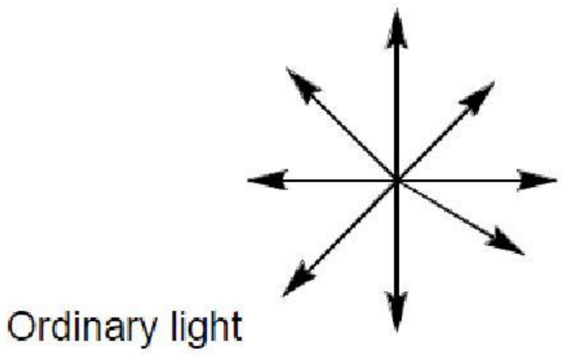
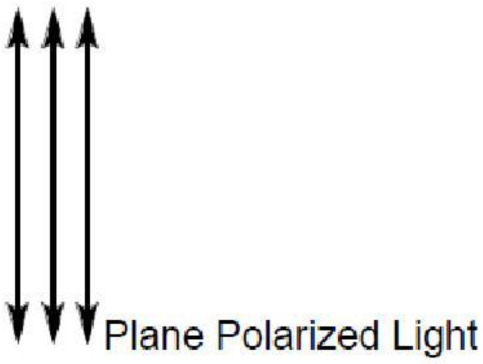
D.N.R.COLLEGE (AUTONOMOUS), BHIMAVARAM
II B.Sc., GEOLOGY-Optical Mineralogy

Ordinary light and polarized light: in ordinary light, the vibrations take place in all directions at right angles to the ray. In the polarized light, the vibrations are confined to one definite plane at right angles to the ray.





White Light, or visible light, is a form of electromagnetic radiation (energy waves produced by the motion of an electric charge). White light belongs to the color spectrum, which defines all forms of light and electromagnetic radiation. The spectrum also includes many forms of light not visible to the human eye, such as ultraviolet and infrared light.

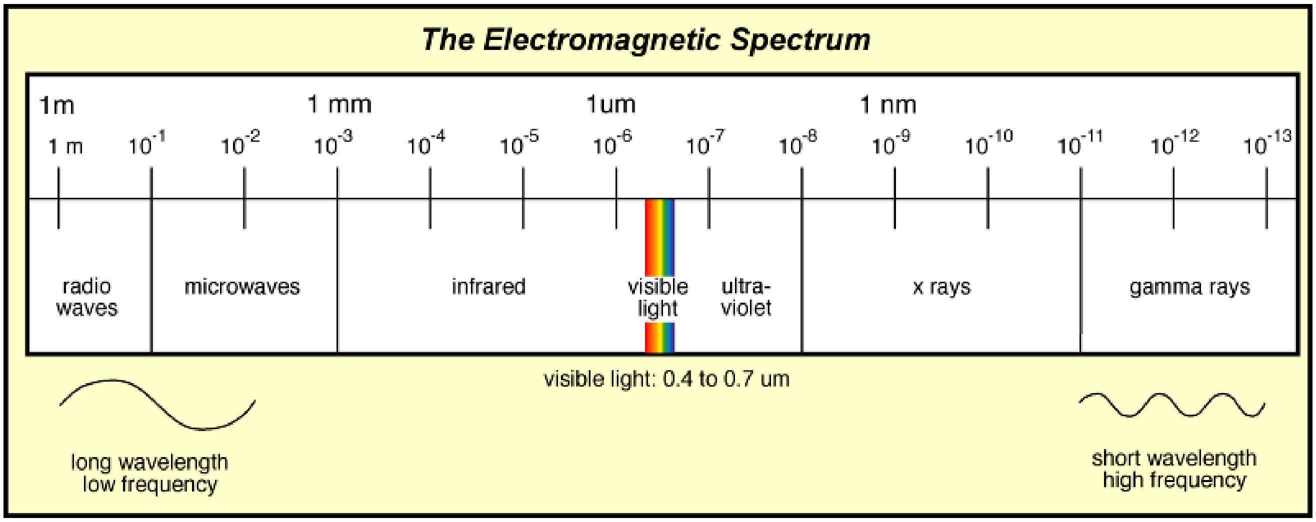
The rate of motion produced by the electrical charge defines the wavelength of light. Different wavelengths produce different types of light; white light encompasses all wavelengths visible to the human eye. White light contains the seven primary colors: red, orange, yellow, green, blue, indigo, and violet.

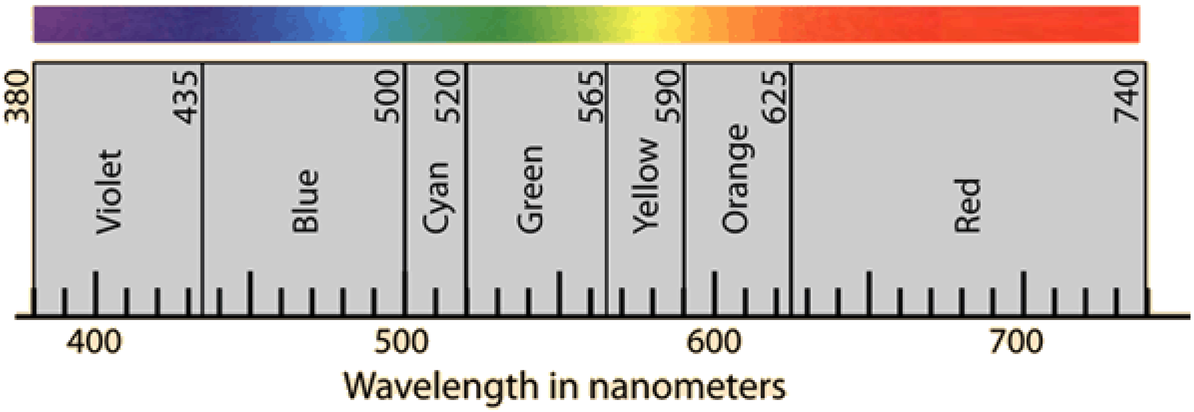
The color white is a composite of all colors. Every substance receives its color from the way white light reacts to it. Light can either be absorbed into a substance, or it can be reflected. The presence of certain elements or chemicals in a substance determine which wavelengths (i.e. colors) are reflected and which are absorbed. The wavelengths reflected off a substance determine its color. For example, if a substance absorbs all wavelengths except for yellow and green wavelengths, which are reflected, the color of the substance is yellow-green. If a substance absorbs no wavelengths but reflects them all, its color is white. If, however, a substance absorbs all wavelengths, its color is black.

In addition to reflection and absorption, light can also be passed through a substance. Light passing through a substance determines its transparency. If all light passes through a substance, and none is reflected or absorbed, the substance is transparent and colorless. These three attributes (reflection, absorption, and passing through) determine the color and transparency of a substance.

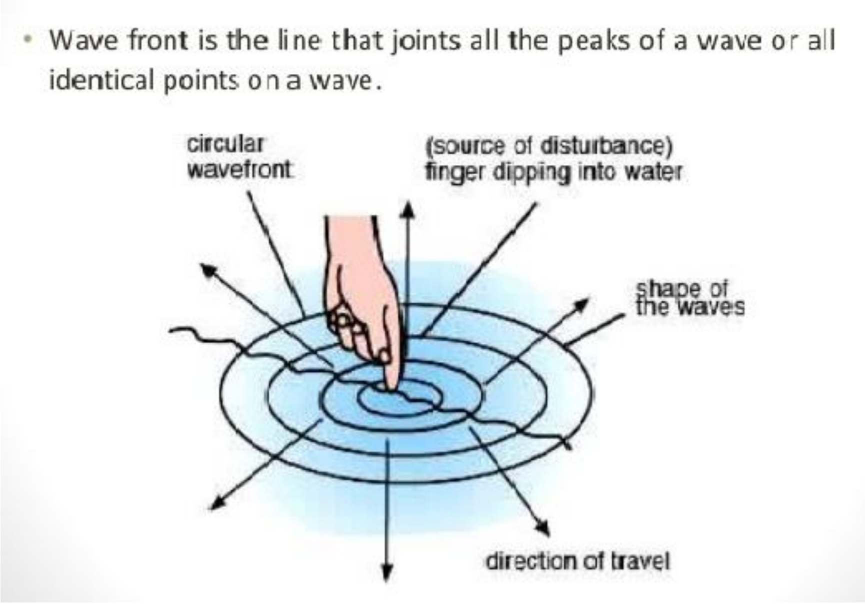
Monochromatic light: the sun's light, called white light, contains essentially all wavelengths of the visible range. This is familiar to anyone, who has observed a rainbow. A ray of white light, on entering a glass prism, is split up into its coloured components- violet, blue, green, yellow, orange and red, each having a definite wave length of its own. The separation of white light into its coloured components is called "Dispersion". Each one of these components of white light is called Monochromatic light, which means light of one single wave-length and therefore of one definite colour.

The colour depends upon the wavelength of the light causing it. For instance, violet light has the wavelength of 410 nm., while red light has the wavelength of 760 nm. Between these two extremities, each of the components of white light constitutes the visible portion of the spectrum. The portion of the spectrum above the red end is the invisible portion, containing the infra-red rays, while the portion below the violet and is again the invisible portion consisting of X-rays, Gamma-rays and Cosmic rays.





Wave surface: it is the surface to which the light rays spread in a given unit of time, and wave-front is the tangential plane at any point on the wave surface. The shape of the wave surface depends upon the relative velocity of propogation of light. If the velocity is the same in all directions, the wave surface is a sphere and the wave front is a circle. If the velocities differ in different directions, the wave surface is an ellipsoid and the wave-front is an ellipse.



- Wave front is the line that joints all the peaks of a wave or all identical points on a wave.

Refractive index (RI):

The constant ratio, cited above, between the sines of the angles of incidence and refraction is called the refractive index of the medium, in which refraction is called index of the medium, in which refraction takes place. Refractive index of a substance is merely a number, which is not expressed in terms of any unit of measurement. It is of fundamental importance in the determination of optical properties of minerals, because from the value of refractive index, most of the other optical properties can be determined. For comparing the refractive indices of different substances, some medium is chosen for reference. The medium chosen in air, whose refractive index is taken to be 1.

Examples of refractive indices of substances:

Water: N = 1.33 Diamond: N = 2.42 Quartz: N = 1.55

(The speed of light varies in substances. The speed of light is different in air, water, and other dimensions, including minerals and gemstones. When light travels from one media to another media, the light bends, or *refracts*, upon entering the second media. This phenomenon can be witnessed with a stick protruding from a pond, where the stick appears to "bend" at the water level. This is caused by the difference in the speed of light in air and the speed of light in water. **How much the light will bend, or the *angle of refraction*, depends on difference in the speed of light of the two substances.** All transparent gemstones refract light, since the speed of light is different in the air than in gemstones.

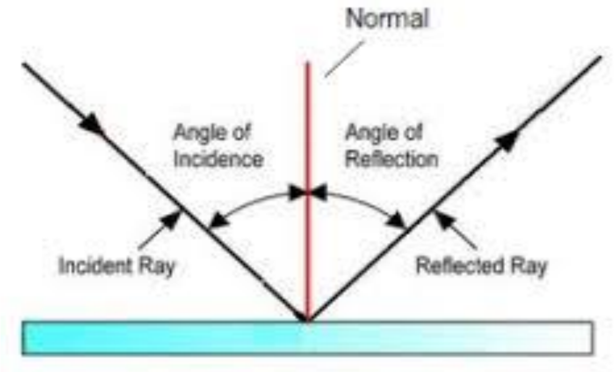
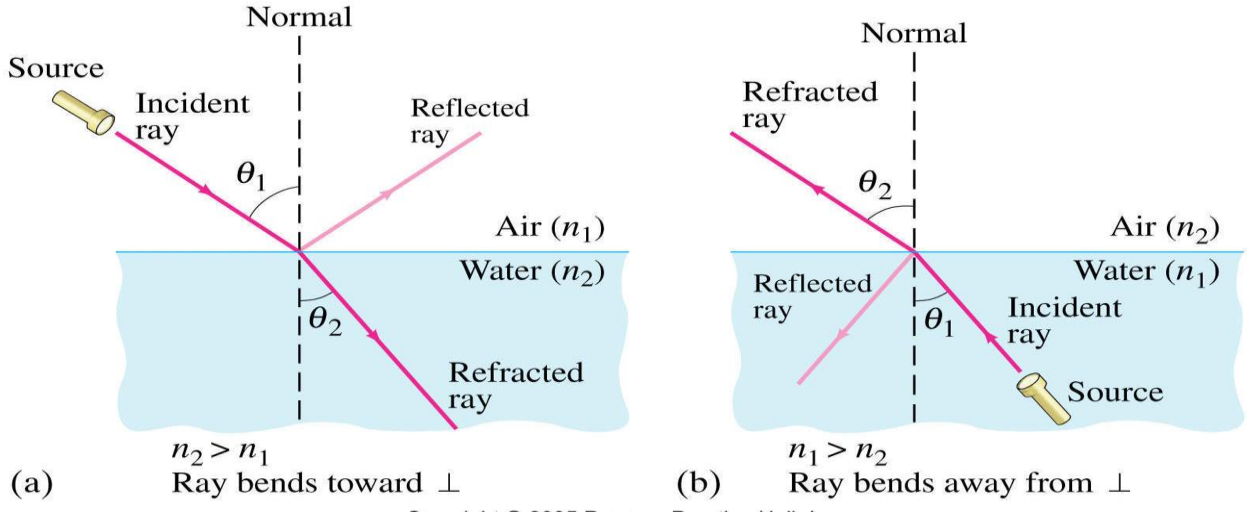


Fig. 1



First examine the passage of light from a given medium into one of lower refractive index.

Every gemstone refracts at a distinct, individual angle. The angle of refraction is directly related the speed of light in the gemstone. The *refractive index* of a gemstone measures the difference between the speed of light in air and the speed of light in the gemstone. This is determined by the gemstone's angle of refraction. Every gemstone has a unique refractive index, meaning every gemstone refracts light at a unique angle.

The refractive index value measures how much slower light travels in the gemstone than in the air. For example, the refractive index of Diamond is 2.42. This means that the speed of light in Diamond is 2.42 times slower than the speed of light in air.

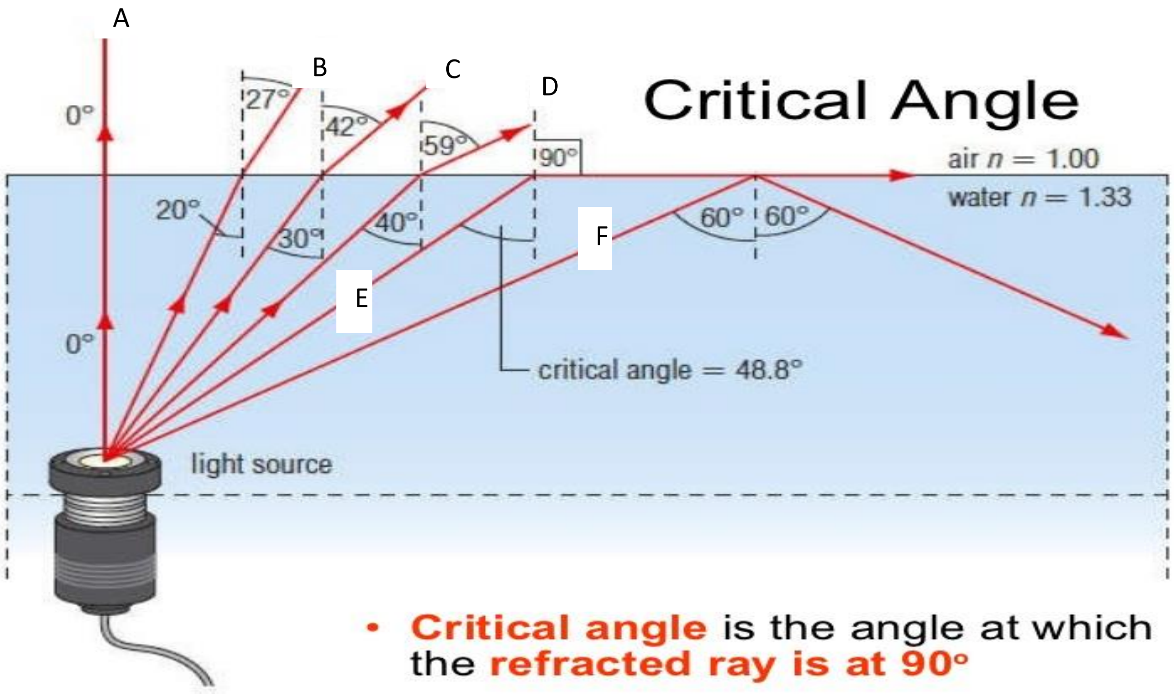
Refractive indices of minerals range from 1.2 to about 3. However, gemstones with a refractive index greater than Diamond (2.42) are generally either synthetic or are too soft for practical gemstone use. The greater the refractive index of a gemstone, the more brilliant or lustrous it is.

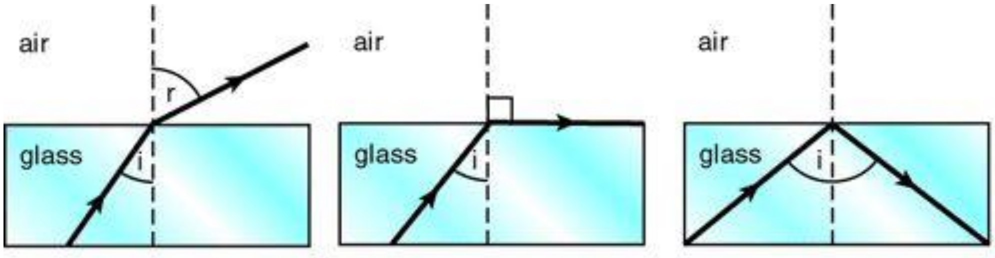
The refractive index of a gemstone is measured with a ***refractometer,*** a tool that measures angle of refraction. This tool is used by almost all gemologists and professional jewelers, for it provides simple, inexpensive, and accurate gem identification. However, a refractometer cannot read values greater than 1.86. Gemstones with refractive indices greater than 1.86 can only be tested by placing them in a liquid with a known refractive index, and then calculating the difference in refraction between the liquid and the gem.**)**

Critical angle and Total refraction

A section through two media, is shown below, the lower having a higher refractive index than the upper. Rays of light travel from a source S and pass from the medium with higher refractive index into that with the lower. Ray A strikes the junction plane between the two media at right angles, so that its angle of incidence is zero and consequently its angle of refraction is zero too. It passes straight on unbent. Rays B, C, D are refracted away from the normal as they pass from the lower medium to the upper. There must be a position, as with ray, E, however, when the refracted ray just grazes the surface between the two media. A ray, such as F, meeting the junction plane at an angle greater than E does, is reflected back into the denser medium. A ray in the position of E is said to make the critical angle with the normal to the junction plane. **The maximum angle of refraction for light of grazing incidence is called the "Critical angle". Light falling on this plane at angles greater than the critical angle is totally reflected.**

Let us reserve the direction of the ray E. The angle of incidence I is 90^0, the angle of refraction r is the critical angle (CA), that is, the sine of the critical angle is equal to the reciprocal of the refractive index. The determination of the critical angle as a means of finding the refractive index is performed with one type of the instruments called **refractometers.**





if the angle of incidence is less than the critical angle, the light refracts away from the normal

if the angle of incidence is equal to the critical angle, the light refracts at 90° to the normal

if the angle of incidence is greater than the critical angle, total internal reflection occurs

Single refraction: it is found that the internal molecular structure may be uniform throughout in some minerals, while it may vary in different directions in others. Light travel with equal velocities in all directions within the minerals, having uniform internal molecular structure, and consequently a ray of light undergoes normal refraction, on entering these substances and passes on without any further change, the original refracted ray remaining as a single ray. This type of refraction is called "Single refraction" in amorphous minerals and minerals crystallizing in isometric system single refraction of light takes place.

Double Refraction: If the minerals have varying internal molecular structure in different directions, light travels with in them with unequal velocities and consequently, a ray of light undergoes the normal refraction first and then due to the varying velocities, the original refracted ray is further split up, by refraction taking place for the second time, into two or three rays, depending upon the particular pattern of the internal molecular structure. This property of splitting of the original refracted ray into two or three rays, resulting from the refraction taking place for the second time, is called "Double Refraction". Double refraction takes place within the minerals crystallizing in all systems except cubic system.

In minerals crystallizing in hexagonal, tetragonal and trigonal systems, double refraction splits up the original refracted ray into two rays. Of these two rays, so produced, one travels with a constant velocity in all directions and is called the "ordinary ray:" while the other travels with varying velocities in different directions and is called the "extraordinary ray". Within these minerals, either the o-ray is faster or slower than the e-ray, with their vibrations taking place at right angles to each other. These vibrations of the faster ray are called fast vibrations and the direction of these fast vibrations is indicated by the symbol, ‘X’, the vibrations of the slower ray are called the slow vibrations and the direction of these slow vibrations is indicated by the symbol ‘Z’, light is resolved into two sets of vibrations fast(X) and slow(Z), in these minerals, resulting from the splitting of the original refracted ray into one O ray and one E-ray, due to these refractions taking place for the second time.

On the other hand, in minerals crystallizing in orthorhombic, monoclinic and triclinic systems, light is resolved into three set of vibrations at right angles to each other, caused by the splitting of the original refracted ray into three rays one O-ray and two E-rays (E1 & E2), due to refraction taking place for the second time, of these three rays, so produced, one ray travels with the maximum velocity (fast ray) and the other travels with the minimum velocity (slow ray), while the remaining one travels with the intermediate velocity. The vibrations of these rays are distinguished as fast vibrations, indicate by the symbol X. intermediate vibrations on indicate by the symbol Y. and the slow vibrations indicate by the symbol Z. this property by which light is resolved into two or three sets of vibrations caused by the refraction taking place for the second time is called double refraction and it is an exclusively characteristic property of all minerals, crystallizing in crystal systems other than the cubic system.

This property of double refraction is very well established by a crystal of Icelandspar and was first observed on this crystal by a French Physist, Erasmus Bartholinus, in 1669. If we cover a dot marked on a piece of paper, with a rhombohedral crystal of Icelandspar and look through it from above, we see two images of the dot-i_1 and i_2 .

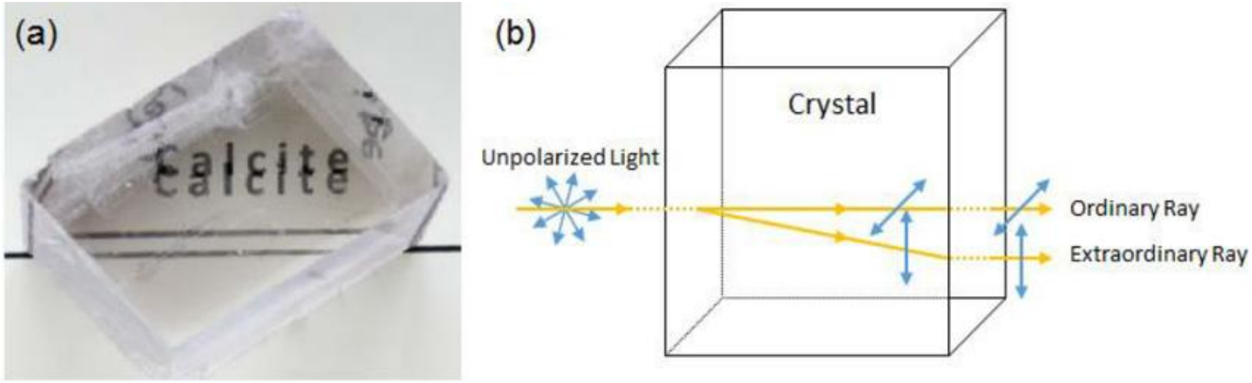
On rotation of the crystal in the horizontal direction, we see that while the upper image remains stationary, the lower image goes on moving in the same direction as the rotation of the crystal, making a small circle around the uppepr image with later as the centre. In this position of the crystal, its c-axis is inclined to the line of vision. In this case, the ray of light, on entering the crystal, undergoes normal refraction. This refracted ray travels with in the crystal with varying velocities in different directions and hence, it is splitup into two rays O ray and E ray each of wghich forms an image of the dot. Since the O ray become E ray has a constant velocity in all directions, the i_1 image remains stationary on rotation of the crystal, while the other i_2 goes on moving, since the E ray has varying velocities in different directions.

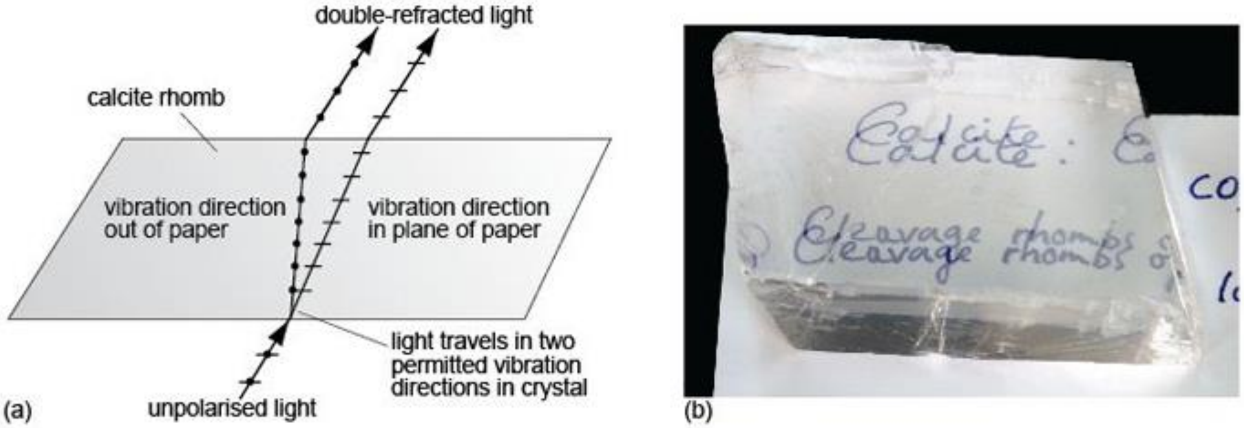
Double Refraction:

We have seen that in isometric substances the refractive index has the same value for all directions. A ray of light entering such a substance remains a single ray, thought bent from its course. Isotropic substances are thus singly refracting.

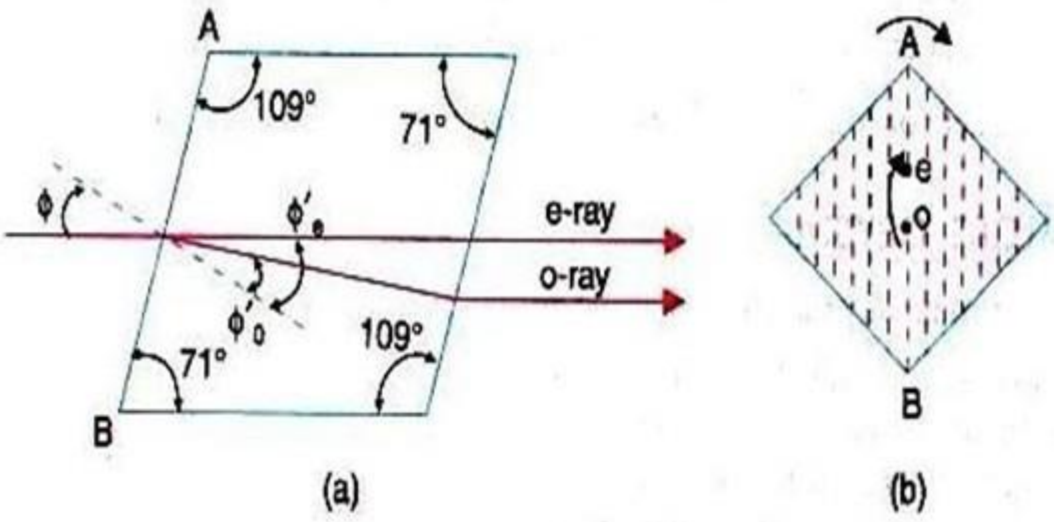
It is different with anisotropic substances. A ray of light passing from an isotropic to anisotropic medium forms two refracted rays. This phenomenon is called Double refraction.

Double refraction is shown by all anisotropic minerals but especially well by the colorless transparent variety of calcite called Iceland Spar.





For calcite, the refractive indices (or speeds) of the two rays are very different, so they travel along quite different paths through the crystal. (b) Double refraction in natural calcite (Iceland spar). The difference in the speeds (i.e. refractive indices) of the two rays is so great that the eye perceives two images.



(Experiment: observations with optical calcite.

• Light passing through a calcite crystal is split into two rays. This process, first reported by Erasmus Bartholinus in 1669, is called double refraction.

°. In the case of double refraction of a normally incident ray of light, at least one of the two rays must violate Snell's Law as we know it. For calcite, one of the two rays does indeed obey Snell's Law; this ray is called the ordinary ray (or O-ray). The other ray (and any ray that does not obey Snell's Law) is an extraordinary ray (or E-ray) (Snell's Law: a law stating that the ratio of the sines of the angles of incidence and refraction of a wave are constant when it passes between two given media.)

The double refraction in most minerals is so weak that it cannot be observed with the naked eye. However, a small number of minerals have a strong double refraction, which is easily seen when the crystal placed over an image appears to "double" the image.

Double refraction is an important guide to gem identification. When viewed through a refractometer, birefringent minerals show two readings – one for each refracted ray of light. Double refraction is a characteristic trait, meaning every specimen of the same gem always has the same double refraction.

Double refraction is measured by the difference of refraction in each light ray. For example, if a gem is placed in a refractometer and shows a double reading of 1.62 and 1.63, its double refraction is .01.)

Twinkling:

In anisotropic minerals, the index of refraction differs with direction. A mineral fragment showing high relief in one direction and low relief in another is said to have variable relief, and such a mineral shows, on rapid rotation of the microscope stage under plane polarized light. Variation in relief with alternation of strongly marked and slightly marked borders, giving a twinkling effect and hence this phenomenon is called Twinkling.

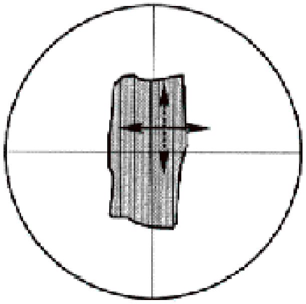
Calcite is a very good example of a mineral, showing twinkling. In calcite, the refractive index for the O-ray is 1.66, for E-ray 1.49 and the refractive index of Canada balsam is1.54. The refractive index (1.66) for the O-ray is very much higher than that of balsam. While that (1.49) for the E-ray is lower than that of balsam. Therefore, the rotation of the microscope stage brings about a strong change from high positive relief to low relief, which may be positive or negative, resulting in the alternation of strongly marked and slightly marked borders-twinkling.

Extinction:

An anisotropic mineral in a thin section exhibits darkness, under crossed nicols, whenever its vibration directions coincide with or are parallel to the vibration planes of the nicols. This property of an anisotropic mineral is called ‘Extinction’. AN anisotropic mineral shows extinction in four positions at intervals of 90^0, alternated by four positions of maximum illumination with interference colours at intervals of 90^0 in a complete rotation of the microscope stage, the angle between a position of extinction and a position of maximum illumination being 45^0 . The vibration directions of a mineral are, therefore, referred to as “extinction directions”. The cleavages and crystal edges are useful to determine the extinction directions. Three types of extinction are recognized and they are

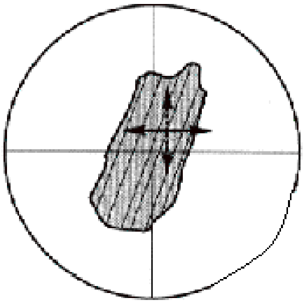
a.) **Straight or Parallel extinction:**

For the case of parallel extinction, the crystal will be at the extinction position when the cleavage is aligned parallel to the cross hairs. Examples: Orthopyroxene, Biotite.



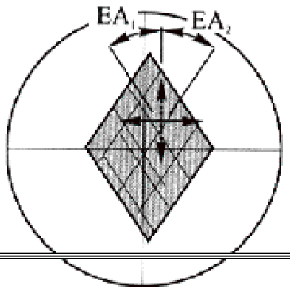
b.) **Inclined extinction:**

For the case of inclined extinction, the crystal will be at the extinction position when the cleavage is aligned angle to the cross hairs. Examples: clinopyroxene, Hornblende.

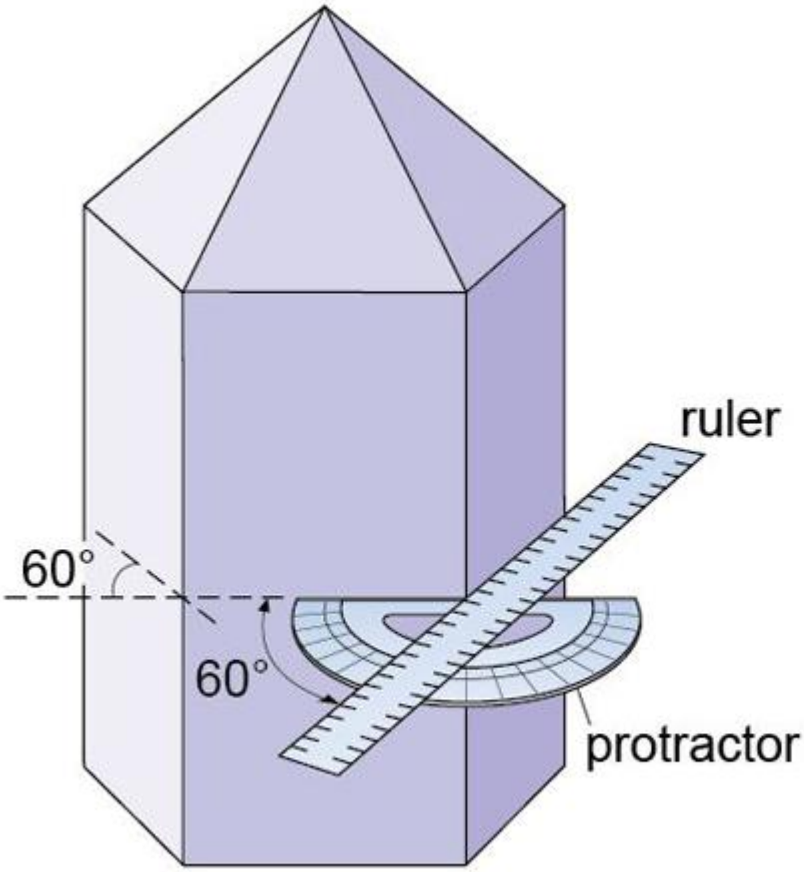


c.) **Symmetrical extinction:**

For the case of symmetrical extinction, the crystal will be at the extinction position and show an extinction angle that is the same on either side of the cross-hair. Examples: Amphibole, Calcite.




Elegant Fused Glass
by Karen


ruler
60°
60°
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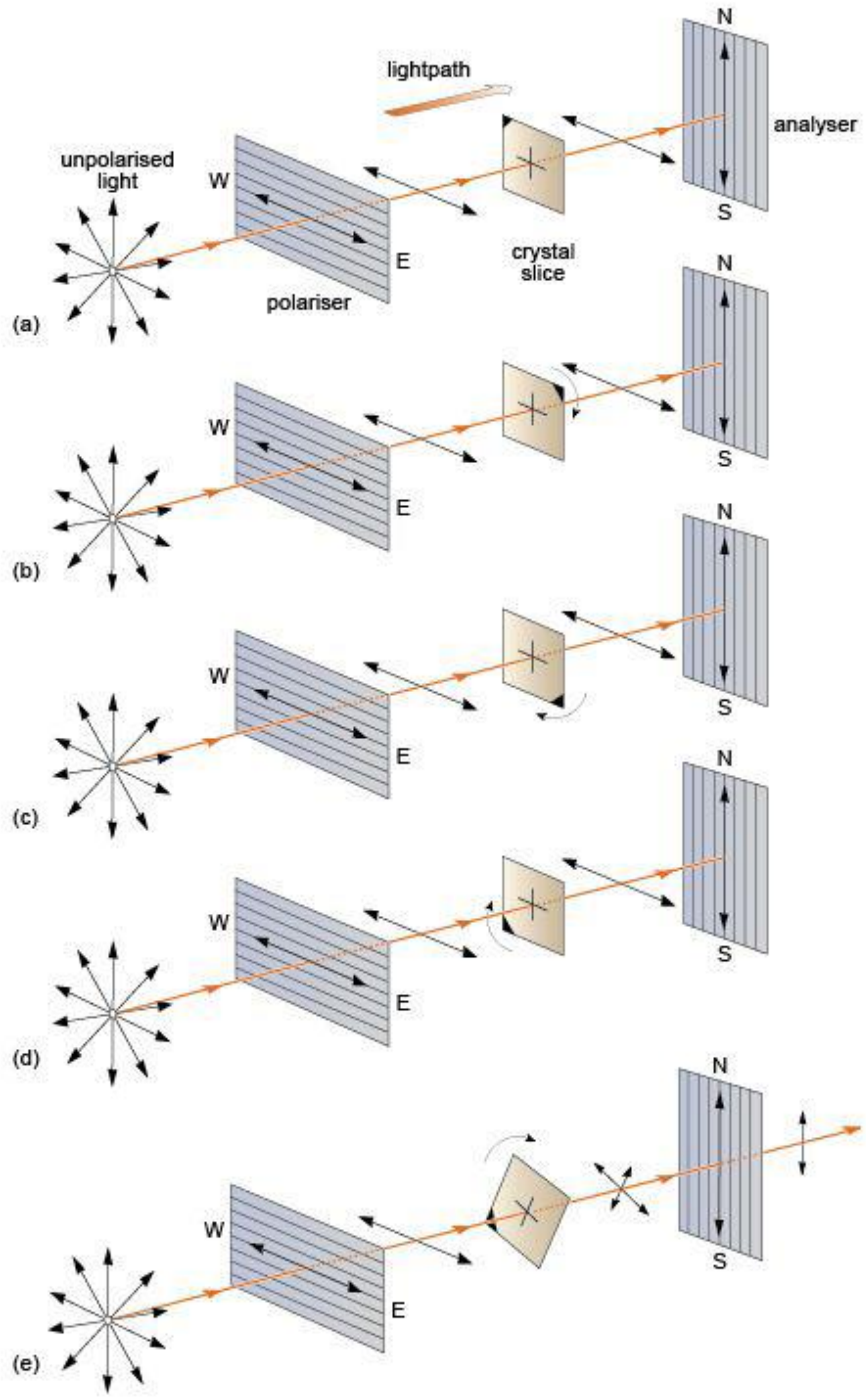


Figure 31 (a)-(d) The four positions in a full 360º rotation of an anisotropic mineral specimen, demonstrating extinction when a permitted vibration direction of the crystal is parallel to the plane of polarisation. (e) The general case when the two permitted directions of an anisotropic mineral do not coincide with the plane of polarisation.

Figure 31e illustrates what happens between extinction positions. Light that has passed through the first polarising filter is polarised in the east-west plane as before. On entering the mineral it splits into two rays, polarised at right angles by the anisotropic mineral. These two rays then enter the second polariser. Their planes of polarisation are at an angle to the permitted direction of the second polariser, which constrains the transmitted component of each ray to the north-south plane, and so light passes through. The *intensity* of the transmitted light varies gradually from zero at the positions of extinction to a maximum at each position halfway between the extinction positions.

Interference colours

As you have seen, in between extinction positions light is transmitted through crossed polars (Figure 31e), but in an anisotropic mineral the two light rays would travel at different speeds in each permitted vibration direction. The second, crossed polariser effectively combines the two rays, but as they have travelled at different speeds through the mineral, they arrive out of step, to an extent (called the optical path difference) that depends on the difference in refraction (the birefringence) and the thickness of the mineral (Figure 32). Consequently, the transmitted light is no longer the mixture of colours that makes white light, but is a single **interference colour** as a result of interference effects between the two waves when recombined. The theory associated with production of interference colours need not concern you here, but the consequences are important.

Figure 32 A light wave splits on entering a crystal through which the two rays travel at different speeds. The optical path difference produces interference colours.

The interference colour observed depends on the optical path difference and hence both the thickness of the mineral and the birefringence of the crystal in its particular orientation. A whole range of these interference colours can be seen when viewing a shallow wedge of quartz between crossed polars. Effectively, because the thickness of the wedge changes gradually while the birefringence remains the same throughout, the sequence of colours is a consequence of the transmitted rays becoming more and more out of step. The result is a 'spectrum' of interference colours called **Newton's scale of colours** - depicted on the **Michel-Levy chart** in Figure 33.

View larger image

Figure 33 The Michel-Levy chart. Interference colours viewed through a quartz wedge, increasing in thickness from left to right, as viewed between crossed polars. The colours are divided into different orders (see text), separated by pinkish-purple bands, as indicated by the red arrows along the top.

If the thickness of minerals to be observed were held constant, then the interference colours of the transmitted light would depend only on the difference in the refractive indices (the birefringence) for the light path in a given crystal. To see the more distinct interference colours shown in the left side of the chart (Figure 33), produced at the thin end of the wedge, the waves must not be too far out of step, so the mineral path must be short. In practice, slices of rock ground down to a thickness of just 30 µm ensure the transparency of most minerals, yet are sufficiently thick for distinct interference colours to be visible. By using this standard thickness of rock slices prepared for optical microscopy, uniformity is maintained, so that all observations of optical features are consistent from mineral to mineral and rock slice to rock slice.

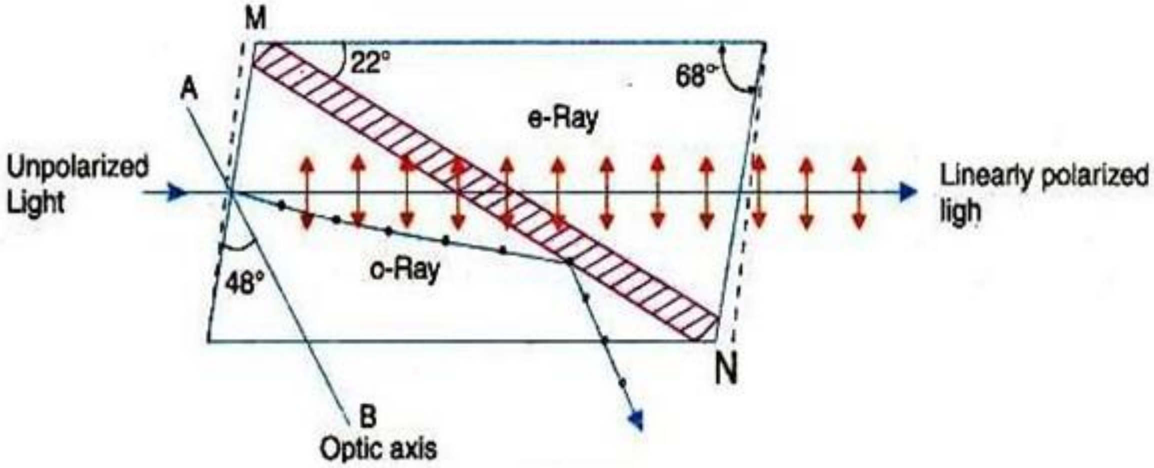
The colour scale of the Michel-Levy chart can be divided into sections, called **orders**, separated by pinkish-purple bands (Figure 33). The more distinct colours at the thin end of the wedge are called low-order colours, and the lighter, less distinct colours at the thicker end are called high-order colours. For a slice of constant thickness, higher-order colours are produced by a mineral exhibiting higher birefringence. Calcite, with its high degree of anisotropy, is such a mineral.

When looking at interference colours, it is important to be aware of possible ambiguity in using the Michel-Levy chart. Some colours - particularly yellows and greens - appear in several places (i.e. in different orders) on the chart. Sometimes it can be difficult to establish the order of a particular interference colour. In general, higher-order colours appear much more washed out and pastel-like than lower-order colours, which are brighter and more vivid (Figure 33).

The refractive indices of an anisotropic mineral are related to its crystallographic axes and so its birefringence will vary according to its crystallographic orientation. This is an important point. If a single crystal of a mineral were taken and sliced in many different orientations, the interference colour would be different for each section - even for sections of the same thickness. In a rock that contains crystals of the same mineral in many different orientations, there will be differences in refractive index, hence birefringence, so that many different interference colours will be observed. However, the extent to which refractive indices can vary, and therefore the range of birefringence, is limited for any given mineral. In practice, it is the *greatest difference* in refractive index (i.e. the largest birefringence) and the **maximum interference colour** that can be identified, that is taken as characteristic (and can be diagnostic) of a particular mineral.

However, for some anisotropic minerals, slices can be cut in such a way that the refractive indices of the two plane-polarised rays are the same. This applies to minerals of the tetragonal, hexagonal and trigonal systems, when looking down their long (*z*) axes. Such a slice is often referred to as a **basal section**.

- How would such a mineral, sliced perpendicular to its long axis, appear between crossed polars?
- It would be in darkness throughout when rotated, just like an isotropic mineral.
- What would be the range of interference colours visible for such a mineral present as grains in random orientations?
- They would range from a maximum interference colour down through a range of intervening colours on the Michel-Levy chart to black.



(μ0=1.66, μe =1.486 and μCanada balms = 1.55)

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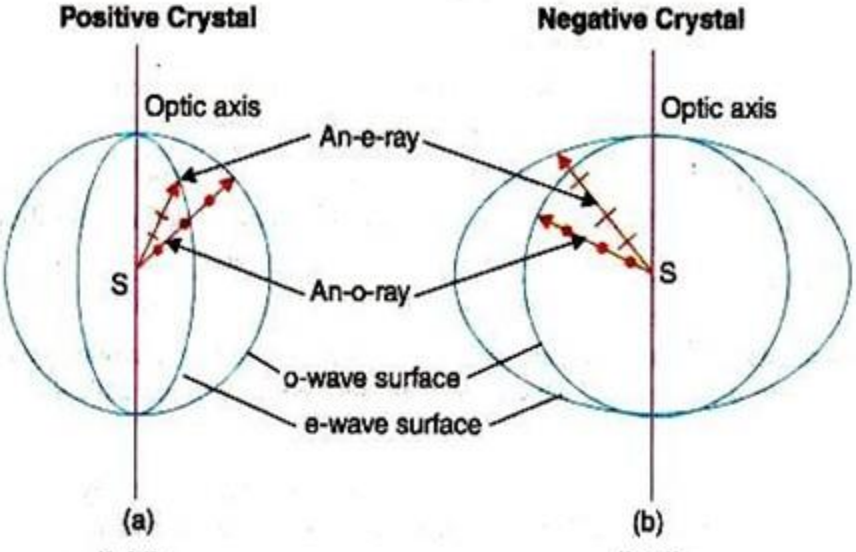

(a) $\mu_e > \mu_0$

(b) $\mu_e < \mu_0$

Huygens wave surfaces produced by a point source *S*-embedded in the birefringent crystal; (*a*) a positive crystal (*b*) a negative crystal.

Huygens' explanation of double refraction in uniaxial crystal

According to Huygens, the each point on a wave front acts as a fresh source of secondary wavelets.He explained the phenomena of double refraction in uniaxial crystal with the help of secondary wavelets.Theory:When any wave front strikes a doubly refraction crystal, every point of the crystal becomes a source of two wavefronts.

☐ **Ordinary wavefront corresponding to ordinary rays.**
Since ordinary rays have same velocity in all directions, the secondary wave front is spherical.Extra-ordinary wavefront corresponding to extra-ordinary rays.Since extra-ordinary rays have different velocities in different directions,The extra-ordinary wave front is ellipsoid with optic axis as the axis of revolution.

☐ The sphere and ellipsoid touch each other at points which lie on the optic axis of the crystal, because two velocity of ordinary and extra ordinary ray is same along the optic axis.In certain crystals like calcite and tourmaline called the negative crystalThe ellipsoid lies outside the sphere as shown in fig.(a).

☐ In negative crystals, the extra-ordinary wavefront travels faster than ordinary wavefront except along optic axis.(ve> v0 and μ0> μe).In certain crystal (like quartz). Sphere lies outside the ellipsoid as shown in fig-b.Such crystals are called positive crystals.In the crystals, velocity of ordinary wavefront is greater than extraordinary wave front except along optic axis.

☐ **Positive Crystal and Negative Crystal:**
In positive crystals the refractive index for e-ray is greater than refractive index for o-ray i.e. μe> μo.In negative crystals the refractive index for o-ray is greater than reflective index for e-ray i.e. μ0> μeIn positive crystals e-ray travels slower than o-ray in all directions except along the optic axis. V0> VeIn negative crystals o-ray travels slower than e- ray in all directions except along the optic axis i.e. V0< Ve

☐ According to Huygen's, ellipse corresponding to e-ray is contained within the sphere corresponding to o-rayAccording to Huygen's, ellipse corresponding to e-ray lies outside the sphere corresponding to o-rayBirefringence or amount of double refraction of a crystal is defined as Δμ=μe-.μoΔμ is positive quantity for positive crystalsΔμ is negative for negative crystals.Example: QuartzExample: calcite

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