Chapter 3

Crystals

Crystals act on light in some fascinating ways and show many important influences on polarisation. Indeed the early studies of polarised light depended entirely on crystals and they have continued to be of fundamental significance. Crystals can affect light in several different ways and the result is often quite complex, although the basis is quite straightforward.

Crystals consist of a three-dimensional lattice of atoms or ions, all held together with extreme regularity. For instance common salt, sodium chloride, has equal numbers of sodium and chlorine atoms in a perfect cubic arrangement (figure 3.1). A crystal of pure sodium chloride is itself cubic and is formed of a single lattice of such cubic cells, each with an edge length of 0.562 nm. This spacing is fairly typical of crystal lattices which are all around one-thousandth of the wavelength of visible light. Since the sodium chloride crystal lattice is exactly the same in each direction, light travels through it at the same speed in each direction—the crystal is said to be isotropic and it has only one refractive index or speed of light. But other crystal lattices do not have the same structure in different directions: light travels each way at different speeds, so they are said to be anisotropic and birefringent, having two main values of refractive index, a maximum and a minimum. Just as with birefringent polymer films (chapter 2), an anisotropic crystal divides polarised light into two components vibrating at right angles and with different velocities of propagation. One component has the same velocity in all directions but the other has a velocity that varies with direction, either greater or less than the other, depending on the crystal. But, in essence, the long rows of very regularly arranged atoms in such a
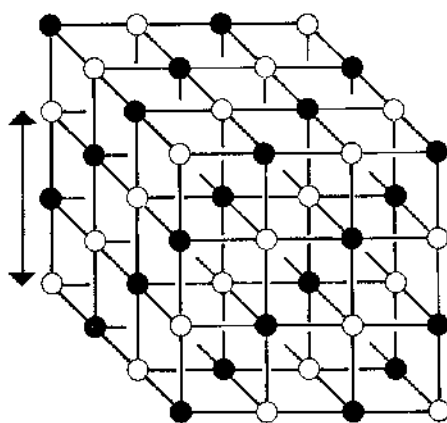
Figure 3.1. The lattice structure of a simple cubic crystal of sodium chloride. Positive sodium ions (charged atoms—dark) and negative chloride ions (charged chlorine atoms—pale) are held by electrical forces to form a regular cubical pattern with a repeat distance, as shown by the arrow, of 0.562 nm (one-thousandth of the wavelength of yellow–green light). On an enormously greater scale, such a lattice forms a crystal that is itself cubic.

crystal can act on light just like the long, parallel molecules of polymers.

Ice is crystalline in structure and a spectacular demonstration is produced by rapidly freezing a shallow dish of water (by pouring liquid nitrogen onto it) between crossed polaroids on an overhead projector. Initially the liquid water is isotropic but as the ice crystals grow, they are birefringent and show up in brilliant colours, each according to its own orientation until they all meet within the solid mass. The example shown in colour plate 12 was frozen more slowly in a freezer compartment. Another nice example is salol (phenyl salicylate) which is very strongly birefringent. Crystals can easily be melted (at 43°) on a glass plate and another warm plate is then pressed onto the melt. As the sandwich cools, the salol recrystallises in a very thin layer that shows splendid colours between crossed polarisers (colour plate 13). As explained in chapter 2, thicker birefringent crystals show no retardation colours because many wavelengths across the spectrum are rotated and all the wavelengths in between are not. So the crystal looks clear between polarisers, whether crossed or parallel, provided that it is properly orientated (figure 3.2). Rotating thick crystals extinguishes the light every 90°, as happens with
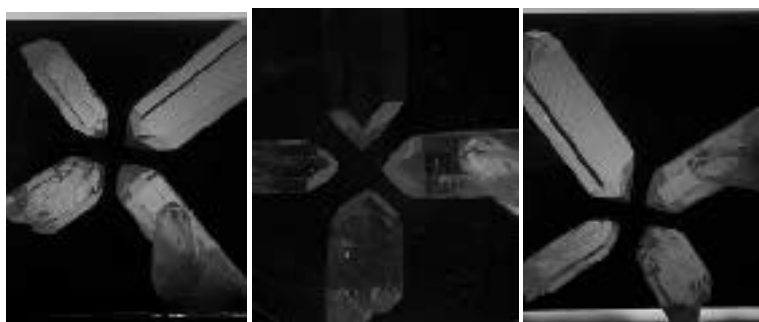
Figure 3.2. Quite large quartz crystals between crossed polaroids. As the crystals are turned they become transparent four times for each rotation as they turn the direction of polarisation; at the intermediate points they can only be seen by reflected background light. No colours are seen, however, unless the crystals are very small (the same material is seen on a microscopic scale in colour plate 16).

a half-wave plate, but the explanation is rather different.

The term 'dichroism' originally referred to crystals that simply looked to be different colours (or clear) when viewed along different axes; indeed the word literally means 'two coloured'. But the effect is often much clearer when different directions of polarisation are used in viewing the crystals. In some cases. one component of the light is absorbed (the crystal is more or less opaque to it) whereas it may be quite transparent to the other component. A good example of a crystal of this kind is tourmaline. As shown in figure 3.3, two thin pieces of tourmaline act just as polaroid film: they are fairly transparent to green light (the colour varies between specimens) but when they are crossed, the combination is quite opaque. Slices of unflawed tourmaline crystals were often used as polarising components in optical instruments (figure 3.11) as they were cheaper than Nicol prisms (described later) although they were generally of an inferior optical quality and their self-colours were sometimes undesirable. Another well-known example of a naturally occurring dichroic crystal is epidote. The artificial crystals of herapathite (iodo-quinine sulphate) were described in chapter 1 as they were a component of early kinds of polaroid.

In other crystals, one component may have only some of its wavelengths absorbed so that it emerges coloured, while the other
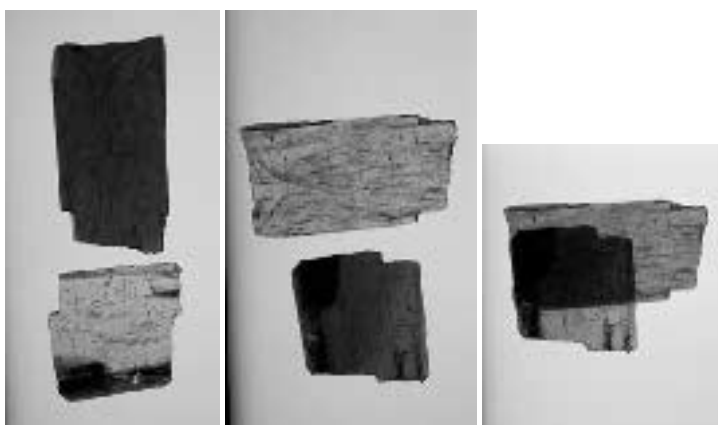
Figure 3.3. Tourmaline is a dichroic crystal: left, slices of green tourmaline one parallel to and one crossed with a background polaroid; centre, the same two pieces, both turned by 90°; right, the same two slices of tourmaline crossed with each other in normal light, with no other polariser.

component is clear. An example is sapphire which is deep blue for one direction of polarisation and clear for the other; since the eye cannot distinguish the different polarisations, they are seen mixed together and the effect is a paler blue. Obviously, any polariser allows one to distinguish immediately between a real sapphire and an isotropic crystal or blue glass. The same relation applies to the red colour of rubies. Alternatively, in some crystals the two components may both be coloured, but of different hues. A good example is copper acetate which is a bluish-green in colour, but when viewed through a polariser the colour changes from deep, royal blue to clear light green as the polariser is turned (this difference is shown in colour plate 14).

Even more variety is added by crystals that are different along three axes rather than two—a property called 'trichroism' or 'pleochroism' (literally 'more colours'), associated with three significant values of refractive index in different directions. These crystals are sometimes different in colour when simply viewed along each axis by unpolarised light (tourmaline sometimes shows this property). But again such crystals may also show quite different responses to polarised light in the different directions. Each self-colour may turn out to have two components under a rotated polariser or the transmitted light may be

absorbed for one direction of polarisation. These effects may be different for each axis of the crystal. In other words each axis may be dichroic in a different way from another axis.

Even when there is no dichroism, most crystals (all except cubic ones) show some degree of birefringence and thus affect polarised light. One of the most birefringent of natural crystals is calcite or Iceland spar (calcium carbonate) whose birefringence was described by the Danish scientist Erasmus Bartolinus in 1670, in what seems to be the first ever observation of an effect due to the polarisation of light. This material is one of the major constituents of the earth's crust, usually in microcrystalline form in marble, limestone, chalk or coral but sometimes as large, clear, rhombic crystals which are found in Iceland ('Iceland spar') and Mexico. The degree of birefringence is expressed by the difference between the two refractive indices, which for calcite are 1.486 and 1.658, giving a large difference of 0.172. Sodium nitrate ('Chile saltpetre') has an even larger birefringence of 0.251 but it is much less convenient to experiment with as it readily dissolves in water and so can easily be disfigured by handling (for this reason it only occurs naturally in very dry conditions as in Chilean deserts). In both these cases the two refractive indices are so different that the two refracted rays can be seen to diverge very markedly. A calcite crystal placed over a dot or other mark on a piece of paper shows two images (figure 3.4) and a sodium nitrate crystal does the same (figure 3.5). If the crystal is rotated, one image stays still while the other one moves in a circle around it. It was this observation, first made by Bartolinus in 1670, that eventually led to the discovery of polarisation and, in turn, contributed greatly to our basic understanding of the nature of light itself. We now know that the 'ordinary ray', which gives the stationary image, has a lower velocity within the crystal than the 'extraordinary ray' that gives the moving image. In some crystals it is the other way round—the ordinary ray is faster.

Viewing the double image through a polariser shows that the two images are polarised at right angles to each other because turning the polariser brightens one image and extinguishes the other in turn. If the dot on the paper is replaced by a small hole in a black card, a polariser can be placed over the hole itself and again the two images seen through the crystal can be extinguished in turn, as shown in figure 3.5 with a crystal of sodium nitrate. A calcite crystal combined with a lens to view the double image of the hole (figure 3.6) makes a kind of polariscope called a dichroscope that is used by jewellers. Any dichroic

Figure 3.4. Left: a calcite crystal over a single typed word on a sheet of paper, showing a clear double image. This spectacularly large, clear crystal belongs to the Royal Institution, whose help is gratefully acknowledged. Right: a smaller calcite crystal over a small hole in a black card. In both cases, rotating a polariser over or under the crystal would extinguish each image in turn, showing that they are polarised at right angles to each other.

Figure 3.5. Left: a small sodium nitrate crystal over a regular array of holes in a black background. Each hole seen through the crystal creates a double image. Centre: the same seen through a sheet of polaroid that suppresses half the images. Right: the same again but with the polaroid turned by 90° to suppress the other set of images instead. Clearly the two sets of images are polarised at right angles to each other.

material placed in front of the hole can give different effects side by side in each image; thus a sapphire gives one blue and one clear image simultaneously, while copper acetate gives one blue image alongside a green image (colour plate 14). Materials with only one refractive index, such as glass, cannot produce such differences in colour between the two images of a single hole.

The impression is often given that calcite crystals also produce a double image of distant objects, but simply looking through the crystal
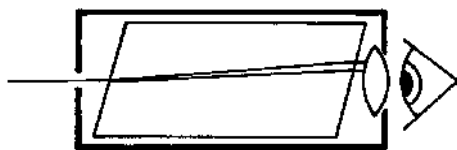
Figure 3.6. A calcite crystal can be made into a simple dichroscope that can be used to reveal dichroism in other specimens. A single small hole, seen through a calcite crystal and a small lens, produces two images that are polarised at right angles to each other. An improvised instrument was conveniently housed in a black plastic film can, and to get a neater edge the hole was drilled in a sheet of metal that was then fixed over a larger hole on the end of the case.

does not work. If one watches through a calcite crystal as a dot or hole is steadily moved further away, the spacing between the images appears to diminish with distance just as if they really are a double structure. The reason is that the two polarised rays diverge within the crystal but when they emerge again they become parallel, although separated by a little over 1 mm for each 10 mm of crystal thickness. So a spacing of, say, 2 mm from a fairly large crystal is easily seen when close to the crystal but it becomes insignificant at a distance of more than 1 m and distant objects just do not look double. But if one looks down into the crystal so that the image is seen after it has been reflected in the intermediate face (figure 3.7), then two images can be seen, each polarised at right angles to the other and at 45° to the plane of the incident and reflected rays within the crystal. This is because the two emerging rays end up diverging by about 20° and produce two well-separated and oppositely polarised images. Figure 3.8 shows how this can be demonstrated and figure 3.9 shows the result.

But this technique is rather inconvenient—for one thing the two images overlap extensively and for another the field of view is very restricted because either the rays entering the crystal or the emerging rays (or both) are close to glancing angles to the respective crystal faces. To make a more practical use of the birefringence of calcite, special 'double image prisms' have been invented. In one design, a 60° prism is cut from a calcite crystal and, instead of producing a spectrum of rainbow colours from each point of the image, it produces two spectra in different directions, each polarised at right angles to the other. A glass prism can then recombine the colours of each spectrum to produce two
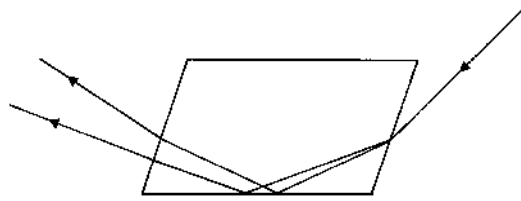
Figure 3.7. A ray of light entering a calcite crystal so that it is reflected at the next face produces a double image because birefringence results in two divergent beams and after refraction they continue to diverge. By looking down into the third face, one can see the two images and simple tests with a piece of polaroid show they are polarised at right angles to each other and at 45° to the plane of the diagram (see figure 3.9). As with most figures in this chapter, the angles are not all depicted accurately but have been altered to help clarity.
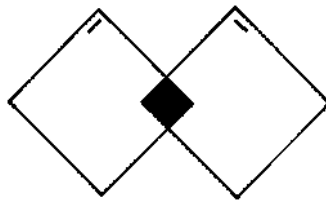

Figure 3.8. The setup used to photograph the polarised images produced by a calcite crystal as explained in figure 3.7. A light box, consisting of a backlit translucent screen, had two square polaroids mounted on it. Their oblique directions of polarisation were set at right angles as shown by marks in the top corners and by the small central area of overlap.

virtually uncoloured images, polarised at right angles to each other and well separated in space.

In 1828 William Nicol realised that one of the divergent beams within an ordinary calcite crystal could be eliminated by using the principle of total internal reflection. He cut across a crystal at a carefully calculated angle and cemented the two halves together again with Canada balsam (figure 3.10). If the angle of the cut is just right, one beam is reflected out through the side of the crystal while the other one proceeds, giving a complete separation of the two polarised components. This design was capable of several modifications (notably one by Sylvanus P Thompson) which together formed the best polarising
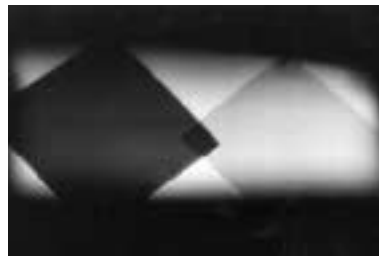
Figure 3.9. A photograph taken through a calcite crystal as in figure 3.7 of the light source shown in figure 3.8. One polaroid appears darkened and the other clear, showing that the whole image had become polarised at 45°. The other image, which emerges from the crystal at a very different angle, is exactly the same except that the condition of the two polaroids is reversed, showing that it is polarised at right angles to the above image. (Reflection, discussed in chapter 7, does not affect the polarisations here because both directions are oblique to the reflecting surface.)
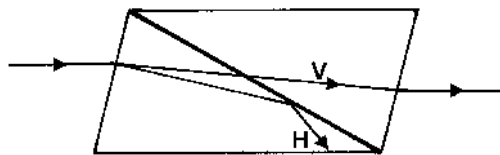

Figure 3.10. A Nicol prism polariser is made by cutting a calcite crystal at the proper angle and cementing the two pieces together again with Canada balsam. Light entering the crystal is divided by the strong birefringence into two divergent rays that are polarised at right angles. The horizontally polarised beam (H) is totally reflected at the sloping interface while the vertically polarised beam (V) continues through the crystal and emerges as 100% polarised light.

components available until polaroid became available in the 1930s. A typical Nicol prism, mounted in brass for use in an optical instrument, is shown in figure 3.11 together with a mounted tourmaline which was a cheaper option. Even today Nicol prisms are often used when the finest optical quality is needed. But they do have drawbacks: very clear crystals, free of flaws, must be used and these are seldom large so that the aperture is restricted; they only work for light beams that lie close to the long axis of the prism, so they have a narrow acceptance angle, and they
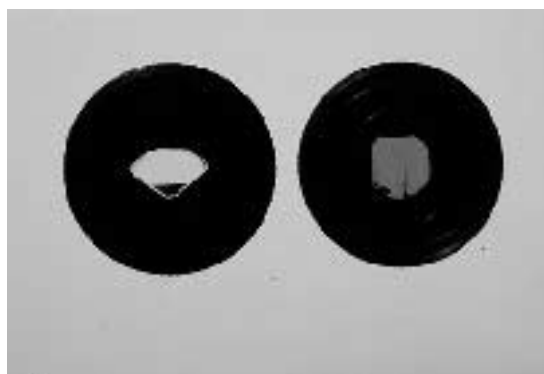
Figure 3.11. A Nicol prism (left) and a tourmaline crystal (right) mounted for use as optical devices, perhaps in a polarising microscope. Both are seen aligned with a background of polaroid. When turned at right angles, both devices become extremely dark, almost opaque.

must be very carefully crafted to make the crystals into actual prisms. The combination of scarce natural material and fine workmanship makes large Nicol prisms very expensive. The double refraction of calcite has also been exploited in other designs for polarising prisms but sheet polaroid has superseded them all for most purposes.

The reason for the very high degree of birefringence in calcite is suggested by the lattice structure of the crystal. The formula for calcium carbonate is $CaCO_3$ and within the crystal the calcium ions and the carbonate (CO_3) ions form separate alternating layers. Each carbon atom is surrounded by its three oxygen atoms in a common plane with other carbonate ions (figure 3.12). These layers of negatively charged ions are linked by electrostatic forces to the intervening layers of positively charged calcium ions and such electrical fields interact with light waves which are themselves electromagnetic in nature. Finally, these atomic lattice planes are at an angle to all the faces of the rhomboidal crystal, so that any light passing between two opposite faces must pass at a slant across millions of sloping planes of interactive charged layers. It is not necessary to understand the details of the interaction in order to expect that components of the light wave polarised in a direction normal to the lattice planes will have a different (actually greater) velocity than those polarised parallel to the lattice planes: i.e. the crystal will be anisotropic.
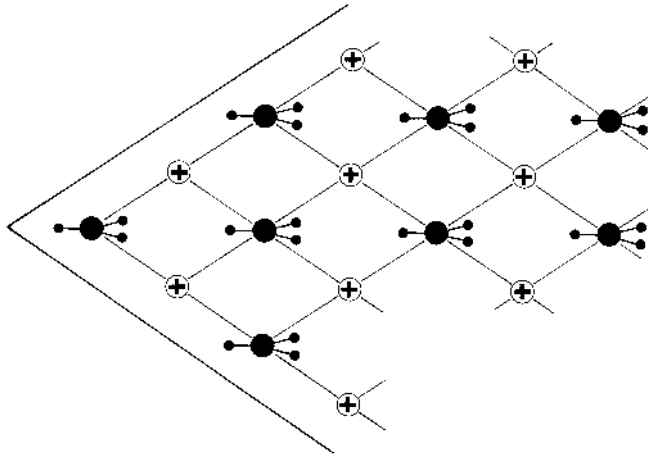
Figure 3.12. The lattice structure of calcite ($CaCO_3$). The horizontal planes of positive calcium ions (shown clear) are interleaved with planes of flat negative carbonate ions (shown as dark carbon atoms each attached to three oxygen atoms). They are bonded together by electrical forces, with each calcium attracted to its nearest three carbonates in the plane above and to three in the plane below (only two can easily be shown in a two-dimensional diagram). These electrical fields interact with the electromagnetic waves of light passing through them at an angle; this happens for light crossing between any opposite faces of the normal rhomboidal crystal, one edge of which is indicated by the straight lines, and accounts for the strong double refraction.

The same explanation applies to sodium nitrate ($NaNO_3$) where sloping nitrate planes are similarly interleaved with planes of sodium atoms.

Another natural crystal that is much used in optical devices is quartz or silicon dioxide. This is even more common in the earth's crust than calcite, since silicon and oxygen are the two most abundant elements and they are largely combined as the dioxide to form a constituent of many rocks, sand and sometimes large, clear 'rock crystals' or coloured amethysts. The birefringence of quartz is only about one-nineteenth that of calcite (0.009 instead of 0.172). But when an application calls for small retardations such as half-wave or quarter-wave plates, the appropriate slices of calcite would be too thin and fragile. Quartz is a much stronger material and the equivalent quartz sheet is also much thicker which makes it stronger and easier to work to the
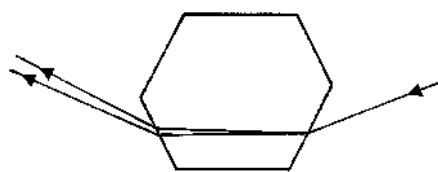
Figure 3.13. Using a columnar quartz crystal as a prism. A beam of light entering the crystal at the right angle to leave through the next-but-one face is divided into two slightly divergent beams that are polarised, one parallel to the axis of the crystal and the other at right angles. The divergence, here shown exaggerated for clarity, is so small that images viewed this way show considerable overlap as well as coloured fringes.

required accuracy. 'Quartz plates' are therefore common accessories for polarising microscopes (see later). Graded retardations are produced by a 'quartz wedge', a much superior component to the simple step-wedge described in chapter 2. Other retarder components are sometimes made of gypsum ('selenite plates' of calcium sulphate: birefringence about 0.01) or of mica (birefringence about 0.036), both of which are easily cleaved to the right thickness. An improvised retardation wedge made of gypsum is described later.

The trick of looking through a calcite crystal at an image reflected internally at one face can also be done with quartz. But because quartz is hexagonal, one can also look at an image that has been refracted from one face of a quartz crystal so that it emerges through the next-but-one face (figure 3.13). In effect the column of the crystal acts as a prism but gives two overlapping images. The divergence of the emerging rays is here very small and most images overlap so much that they look blurred rather than simply double, and of course there are also strong colour fringes. Nevertheless if one looks at a narrow slit or a linear light source (figure 3.14), there are two separate images very close together and polarised at right angles (figure 3.15).

The birefringence of a quartz crystal can also be demonstrated by using it as a prism to throw a spectrum onto a screen. Draw the blinds of a sunny window, leaving a narrow gap, and hold the crystal there so that the sun shines on it. A patch of light, coloured by a rainbow-like spectrum, will be thrown somewhere on the walls or ceiling. But the appearance of this coloured patch will be rather unfamiliar. Instead of a single patch, as with a glass prism, there are two overlapping patches
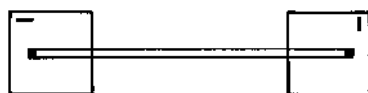
Figure 3.14. The setup used to photograph the double image that can be seen when a quartz crystal is used as a prism, as shown in figure 3.13. In order to avoid overlap between the images, a narrow source is necessary. Here a rather distant tubular fluorescent lamp was covered with a polaroid over each end, one with its polarisation direction vertical and the other horizontal as shown by the marks in the corners.
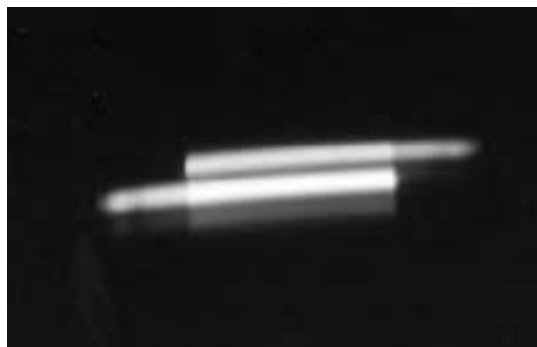

Figure 3.15. The double image of the lamp shown in figure 3.14 photographed through a large quartz crystal kindly lent by Stuart Adams. The apparent lateral displacement between the images is due to the fact that each is polarised at right angles, one vertically and the other horizontally. So the polaroid at the left is opaque in one image and the polaroid at the right is opaque in the other.

just over 1° apart (figure 3.16)—about 2 cm at a distance of 1 m. By turning a piece of polaroid in the light path, each spectral patch can be extinguished in turn, showing the normal sequence of colours and also proving that they are polarised at right angles to each other. When the same experiment is done with a calcite crystal, the two patches are separated by about 20° (i.e. 40 cm at 1 m) due to the much greater birefringence. They are so far apart that one of them might be taken for a stray reflection within the crystal, and it is only by using polaroid to extinguish them alternately that they can be clearly related to each other.

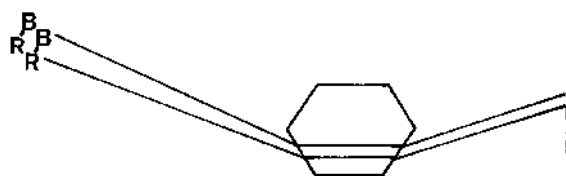Quartz also shows, much more than other natural crystals, another

Figure 3.16. Sunlight can be refracted by normal-shaped crystals to produce rainbow spectra. A 'pencil' crystal of quartz placed in sunlight, passing through a slit on the right, makes two spectra that just overlap as they diverge by just over one degree. They are polarised at right angles to each other, and a polariser rotated anywhere in the light path can remove either of the spectra and so clarify the sequence of colours (B—blue to R—red). A calcite crystal gives a much larger separation of around 21° due to its much higher birefringence.

property, called optical activity. Crystals do not show birefringence for light passing along their optical axis—the line normal to their symmetrical lattice planes. In cubic crystals all three directions are optical axes so there is no birefringence at all, but anisotropic crystals have one or two axes for which this applies (when there are two they are divergent, not at right angles). Nevertheless, when polarised light passes along the optical axis of quartz it is steadily rotated, depending on the length of its path through the crystal. The mean rotation is about 21° per millimetre of crystal but it depends rather strongly on wavelength, so that deep blue light is turned three times further than red (50° and 16° respectively). When such an optically active crystal is viewed along its optical axis and between crossed polarisers, therefore, it gives no extinction but shows colours that change as one polariser is rotated. Unlike the 'twisting' effect of birefringence (see chapter 2), light subject to optical activity remains linearly polarised at every stage so that the effect really is a simple rotation of the polarisation direction alone. Some quartz crystals rotate it clockwise and some anticlockwise. A few other kinds of crystal also show optical activity but not usually as strongly as quartz (an exception is cinnabar, mercury sulphide, which is about 20 times more effective than quartz). Some cubic crystals, which are not birefringent at all, show optical activity along all three of their axes and sodium chlorate is a good example, giving about 3° per millimetre. The explanation of optical activity will be presented at the end of chapter 5 in which the reason for the phenomenon is discussed in some detail.

Geologists exploit the fact that most crystals have distinctive effects

on polarised light which can be measured fairly easily and are catalogued in reference tables. Most igneous rocks consist of a mixture of very fine crystals of different minerals. If the rock is carefully ground down to a slice about 30 μm (thousandths of a millimetre) thick, then light can shine through the individual constituent crystals (colour plate 15). Examining these rock sections between crossed polarisers under a microscope not only makes a beautiful display of retardation colours but allows each crystal to be characterised and, in conjunction with other physical attributes, to be identified.

Geological microscopes for quantitative work vary in their arrangement according to the preferences of their designers and makers. But basically they all have arrangements to introduce polarisers both below and above the specimen stage and also to include various accessories such as calibrated retarder plates. With just a little ingenuity, any basic microscope can be adapted to produce striking effects and, with care, even quantitative measurements. A now obsolete device that was once used for such work was called a 'selenite stage', referring to its use of gypsum retarder plates. It was placed on the microscope stage and had a slider that could insert a polar of tourmaline and a gypsum or mica retarder directly under the glass slide bearing the specimen. It thus avoided problems with polarised reflection from the mirror (chapter 7) and birefringent stresses in the substage condenser lenses (chapter 2). With the advent of sheet polaroid instead of bulky Nicol prisms or coloured tourmalines, such a special slide carrier is quite simple to improvise and makes observations less fiddly, although all the effects may also be easily seen without it. A proper geological microscope also has a rotating specimen holder with a built-in protractor but this is only necessary for making actual measurements of optical constants. The second polaroid can be fitted to a cap on top of the eyepiece where it is easily rotated. The photographs in colour plates 15, 16, 19, 20, 21 and figure 3.17 were all made with such a home-made set-up. It is not even necessary to have thin rock sections, which are difficult to prepare and quite expensive to buy, because small clear crystalline fragments such as silver sand (rough quartz) give splendid effects without any preparation at all (colour plate 16).

The professional geologist uses three basic accessory retarders. A quarter-wave plate, once commonly made of mica, enhances or diminishes the retardation of an observed crystal and is used to distinguish between the directions of the ordinary and extraordinary rays in a specimen. A full-wave plate, usually of gypsum, was sometimes

called the 'tint plate' because, between crossed polarisers, its purply red colour (the 'tint of passage' or 'sensitive tint') is unmistakably reduced to red or increased to blue as a sensitive detector of quite small crystal birefringences that might not be observed directly. Both these accessories can easily be improvised by finding cellophane films with retardations of about 150 nm and 575 nm respectively (chapter 2). Plain films with other retardations are worth trying for their aesthetic effects (colour plate 15) although they have no real practical value. Pieces of mica can be obtained from some capacitors in older radio receivers (colour plate 17) but they are generally rather small and have no real advantages over films. The mounted films shown in colour plate 5 were made for use with a microscope stage and were used in preparing colour plate 15.

The third standard accessory is a calibrated quartz wedge of continuously varying retardation, from near zero to about 1700 nm or even 2400 nm, thus covering all colours up to the third or fourth order. This component is used to make quantitative measurements by overlapping it with a specimen crystal and observing the change of the retardation, as on a scale. It is not easy to improvise a quartz retardation wedge because quartz is very hard and difficult to work—it is harder than a steel knife blade and will scratch glass. Gypsum is very much softer and gives almost the same retardation, so quite respectable optical retardation wedges (colour plate 18) can be made by carefully rubbing thin slivers of gypsum on a fine stone and examining them frequently between crossed polars to check progress. Because gypsum is so soft and fragile, it is difficult to grind the thin edge to give less than about 250 nm retardation but this can be remedied by simply superimposing an appropriate cellophane retarder film over the whole wedge. The film is orientated so that it counteracts the effect of the thin end of the crystal, that is until the end becomes black between crossed polarisers. All other retardation values are reduced by the same amount of course and the sequence of colours 'slides' along the wedge. A similar trick is often used even in professionally made quartz wedges. Cruder step-wedges can be made from successive layers of adhesive tape (chapter 2, colour plate 4).

As an alternative to a wedge, very small calibrated changes of retardation can be introduced by inserting a mica plate into the light path and then tilting it to increase its effective thickness. This 'Senarmont compensator' can be made extremely sensitive but it cannot fit close to the specimen and so needs to be placed within the tube

of the microscope, which therefore requires rather major modification. Another method is to superimpose two different retarders, one of them quite fine such as a quarter-wave plate that can be rotated so as to add to or subtract from the larger retardation. The rotating ring can then be calibrated to give the combined retardation in nanometres. Several more elaborate compensators have been designed and manufactured for professional use.

Geologists also characterise crystals by the interference figures they produce in convergent beams of light—also called conoscopic figures. This requires the microscope to be fitted with simple accessory lenses. Although these figures are due to polarised light, their explanation is outside the scope of this book but can be found in any text of optical mineralogy or crystallography.

Ordered, crystalline structures are found in many natural, organic materials. Structures within animal and plant tissues, as well as products derived from these, show some beautiful retardation colour effects when viewed under a polarising microscope. Examples include hair (colour plate 19), tendon and silk (colour plate 20) from animals and cell walls (and hence kapok and cotton: colour plate 21) from plants. Less surprisingly, perhaps, many cell inclusions are crystalline, including starch grains (figure 3.17) that form the food stores of plant cells. The polarising microscope is therefore a valuable tool for detecting any regularity in molecular structure. But although it is widely used by a variety of specialists, the simple basic techniques deserve to be tried much more generally. They are, after all, very simple to improvise and they can then yield results that are not only beautiful and diagnostic but can easily be made quantitative and highly accurate if necessary.

Crystals of a rather different kind, now in widespread use, are liquid crystals. These are composed of molecules that, between certain temperature limits, spontaneously align themselves in one direction. They are not rigidly bound as in a solid crystal, yet they are not totally disorganised as in a melted liquid. The nature of liquid crystals was first made clear, following their discovery in 1888, by studying them under polarised light. There are several types of liquid crystal but some are birefringent and so twist the direction of polarisation of light, while some are asymmetrical (see chapter 5) and produce circularly polarised light (see chapter 8). The individual molecules may also align themselves with an electric field that then determines the crystal axis, and this is the basis of the liquid crystal displays (LCDs) now used in most pocket calculators, digital watches and miniature TV screens. The details vary
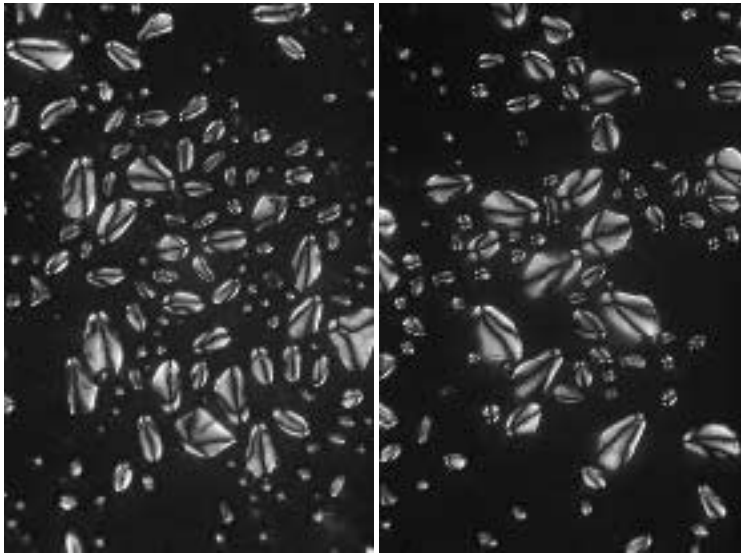
Figure 3.17. Starch grains are the food reserves stored by many plant cells and may ultimately form a staple diet of humans. They have a crystalline structure that is laid down as successive layers around an initial point called the hilum, so that the optical properties radiate outwards in all directions. Between crossed polarisers, therefore, the grains reproduce all the successive views of a rotated crystal: four bright bands alternating with four lines of extinction. In the grains of potato cells, seen here under the microscope, growth is unequal and the grains are oval and excentric, with the hilum towards one end, unlike grains of wheat starch which are spherical with the hilum at the centre.

between different designs but typically a thin cell (about 10 μm thick) of liquid crystal is placed between parallel polaroids. If the optical axis is normal to the polaroids (along the light path) the cell remains transparent but an applied voltage can rotate the molecular crystal axis by 90° to lie across the light path. The cell is then birefringent and acts as a half-wave plate, so the plane of polarisation is rotated 90°. The cell then blocks the light path and looks black.

A set of seven such cells can be used to form all the familiar numerical characters from 0 to 9, while more elaborate arrangements are able to produce alphabetical characters or more complex images. One striking property of LCD displays is that they consume extremely small

amounts of power; only 1 watt would be needed to maintain 100 m^2 in the 'switched on' condition. This makes them very attractive for use in pocket calculators for instance, especially those powered by small solar cells. One can easily detect the presence of polarisers in LCD displays by viewing them through another polaroid and rotating it: the screen darkens and lightens as would be expected. But the design of LCD displays is sometimes unfortunate: those used in the instrument panels of cars may not be aligned with polaroid sunglasses worn by the driver so that their apparent brightness is degraded and they can be completely blocked by a slight tilt of the head.