Chapter 2

Changing direction

Interesting things start to happen when polarised light passes through cellophane. A simple jam-pot cover, obtainable in packets of 20 from a newsagent, can rotate the direction of polarisation by 90°. One such film, placed between crossed polarisers, can twist the direction of vibration of light from the first polariser so that it then passes freely through the second. It thus appears as a clear, circular 'window' through the darkened background—the effect is especially striking when done on an overhead projector (figure 2.1). But this only happens with certain orientations of the disc, for turning it makes the 'window' darken and brighten four times during each rotation. The explanation for this depends on a property of the film called birefringence.

Cellophane is a polymer formed by the joining together of glucose molecules in long chains, and to make a thin film the material is extruded under pressure through a narrow slot so that the polymer chains become aligned. Now light vibrating in a direction parallel with the polymer chains propagates through the film at a different speed from light vibrating at right angles, across the polymer chains. The speed of light in any material is responsible for the refraction or bending of the rays when entering or leaving, and is indicated by its refractive index, or its 'refringence'. So a material with two speeds of light, depending on the direction of polarisation, must have two refractive indices and is said to be birefringent. In a thin film of cellophane, the two different angles of refraction are not noticeable but the two speeds can have a profound influence on polarisation.

[Some readers may prefer to skip the next two paragraphs although the argument is well worth following as it may dispel

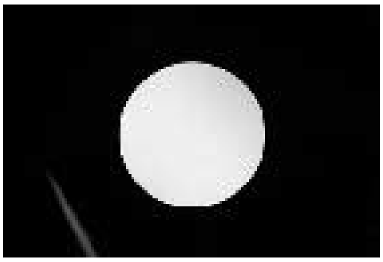

Figure 2.1. A jam-pot cover placed between crossed polaroids may form a bright, clear 'window' by twisting the polarisation direction through 90°. Rotating the cover by 45° in either direction 'closes the window'.

much of the 'mystery' often associated with polarised light; but the aesthetic effects that follow can be enjoyed without necessarily tackling the theory of their origins.]

The direction of polarisation of a wave can be simply represented as an arrow, like a hand on the face of a clock, that shows the direction of vibration as seen when the light is approaching (figure 2.2). If the length of the arrow is then made proportional to the amplitude of the wave, it is called a vector. Now any vector can be considered to be equivalent to two other vectors with any two directions and lengths; if the pair of arrows are used to make two sides of a parallelogram, then the diagonal between them is the equivalent single vector or resultant (figure 2.2). They are just like a parallelogram of forces and indeed they do actually represent the forces of the electrical field associated with the light wave.

When the direction of polarisation is either parallel with the polymer chains or at right angles to them, then the light is unaffected, apart from a slight delay in traversing the film. But when the direction of polarisation is at 45° to the polymer chains, it is divided into two components that traverse the material with slightly different delays, so that on emergence one component is retarded with respect to the other. Now a jam-pot cover gives a relative retardation of just half a wavelength, so that it acts as what is called a half-wave plate. In the retarded wave, the peaks come where the troughs would have been (and vice versa) so the vector arrow is effectively

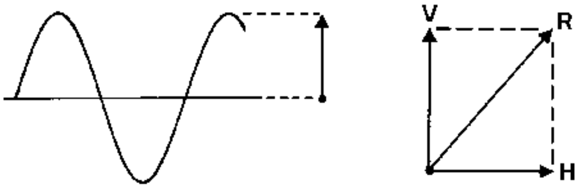

Figure 2.2. Left: a simple wave can be represented by an arrow called a vector whose direction indicates the direction of the vibration and whose length indicates its strength or amplitude. It is as if the wave is viewed as it approaches, and only the height and direction of the peaks are shown. Right: a vertically polarised wave (V) and a slightly weaker horizontally polarised wave (H) are together equivalent to the resultant vector (R), as shown by completing the parallelogram and its diagonal. As the original two arrows are at right angles, the parallelogram becomes a rectangle.

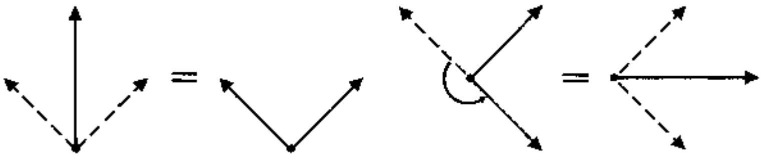

Figure 2.3. Vectors can be used to explain what happened in figure 2.1. Left: vertically polarised light passing into the cellophane film is divided into two equivalent components at right angles to each other and vibrating in the 'privileged directions' of the material. Right: on emerging from the film one wave has been delayed (or retarded) by half a wavelength so that its vector now points the opposite way and the resultant recombined wave is now horizontal, having been effectively rotated through a right angle.

inverted, and when it is recombined with the other arrow, the resultant is at right angles to the original (figure 2.3). As a result all the polarised light is rotated by 90° and passes through the second polariser. In general, the direction of polarisation is rotated by twice as much as the angle between it and the 'special axis' of the film. So turning the jam-pot cover turns the direction of polarisation by twice as much (figure 2.4) and a whole rotation of the film turns the vibrations by two rotations; it ends up unchanged, having been aligned

> and again crossed with the second polariser four times in the process. This, however, is a special case; if the film is much thinner, giving less than a half-wavelength retardation, then only a proportion of the light is twisted and can pass through the second polariser. A half-wave retardation set at 45° is just enough to twist all the light by 90°, while greater retardation twists an increasing proportion by 180° until a full wavelength retardation leaves all the light vibrating in this direction. This account is therefore somewhat simplified, though not incorrect. A more detailed explanation of what happens with retardations less than or greater than half a wavelength is given in chapter 8.

What is not easily noticed in this demonstration is that not all wavelengths are rotated by the same amount because a given value of retardation can only be exactly half a wave for one particular wavelength. A delay of 287 nm is half a wavelength for yellow light of wavelength 575 nm, but it is 0.64 of the wavelength for blue light of 450 nm and only 0.41 of the wavelength for red light of wavelength 700 nm. (It is sometimes said that this is offset for some materials because the refractive index itself varies with wavelength; but the degree of birefringence, which causes the retardation, is actually greater for shorter wavelengths, thus increasing this disparity. The essential argument, however, is much simpler because a fixed retardation, common to all colours, must necessarily delay each by a different proportion of their wavelength and so affect them differently.) Due to the shape of a simple wave, both the proportions quoted earlier for a half-wave delay give amplitudes that are quite close to those of their respective peaks (figure 2.5) and the resulting rotations are so similar that the differences pass unnoticed. With greater retardations, however, the differences become clear: a 'full-wave' retardation of 575 nm returns the vector for yellow light to its original position (just one wave later) so that it is again blocked by a crossed polariser, whereas red light is turned less and blue light more, so that quite a lot of each gets through and the effect of the mixture is purple.

Brilliant colours are seen when several different films are laid between crossed polarisers. The jam-pot-cover film shown in figure 2.1 is about 20 μm thick and gives a retardation of just about 235 nm—half the wavelength of blue light of 470 nm wavelength; the effect still looks quite uncoloured or 'white' with perhaps a very faint yellowish

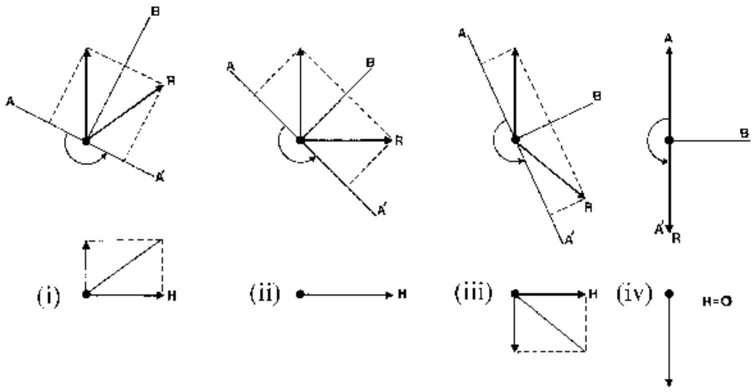

Figure 2.4. Vector diagrams show that as the half-wave retarder film of figure 2.1 is turned, the plane of polarisation is rotated by twice as much. Thick lines show the vectors, thin lines the privileged directions in the retarder and dotted lines are for construction only. In each case the initial vertically polarised light is divided into two components A and B, vibrating at right angles in the 'privileged directions' of the film. Component A is then retarded by half a wave and is effectively inverted to lie along A′. When B and A′ emerge from the film they combine to form the rotated plane of polarisation. Finally, as shown in the corresponding lower diagrams, a horizontal polariser again divides the polarisation into two components, vertical and horizontal, and passes only the horizontal one. The light was originally blocked between crossed polars but in (i) some of it becomes horizontal and is passed; in (ii) the privileged directions reach 45° (as in figure 2.3) and all the light is turned by a right angle; in (iii) the polarisation is turned even further and the result is dimmed, while in (iv) one privileged direction is vertical and has no effect so that the light is once again blocked. A complete rotation of the film 'opens and closes the window' four times.

tinge. But when two such jam-pot-cover films are overlaid, in the correct relative orientation, they give a combined retardation of 470 nm and the emergent light is orange, while three such films give a retardation of 705 nm and the effect is blue (colour plate 1). With thin films that seem to be uncoloured, the individual retardation can easily be assessed by combining several films in this way. A jam-pot cover that is simply folded at random can produce some beautiful colour effects (colour plate 2). Thicker films that give greater retardations and brilliant

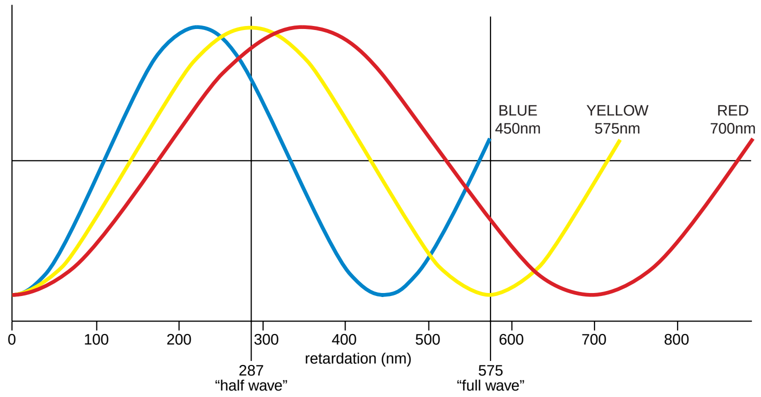

Figure 2.5. The spreading of waves of different wavelengths when subjected to various delays. A 287 nm delay is just half a wave for yellow light, a bit more for blue and a bit less for red. After a 575 nm delay the waves are spreading apart quite significantly. This disparity is actually increased slightly because the delays are generally rather greater for shorter wavelengths.

colours between polars may be obtained from the display wrappers from greetings cards or chocolate boxes (colour plate 3). And of course what is blocked by crossed polarisers will pass through parallel polarisers, so rotating either of the polarisers causes all the colours to change to their complementary colours.

Gradually increasing the thickness of birefringent material, and thus the retardation, produces a sequence of colours as different wavelengths in turn are blocked by the crossed polaroid. The sequence for crossed polarisers runs: black for a film too thin to be effective, paling to white for a 'half-wave' retardation of 287 nm, then yellow, orange, vermilion red and purple for a 'full-wave' retardation of 575 nm. The sequence then continues with a second series: blue, green, yellow, orange, red and a second purple for a 'two-wavelength' retardation of 1150 nm. Further series repeat this latter sequence except that with each repetition the colours become paler. After about the sixth series they are so faded that they are practically indistinguishable. This is because there are so many rotations, and waves of different wavelength become so separated, that no large part of the spectrum is anywhere completely blocked and the result begins to look white again.

When this happens there is actually a series of narrow wavelength bands that are rotated while the bands in between return to their original directions. The latter form dark bands at intervals throughout the spectrum that can actually be seen through a spectroscope. This effect can be easily demonstrated with a compact disc (CD) record that shows rainbow spectra when a bright light is reflected from its back. Shining the light through a 'sandwich' of a retarder that looks white between crossed polaroids (or viewing the CD through such a sandwich) shows dark bands whose spacing depends on the retardation; about 20 jam covers gives three or four dark bands. The bright regions across the spectrum add together to make the material look clear and uncoloured between crossed polarisers, always provided that it is properly orientated; rotating the material still makes it darken every quarter turn. This will be seen again in chapter 3 where thick crystals may be colourless but thin flakes are often highly coloured between crossed polarisers. A really thick crystal, say 1 cm of quartz, gives so many bright and dark bands that their separation may not be possible with the simple CD trick.

The purple colour produced by a full-wave 575 nm retardation is often called the 'sensitive tint' or the 'tint of passage' because a slight increase in retardation makes it look blue while a slight decrease turns it red. If a film of this retardation is superimposed on another material, it can reveal the presence of very slight birefringence (optical retardation) that might otherwise pass unnoticed. The actual values of retardation can be measured by superimposing a graduated 'wedge' of various known retardations and assessing the change in colour. Such retardation wedges are often made from quartz (see chapter 3) and offer values from 'zero' to 2000 nm or more, thus producing three, four or more series or 'orders' of colours. Retardation wedges that can easily be made by hand from gypsum are also described in chapter 3. Colour plate 4 shows an even simpler homemade step-wedge with progressive steps of 55 nm, made by adding successive layers of transparent adhesive tape. Since a retardation in space is equivalent to a delay in time, such a wedge can also be considered as a variable delay line. One step of 55 nm is equal to a delay of 18×10^{-17} s or 180 millionths of a millionth of a millionth of a second! Being able easily to create, measure and control such tiny time intervals using only such simple materials is very satisfying.

The sequences of colours, produced by subtracting different bands in turn from the spectrum in this way, are generally called Newton's colours or interference colours because they also appear in interference effects such as the Newton's rings experiment or in bubble films or when oil is dispersed on water. But in the case of retardation colours in

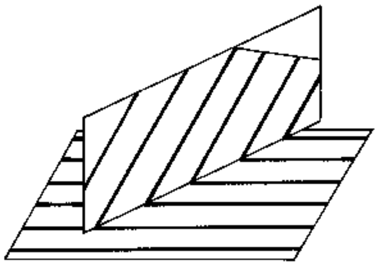

Figure 2.6. A diagram showing how a diagonal mirror (shown upright) can effectively rotate the direction of polarisation (represented by horizontal stripes). This simple geometrical change gives the complementary colours for any given retardation, provided that the mirror and the retarders are all placed between the polarisers.

polarised light no actual interference occurs and attempts to explain the phenomenon by reference to interference are unhelpful and sometimes actually wrong.

> [Two waves polarised at right angles, as in the birefringent film, are unable to interfere at all; when they emerge from the film there is no longer any reason to regard them as separate and they should be resolved into a single resultant; the effect of the second polariser on this resultant can be decided quite simply in the usual way. This avoids some quite elaborate mental and semantic gymnastics. When the retardation is one wavelength so that the two waves once again coincide, the vector returns to its original direction and the resultant wave is blocked by the second, crossed polariser; no interference occurs and the resultant does pass through aligned polarisers.]

Another name sometimes used for this sequence of colours is ‘absorption colours’ and this is quite apt because they are formed when some parts of the spectrum are removed or absorbed, in this case by the second polariser. Here, however, the name retardation colours will be used in order to emphasise the way in which they are produced.

A very striking and instructive effect can be produced when a mirror is introduced between the polarisers, for the colours may be dramatically changed in their own reflections (colour plate 5). This effect is amazing at first sight because no-one ever expects an object to look a completely

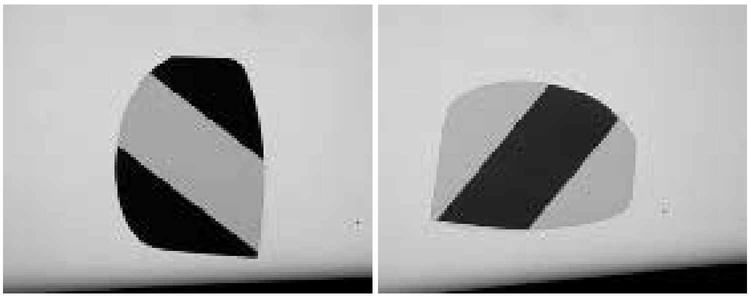

Figure 2.7. One of the most easily improvised polariscopes for detecting polarisation of light, sometimes called Minnaert's design. It can be made by adding a strip of Sellotape diagonally across a piece of polaroid at 45° to its direction of polarisation. The retardation is generally about half a wave (here about 300 nm) and gives a clear contrast in polarised light, except when the polarisation direction is exactly halfway. It is shown in two orientations over a background polariser.

different colour in its own mirror image. The mirror must be held at 45° to the direction of polarisation which, as reflected in the mirror, appears to run away at 90° to the original direction (figure 2.6). The crossed polarisers now appear to be light in the mirror and any colours produced by retardation films are changed into their complementary colours. A more formal demonstration of this is seen with a graded retardation wedge (taken from colour plate 4) and its reflection, as shown in colour plate 6. Of course the colours are not changed if the mirror is held *after* the second polariser, or indeed if the mirror is held parallel to or at right angles to the polarisation direction. Even more mystifying at first sight is the fact that a surface-silvered mirror or a polished metal reflector shows different colours from those shown in a standard back-silvered glass mirror. This phenomenon will be explained in chapter 8.

Retardation colours can be exploited in some interesting ways. In chapter 1 two simple polariscopes were described. Instead of producing a brightness contrast by two polarisers side by side, 'Minneart's polariscope' achieves the same result by a single polariser with a diagonal strip of half-wave retarder film. An easily improvised example is a strip of sellotape placed at 45° across a single piece of polaroid (figure 2.7). The tape, on the side facing the light source, forms a retarder film with a retardation of around 300 nm, acting almost as a half-wave plate and thus producing a strong contrast if the light is polarised. But a visual contrast of two colours is often thought to be more sensitive than a contrast of 'grey' intensities. So another alternative is to use two polarisers orientated at right angles and to cover them both (on the far side) with a retarder film of say 650 nm. Then polarised light will produce a blue colour alongside the complementary yellow (colour plate 7). Simply reversing the device makes the retarder film ineffective so the colours disappear and are replaced by grey contrasts (as seen earlier in figure 1.4). The user can easily compare each method and choose between them. Other colour pairs, say green and red, may be preferred and can be obtained by using different thickness of retarder film.

A quite magical result is obtained when polarisation colours are used in a kaleidoscope. Three mirrors fixed at 60° in the normal way produce a repeated pattern with sixfold symmetry. But instead of using coloured materials to produce the initial image, pieces of clear cellophane of random shape and thickness are jumbled together. Two polaroids, one on each side of the 'specimen chamber', then produce a variety of polarisation colours. When an attractive pattern is seen, rotating one polaroid changes all the colours without altering the pattern. Any gaps between the 'coloured' pieces simply change between light and dark, but if another retarder film is stretched across the whole chamber, these background holes themselves become coloured. Rotation of this film independently of the other elements modulates all the colours in the image, not just the background. A virtually infinite variety of images and colours can be obtained simply by rotating the appropriate supporting collars (colour plate 8).

I once imagined this was an original invention but then discovered that it had been patented in Beijing in 1985. The patent is probably invalid, however, because Sir David Brewster, the inventor of the kaleidoscope, described the method himself in 1858! His book on the kaleidoscope was published in 1819 and the second edition 39 years later had an additional chapter describing just how to use sheets of herapathite and/or a Nicol prism as polarisers and pieces of mica, selenite or other crystals as retarders (all described in chapter 3). He would surely have welcomed a gift of polaroids and cellophane films from the 20th century! Both his and the Beijing instruments placed the second or 'analyser' polariser at the eyepiece so that it can be small and consist of a Nicol prism, say. But this alters some of the colours that are seen after multiple reflection as explained earlier. It is better to place both polaroids in front

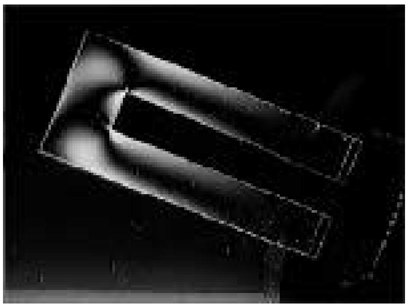

Figure 2.8. A simple U-shaped piece of perspex is normally invisible between crossed polarisers but when the arms are squeezed together gently, the internal strains so produced are clearly revealed due to their birefringence.

of the mirrors although this needs both of them to be as large as the specimen cell itself.

Some polymers such as polymethyl methacrylate (Perspex, Plexiglas etc) do not show birefringence in normal manufactured sheets. But if mechanical stresses are applied, then the internal strains in the material become birefringent and these areas can be seen as light–dark or coloured fringes if viewed between crossed polarisers (figure 2.8). This effect forms the basis for an industrial technology called photoelastic stress analysis. Any engineering component, from a simple lever or a gear wheel to a railway bridge or a cathedral arch, is first modelled in polymer resin such as methacrylate or epoxy. Then stresses are applied to simulate the loads to be expected in real situations and the distribution of internal strains can be analysed in polarised light (figure 2.9). This allows the design engineers to add strength where necessary and save material where possible. Two-dimensional or three-dimensional examinations can be made. In one variant of this technique, some actual components (of steel, say) are coated with a layer of resin and the surface strains are then viewed by reflected light. While in some ways more realistic, this method cannot show internal strains within the material.

Many common objects are made from polymer resins by heat forming or other moulding techniques. In these cases the strains imposed during shaping are retained or 'frozen in' and are easily revealed by viewing between crossed polarisers. Examples abound in any domestic environment and some examples are shown in colour plates 9 and 10.

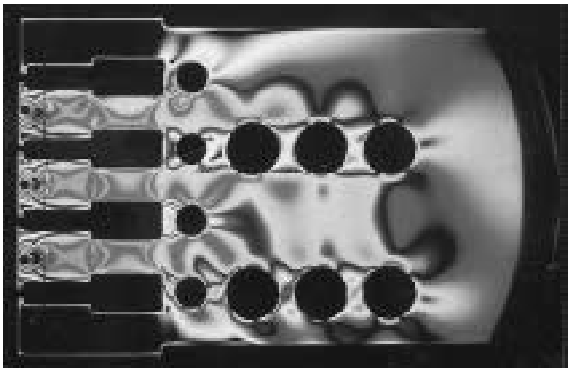

Figure 2.9. An epoxy resin model of part of a large electrical generator viewed in a professional polariscope. The coloured fringes show the strains induced by simulated centrifugal force. (By courtesy of Ken Sharples, Sharples Stress Engineering Ltd, Preston.)

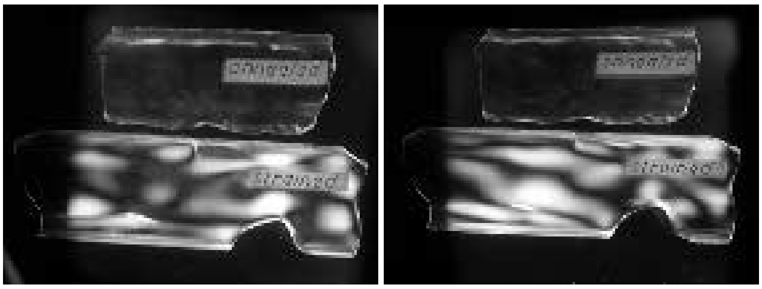

Figure 2.10. Two pieces of worked glass viewed between crossed polarisers. One was allowed to cool immediately and its internal strains show as photelastic fringes; the other was kept overnight in an annealing oven at 565 °C (not quite hot enough to soften the glass) which allowed the strains to dissipate, as shown by the absence of fringes. (Made and kindly loaned by John Cowley, Glass Workshop, Queen Mary, University of London.)

Birefringence also occurs when glass is strained and becomes permanent if the glass is cooled too rapidly after being worked. Such strains make for fragility, so glassblowers often examine their finished work between crossed polarisers and put it in annealing ovens until the strains are relieved. In the example shown in figure 2.10, one specimen was left overnight in an oven at 565 °C, which eliminated all the strains that are still evident years later in the other piece, which had been cooled rather quickly.

Some car windscreens show darkened or coloured patterns when seen through polaroid sunglasses. These screens have been toughened by heat treatment followed by deliberately rapid cooling; the resultant permanent strains ensure that under impact the glass shatters into relatively harmless small granules rather than breaking into sharp shards. The strained regions, however, are birefringent and show up under a variety of circumstances if the driver wears polaroid sunglasses: for example when the incident light is polarised by reflection, say by a wet road (see chapter 7) or comes from the blue sky (see chapter 6). Even light that is not polarised will be partly reflected from the glass and this has a polarising action (see chapter 7), causing the transmitted light to be partly polarised. The patterns may even be seen without polaroid glasses if the windscreen is itself seen by reflection in another window or in the car's paintwork. Many windscreens are strengthened by being laminated instead of being heat toughened and do not show these effects on polarised light. Laminated screens are therefore preferable if the driver likes to wear polaroid sunglasses.

An extreme example of stressed glass is shown by Prince Rupert's drops, so named because they were demonstrated to Charles II in 1661 by Prince Rupert of Bavaria. They consist of molten glass, about 1 cm in diameter, that has been dropped into cold water and so cooled very rapidly. Glass shrinks as it solidifies, so after the outer part of each drop has hardened very quickly, the inner parts cannot shrink as they should and a central space, assumed to be a vacuum, is left. The internal strains are so high that coloured polarisation fringes are very close together (colour plate 11). Although the heads of these glass drops are extremely robust, a slight scratch on the long 'tail' causes the whole object to disintegrate explosively into tiny fragments. They should therefore be treated with great care.