

Birefringence for facetors I : what is birefringence?

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Everyone who is interested in faceting is likely to have seen the double image that is visible through a crystal of calcite. Most know that this is due to a property called 'birefringence' and that highly birefringent materials are often prone to cleavage and hard to polish. This article is written for people whose knowledge ends there, but who wish to know more. Why, for example can the double image be reduced by cutting a gem with appropriate orientation within a birefringent crystal (Figure 1.1) but not eliminated entirely? What does the following entry (from 'Color Encyclopedia of Gemstones' by Arem) for corundum mean: birefringence = 0.008-0.009, $n_o = 1.757-1.770$, $n_e = 1.765-1.779$, uniaxial (-) ?



Fig 1.1 Comparison of a non-birefringent gem, strontium titanate, left, with a highly birefringent one, titanium dioxide (rutile) on the right. Although the rutile was cut with the optical axis perpendicular to the table to minimise the effects of birefringence, this property is evident from a few bright facets, which appear double. The rutile and strontium titanate were obtained from Gram Faceting (Jeff Graham) and Osprey Trading (Paul Kessler) respectively.

To start with, we have to consider the nature of light. Light is essentially similar to a radio wave, manifesting itself as a transverse oscillating electric force which is always polarized, in the sense that the direction of the force is always in one plane. Unpolarized light is sometimes spoken of, but this just means it contains a mixture of waves, polarized in different planes, so that there is no net polarization. If a broadcast radio wave which is polarized with its electric force vertical reaches an antenna which is also vertical it drives electrons up and down the wire, producing currents which can be amplified to work the receiver. If the antenna is rotated so that it becomes horizontal this does not occur and the signal cannot be detected. In a crystal, charge (again in the form of electrons) is able to move up and down in specific directions when driven by appropriately polarized light waves, but does not move if the plane of polarization is at right angles to the permitted direction of

charge-movement in the crystal. A key point here is that the light wave is slowed down if energy is transferred to the electrons, moving them in this way (Figure 1.2).

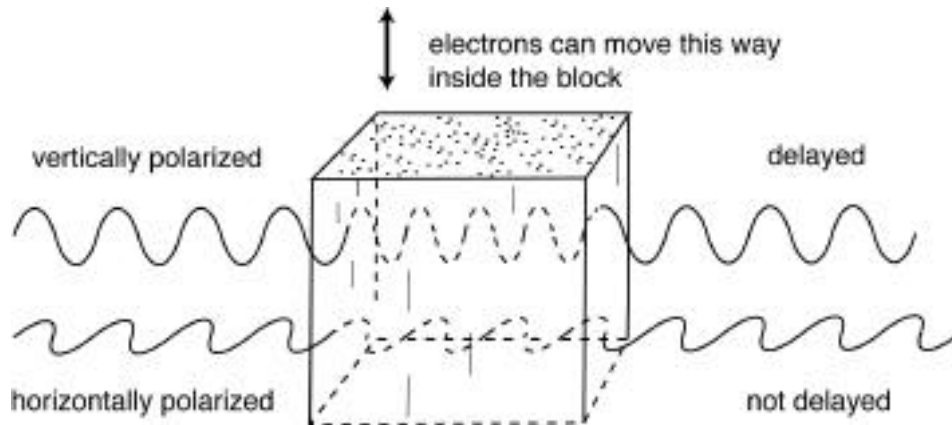


Figure 1.2 Light passing through a birefringent block of material. The frequency is constant, but the vertically polarized light travels more slowly, and waves are bunched together inside the material.

The refractive index (n) is defined as the velocity of the light in the crystal divided into the (higher) velocity of light in a vacuum. The crystal in Fig 1.2 has two refractive indices: one higher (corresponding to slow propagation) for light polarized in the direction in which charge can move and another, lower, value for light polarized perpendicular to this. These two indices are usually denoted by n_e and n_o , or, in Arem's book, e and o . If you try to measure the refractive index of a birefringent crystal in an Abbe refractometer, you may actually see two boundaries (though they are unlikely to correspond exactly to the two values of n given in the tables because they will vary with the cutting angle). Birefringence is characteristic of a material, and is defined simply as the difference between the maximum and minimum refractive index values. Since both are dimensionless fractions, the result is just a number without any special units. Rutile, with a birefringence of 0.287 and calcite with 0.172-0.190 are among the most highly birefringent materials known but quartz has a low birefringence (0.009), as does corundum (see above). These latter two minerals need not be specially oriented when you are cutting gems. You can observe the double refraction in a suitably oriented quartz block, but it needs to be 20x thicker than a calcite rhomb to give the same separation of the images. Note the weasel words 'suitably oriented', which will be explained in the next article.

Both the English (*birefringence*) and German (*Doppelbrechung*) words for this remarkable property refer to the splitting of the light, but the splitting is actually not the defining characteristic. Relatively few people know that if the angle of the rays through the crystal is chosen carefully, splitting can be eliminated completely. Fig 1.3 shows a cuboctahedron of synthetic rutile (titanium oxide) which I have chosen because it is easier than calcite to cut without spontaneous cleavage.

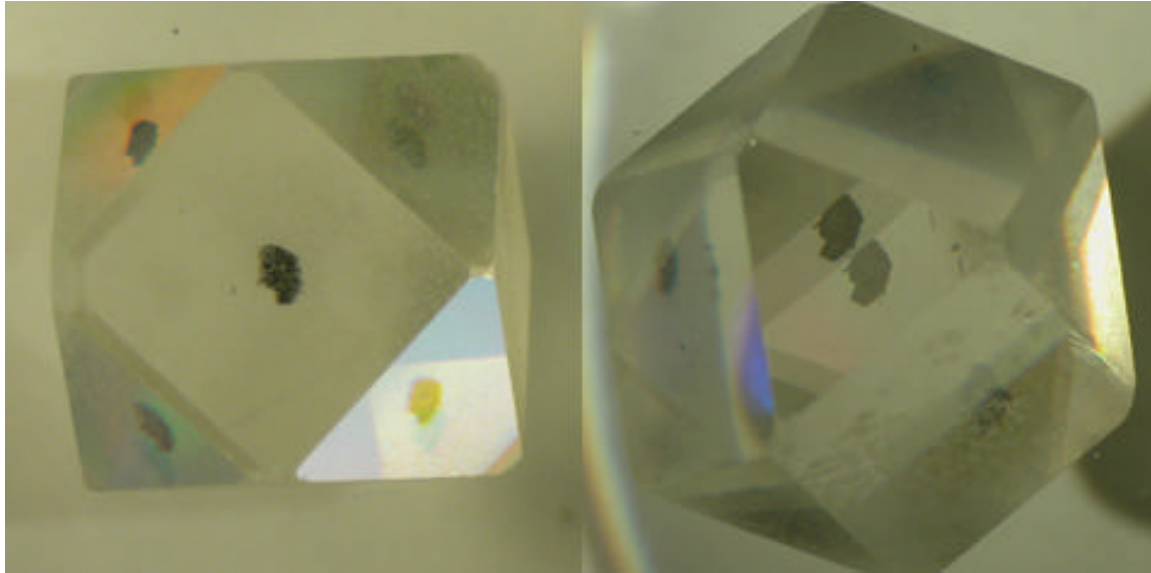


Figure 1.3 A cuboctahedron cut from synthetic rutile placed on top of an ink spot.

A cuboctahedron is not a natural cleavage form of rutile: I have imposed it on this crystal in order to reveal its optical properties. When an ink spot is viewed through any of the square faces, there is no image doubling, but the doubling is invariably seen through the triangular faces. Experiments of this type show that in calcite and rutile there is one direction of view (called the optic axis or *c*-axis) in which there is no splitting, and, also, there is no splitting in any of the infinite number of directions at right angles to the *c*-axis. Every other direction of view shows some degree of splitting. Note that in the jargon of crystallography, a direction is called an 'axis'. If you want to minimise the doubling of the facet boundaries in a cut gem, it is best to orient the table of the stone perpendicular to the *c* axis (as in the rutile in Fig 1.1) or parallel to it. This results in a nice image of the culet, without any visible doubling of the facet boundaries. However, rays that are reflected within the gem are likely to be split; facet boundaries may well appear double when viewed through the crown mains and bright double reflections may occur (Fig.1.1). These tell-tale signs of birefringence can

be used to distinguish moissanite from diamond, which is difficult by other standard methods, including thermal conductivity.

The arrangement of atoms in the calcite crystal is known, and it suggests an explanation for the c-axis. Looking along this particular direction, the atoms appear to be in a highly symmetrical arrangement with six-fold rotational symmetry (Fig.1.4 a).

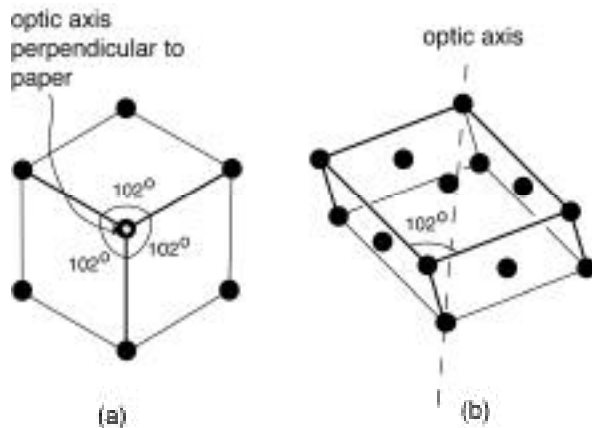


Figure 1.4. The atomic lattice of calcite, viewed from two different directions.

Only the calcium atoms are shown, but the arrangement of the carbon and oxygen atoms shows the same symmetry. There is no reason why light should travel more rapidly along this direction when it has one particular polarization plane rather than another. The refractive index, in other words, is polarization-independent, because there is no net direction perpendicular to this axis in which charge within the crystal can be shifted more easily than at right angles to it. However, looking perpendicular to the c-axis or oblique to the axis (Fig. 1.4b), atoms appear to be arranged in lines, and it is easy to see why the index should be polarization-dependent for rays passing along this line of view. In fact, symmetry (which is the visible manifestation of the way the atoms are arranged) allows us to predict whether a crystal will be birefringent or not, even without knowing the atomic arrangement. All crystals in the isometric or cubic class, including diamond, sodium chloride, cubic zirconia, strontium titanate, garnet, YAG and spinel are non-birefringent or isotropic, and can be cut and faceted with equal ease in any orientation. All others are birefringent to some degree, and tend to need orientation. Some facets on gems of birefringent material may be much harder than others, and/or more difficult to polish, but this is never true of non-birefringent gems.

A special diagram which shows the optical properties of a crystal can be drawn in the following way. First draw the optical axis as a straight line on a sheet of paper and mark a point O on it. Then imagine a ray of light perpendicular to the paper (i.e. at right angles to the optical axis) and passing through O. This ray can be polarized parallel to the optical axis, at right angles to it, or at any other angle to the axis, but it will experience a different refractive index in each case. Draw a second line through O at right angles to the first one, and with a length proportional to the refractive index for light polarized at right angles to the optical axis. Draw a third line, also centred on O, but superimposed on the optical axis line and with a length proportional to the refractive index for light polarized parallel to the axis. Repeat this for all other angles of polarization, so that you have a star-shaped family of lines. The ends of these lines all fall on an ellipse. The more birefringent the crystal, the more strongly this ellipse will differ from a circle. This construction can be extended into three dimensions by imagining rays such as one running in the plane of the paper through the central point and at right angles to the optical axis. A similar ellipse can be drawn, but this time it is situated in a plane perpendicular to the paper and containing the optical axis. A family of ellipses can be drawn in different planes, each corresponding to a ray at a particular direction through O and perpendicular to the optic axis. These ellipses define a three-dimensional surface, which is, for many crystals, an ellipsoid (Fig.1.5).

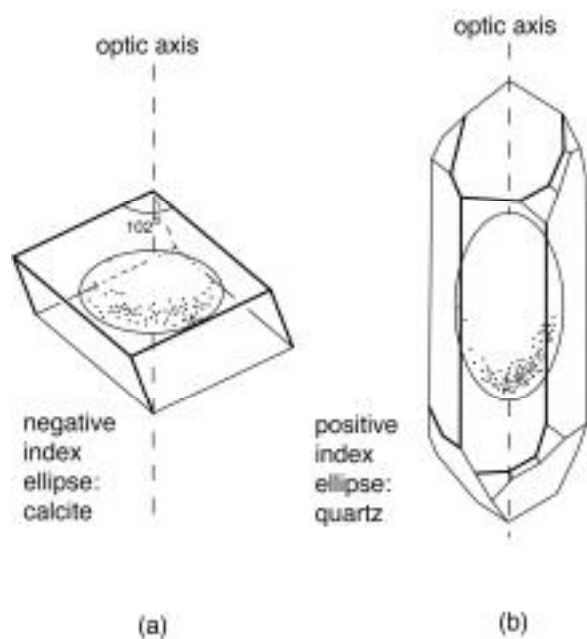


Figure 1.5 The indicatrix surface for two different minerals, oriented in relation to crystal form.

For an isotropic material the ellipsoid is a sphere. This surface is called the indicatrix for the crystal: it is a daunting name, but is just a surface in a three-dimensional diagram showing in a convenient way how the index varies with polarization direction for all possible light directions through the crystal. For calcite, the indicatrix is compressed along the axis, like the planet earth (this is called negative birefringence) and for quartz it is stretched out along the direction of the optical axis (this is positive) (Figs 1.5 a and b). The negative sign in Arem's book, quoted above, means that for corundum, as for calcite, the index is lower for light polarized parallel to the c-axis (which lies along the six-fold axis of the hexagonal corundum crystals). The indicatrix for corundum is, in other words, compressed along the axis like that of calcite. Incidentally, this leads to another definition of an optical axis. An optic axis is a direction perpendicular to any circular planar section through the indicatrix. We now know the meaning of most of the data on corundum in Arem's book.

The simple type of birefringence described above, in which there is only one optical axis, termed the c-axis, occurs only in crystals of the hexagonal and tetragonal classes. These are the classes which show hexagonal prisms or rhombs with an obvious threefold axis of rotational symmetry or, in the tetragonal class, a fourfold axis. A large number of important materials do crystallize in this way, including ice and gemstones such as quartz, sapphire, ruby, tourmaline, emerald, aquamarine and other beryls and silicon carbide (moissanite).

How do you find the direction of the optical axis in a piece of rough? It's obvious if you have well-formed crystals, since the optic axis is parallel to the axis of rotational symmetry. It is more difficult if you have tumble-polished stones or a synthetic boule. The best method is to view the rough between crossed polarizers (it may help to immerse it in an index-matching oil, though corn cooking oil is good enough). The view that gives maximum darkness corresponds to looking along the optical axis, provided the stone remains dark when it is rotated around this axis. Spheres of quartz, or, better, sapphire, are good for demonstrating this effect (the latter are made for focussing light into optical fibres and the smaller ones can be bought quite cheaply from Edmunds Scientific Inc.). In these, the optic axis is revealed as the dark centre of a beautiful celtic-cross-like interference pattern.

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