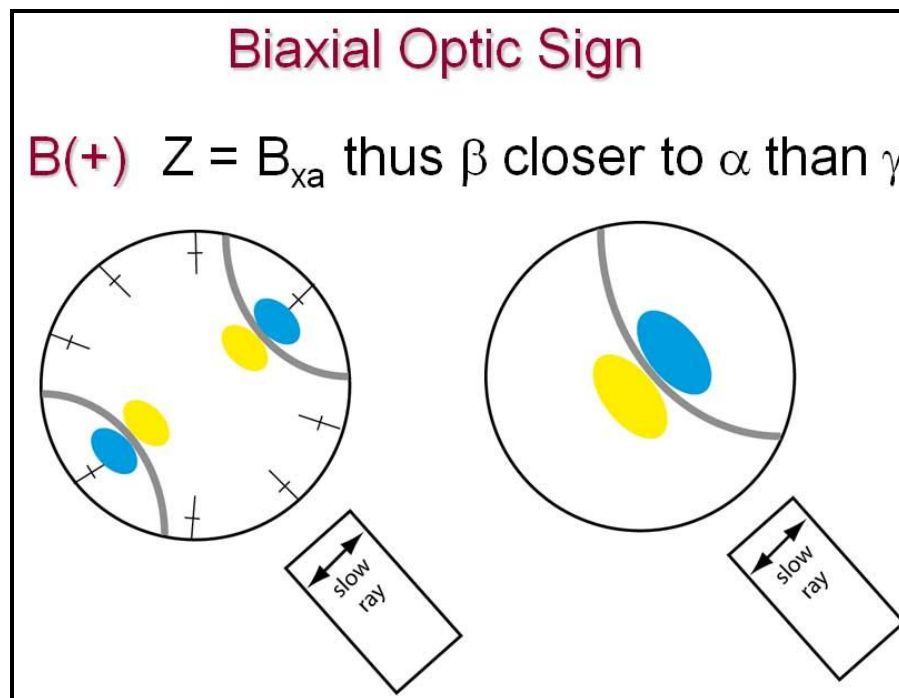
The clearest feature produced by the mica plate is the formation of two spots near the center of the black cross in the quadrants where subtraction occurs.

Important note:

Gypsum plate is usually used to determine the optic sign when low-order interference colors or no colors at all are seen in the centered optic axis figure. But in other case mica plate is used.

Determination of optic sign of biaxial crystals

The optic sign of biaxial crystals can be best determined on acute bisectrix I.F and optic axis – centered I.F with the aid of gypsum and mica plates. Let us assume that a (0) or (90) But for biaxial positive the position of color will changed as in the biaxial.



Indication of optic sign of the biaxial crystal when the section is acute bisectrix (left) and when the section is optic axis –centered

Optic sign, biaxial indicatrix and Figures

Optic sign of uniaxial crystals

The definition of the optic sign is based on the relative indices of refraction of the ordinary and extraordinary rays. If the ordinary ray is the fast ray (with a smaller index of refraction), then the uniaxial crystal is optically positive. If the ordinary ray is the slow ray (with a larger index of refraction), then the uniaxial crystal is optically negative.

The optic sign can be determined by using the interference figures and accessory plates. There are two ways to determine the optic sign using an optic-axis interference figure (OA figure).

- Insert a mica or gypsum plate. If the color of the NE-SW increases, the crystal is optically positive.
- Insert a quartz wedge. If the isochromes in the NE-SW quadrants move inwards (the number of isochromes increases), the crystal is optically positive.

Biaxial Indicatrix and optic sign

The biaxial optic class includes the orthorhombic, monoclinic, and triclinic crystal systems. To describe their crystallographic properties, it is necessary to specify the lengths of the unit cell along all three crystallographic axes. Similarly, to describe its optical properties it is necessary to specify three different indices of refraction: $n_\alpha < n_\beta < n_\gamma$.

By convention, the biaxial indicatrix is a triaxial ellipsoid elongated along the Z axis and flattened along the X axis.

- n_α is plotted along the X axis
- n_β is plotted along the Y axis
- n_γ is plotted along the Z axis

The maximum birefringence of a biaxial mineral is always $n_\gamma - n_\alpha$.

The biaxial indicatrix has three principal sections: the X-Y, X-Z, and Y-Z planes.

- The X-Y section is an ellipse with axes n_α and n_β
- The X-Z section is an ellipse with axes n_α and n_γ
- The Y-Z section is an ellipse with axes n_β and n_γ

The biaxial indicatrix has two circular sections with the radius n_β . The two circular sections intersect at the Y axis. The directions that are perpendicular to the two circular sections are the optic axes. Both optic axes lie in the X-Z plane. The X-Z plane that contains the optic axes is also called the optic plane.

The acute angle between the optic axes is the optic angle or $2V$ angle. The axis (either X or Z) that bisects the $2V$ angle is the acute bisectrix or Bxa . The axis (either Z or X) that bisects the obtuse angle between the optic axes is the obtuse bisectrix or Bxo . The Y axis, which is perpendicular to the optic plane, is called the optic normal. The definition of the optic sign is based on whether the X or Z axis is the acute bisectrix. If the

acute bisectrix is Z, it is optically positive. If the acute bisectrix is X, it is optically negative. The optic sign can also be defined based on $2V_x$ and $2V_z$. If $2V_x > 90^\circ$, $2V_z < 90^\circ$, it is optically positive. If $2V_x < 90^\circ$, $2V_z > 90^\circ$, it is optically negative. Note that this definition in Nesse is mistaken.

Biaxial interference figures

Depending on the mineral orientation with respect to the sample stage, there are five different types of biaxial interference figures

- Bxa figure: Z (+) or X (-) is vertical (perpendicular to the stage)
- Centered optic axis figure (OA figure): one of the optic axes is vertical
- Bxo figure: X (+) or Z (-) is vertical
- Optical normal figure: Y is vertical
- Off-center figures: this is the general case

Determine the optic class, the optic sign and the optic angle (2V) of biaxial crystals

Biaxial figures are distinctly different from uniaxial figures for most mineral orientations.

- A simple way to distinguish between uniaxial and biaxial minerals is to rotate the stage and see whether an isogyre curves. The isogyres are always straight for uniaxial figures. They are mostly curved for biaxial figures.
- Another way to identify a biaxial mineral is to observe the separation of the isogyres in a Bxa figure upon rotation of the stage. Bxa and OA figures are commonly used to determine the optic sign and optic angle.

Optic sign determination using a Bxa or optic axis (OA) figure:

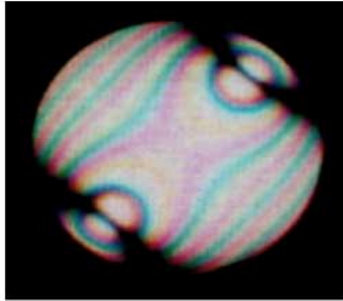
For a biaxial mineral with a positive optic sign, color increases (adds) in the convex area.

For a biaxial mineral with a negative optic sign, color decreases (cancels) in the convex area.

Optic angle determination:

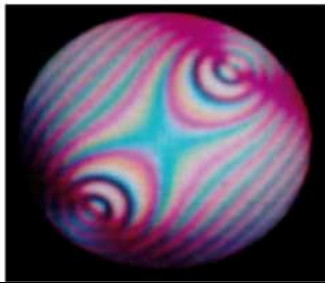
- Rapid estimate of $2V$ can be obtained based on separation of isogyres in a Bxa figure (Fig. 7.29, Nesse page 97). The separation increases with increasing $2V$.
- It can also be obtained based on the isogyre curvature in an optic axis figure (Fig. 7.32, Nesse page 100). The curvature of the isogyre decreases with increasing $2V$.

Biaxial Optic Sign (+)



Without gypsum plate -

Polarisation colours increase away from isogyres



With gypsum plate -

Colours increase by 1° in NE quadrant = +ve

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