Chapter 7

Reflection

One afternoon in 1808 a French scientist called Etienne-Louis Malus discovered something remarkable about light reflected from transparent materials. From his home in the rue d'Enfer in Paris, Malus examined the sunlight reflected from a window in the Palace of Luxembourg, just over 1 km away to the north-northeast. Looking through a birefringent crystal, he expected to see two images of equal brightness (see chapter 3) but instead he found that if he rotated the crystal around the line of sight, each image from the window was dimmed in turn every 90°. As night was drawing on, he continued his observations with candlelight reflected by glass (as in figure 7.1) and also when reflected in the surface of a bowl of water. He found that the effect was most marked when the angles of incidence and reflection were around 55°, though slightly more for glass than for water.

The details of this important story often vary in the telling: sometimes it is said a calcite crystal was used, sometimes a quartz, and even the date is quite often misquoted. Malus' early papers on the subject (from December 1808) do not seem to relate the original circumstances, which were anecdotally recounted only in 1855 by his friend Francois Arago, in a posthumous appreciation of Malus commissioned by the Academie des Sciences. Arago only referred to the use of 'a doubly refracting crystal', but he was also discussing calcite in detail in adjacent paragraphs. The use of quartz is usually much trickier because the two images overlap so much (see chapter 3) and therefore might seem less likely. On the other hand the glint from a window 1 km away is quite small and could give separated images through a quartz crystal, although a candle flame would probably be too large a source in a domestic room.

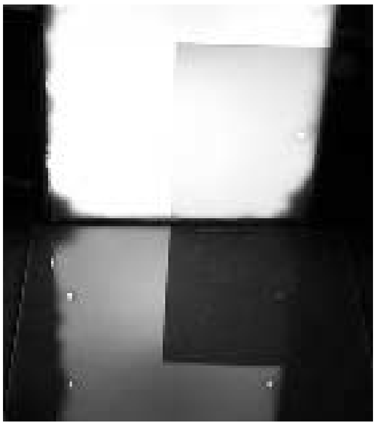

Figure 7.1. Polarisation by reflection in a sheet of glass. A vertical light box (a backlit translucent screen) has a piece of polaroid propped against its lower right, with the polarisation direction vertical. Light from the screen reflects well from a horizontal sheet of clear glass and also passes quite well through the polaroid. But light from the polaroid is not reflected in the glass because it is incident at around Brewster's angle at which only horizontally polarised light can be reflected.

The Palace of Luxembourg housed the Senate as it still does today. The garden, which is open to the public, now has tall plane trees and there are tall buildings near the Passage d'Enfer that would almost certainly obscure the view, even from the top floor. But one can get a splendid bird's eye view of the whole area from the top of the 200 m high Montparnasse Tower, a little more to the west and a comparable distance from the Palace. From there I found that a small quartz column easily resolves glints from the Palace as double images. A visit to the Palace garden also showed that the windows open on hinges, thus allowing the possibility of being set at a reflecting angle, although the building itself is arranged exactly north–south. But the sun must have been low that day in 1808 for its reflection to be seen at a distance over level ground, so the event must have started late in the day. In mid-summer the setting sun, as reflected to the Passage d'Enfer by a suitably opened window, would have an angle of incidence within about 7° of Brewster's angle (see p 74)—close enough to give a high degree of polarisation since the maximum effect is not at all critical.

Those seemingly simple observations have been hailed as a great turning point in our understanding of optics and the nature of light. At that time there was great puzzlement over the two rays produced from a single source by a birefringent crystal (see chapter 3). When two similar crystals are superimposed, the two rays may be split into four; but as one of the crystals is turned, the four become two and at one point (provided the two crystals are equally thick) even fuse to become one. This was thought to be a curious and inexplicable property of the crystals themselves, but Malus now showed that the nature of the light itself is different in the two rays. Light reflected from glass or water was clearly unusual in some way since it could form either of the beams normally produced by a birefringent crystal, depending on the orientation of the crystal. This light must therefore have some characteristic of its own that is expressed at right angles to its path.

This new way of producing polarised light by reflection very soon led a number of investigators to develop the first explanations both of double refraction and of the nature of polarisation itself. In 1808 the Academie des Sciences in Paris had offered a prize for a theory of double refraction in crystals and it was awarded to Malus in 1810; he died in 1812 aged only 37. Polarisation by reflection has also proved to be of great practical importance because in all optical devices every surface, including those of lenses, introduces some reflection and therefore some polarisation, and this may affect their operation, as discussed in detail later.

We now know that the two beams from a birefringent crystal are polarised in opposite ways and that Malus's observation of alternate dimming of the beams shows that light reflected by shiny, non-metallic surfaces is itself polarised. The direction of such polarisation is at right angles to the plane of the incident and reflected rays and this gives a simple way (as promised in chapter 1) to find which way any given piece of polaroid is aligned. Look through it at a reflection from any horizontal, shiny surface (water, glass, polished wood or gloss paint) and rotate the polaroid until the reflection dims. The direction of polarisation for transmission through the polaroid is then vertical and can be marked in one corner.

Malus soon showed that any light reflected from a piece of glass at an incidence of 57° can be reflected again from another, parallel piece (thus also at 57°), but when the second piece is rotated around the incident axis (figure 7.2) its reflection is extinguished twice in every turn. At angles of incidence other than 57° the dimming is less effective.

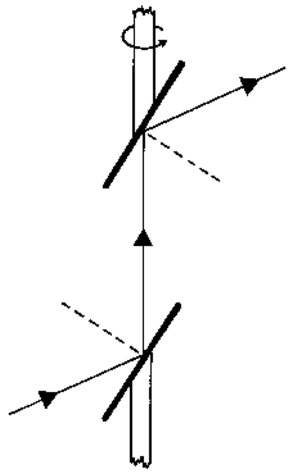

Figure 7.2. Malus's experiment. Two parallel glass sheets reflect light at an angle of incidence of 57°. But when the upper one is rotated around the vertical axis, the emergent beam fades twice as it swings round in a circle. The plates act as polariser and analyser, or second polariser.

The same effects were seen when light was reflected from glass and water in turn. Then in 1814 David Brewster realised that this 'best' angle of incidence is the one whose tangent is equal to the refractive index of the reflecting material. This is now known as Brewster's angle, at which reflected light is fully polarised. Thus the Brewster angle for glass is 57° because its tangent is 1.54 and that is the refractive index for glass. Brewster's angle also has the property that the reflected ray and the refracted ray entering the material are at right angles to each other (figure 7.3).

At Brewster's angle, only around 15% of the incident light is reflected but as it is very nearly 100% polarised, a simple reflector can be used as a very cheap polariser of wide aperture. As Malus found, a second reflector can act as a second polariser or polar analyser, reflecting the light to a varying degree, depending on its orientation to the direction of polarisation from the first reflector. This then completes a simple but very effective home-made polarising apparatus. The reflectors are best made from black perspex (plexiglass) but clear perspex will do perfectly well if the back face is painted black (without the paint there

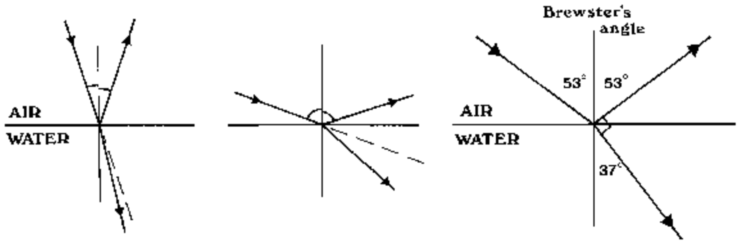

Figure 7.3. Brewster's angle. At the surface of a transparent material a beam of light is partly reflected and partly refracted. At high incidence (left) the two ongoing beams form an obtuse angle and at low incidence (centre) an acute angle. They are exactly at right angles to each other (right) when the tangent of the angle of incidence is equal to the refractive index (57° for glass in air). The reflected light is then virtually 100% polarised, in a direction normal to the plane of the diagram.

are distractions due to both transparency and double reflection). Glass is even cheaper but it is fragile. The plates, say about 10 cm $\times$ 15 cm, must be mounted in rectangular cardboard frames so that they lean across the axis at 34° (i.e. $90° - 56°$ for perspex, or $33° = 90° - 57°$ for glass, to be rather unnecessarily precise). A hole cut in the cardboard wall completes the optical pathway (figure 7.4). A sheet of clear perspex or glass, placed on top of one frame, can then support the other and also the objects to be examined. Relative rotation around the vertical axis allows the polarisers to be set parallel or crossed as required. With a little ingenuity the whole apparatus can be made to fold flat when the reflectors are removed so that it can all be stored in a shallow box.

This very simple device, or variants of it, can be used to demonstrate most of the vivid effects described in chapters 2 and 3 without the expense of large sheets of polaroid. Indeed until the 1930s reflection from glass was the only way to obtain large polarisers since both Nicol prisms and tourmaline crystals were necessarily small. A pair combined as shown in figure 7.4 was called a reflecting polariscope. It does have two drawbacks, however. First, the effectiveness is somewhat degraded towards the edges because the incident light and the line of view cannot be strictly at Brewster's angle across the whole field, especially if source and viewer are nearby. Second, the reflection is rather weak (at most

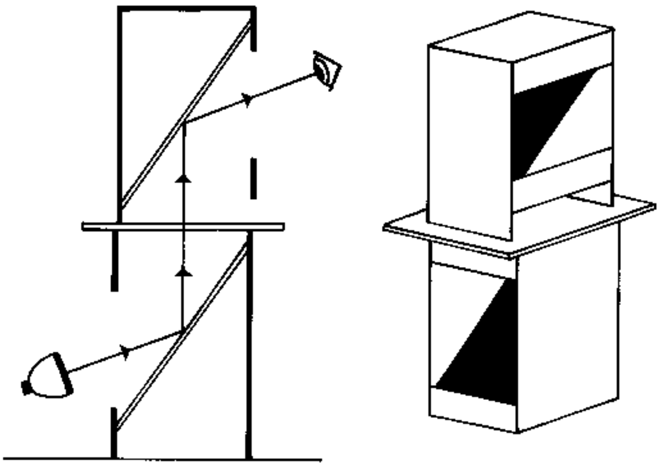

Figure 7.4. A reflecting polariscope made with two perspex sheets in cardboard stands. Left: a section showing how light is reflected twice at Brewster's angle giving the bright field effect of parallel polarisers. Right: a view of the device with the top rotated to give the dark field effect of crossed polarisers.

only about 15% of the incident light is reflected at the first surface) but this can easily be compensated for by using a bright source such as a small halogen lamp.

One way in which the brightness can be increased is to use a stack of parallel, transparent plates and take either the reflected or the transmitted light, usually the latter. At Brewster's angle the light reflected from one surface is dim but very strongly polarised. So the remaining light that passes onwards through the plate will be partially polarised by the subtraction. This light then meets the second face of the plate at Brewster's angle (due to refraction the angle is now different from the original incidence but it matches Brewster's angle exactly since in a denser medium it is the cotangent, not the tangent, that is equal to the refractive index). Light reflected back into the plate, therefore, is again totally polarised and the light passing on into air is a little more polarised (figure 7.5). So it would seem that passing this light through other, parallel transparent plates will reflect away more and more of the light polarised in one direction, making the remainder progressively more polarised. If the plates are very clear, this ongoing beam may be very

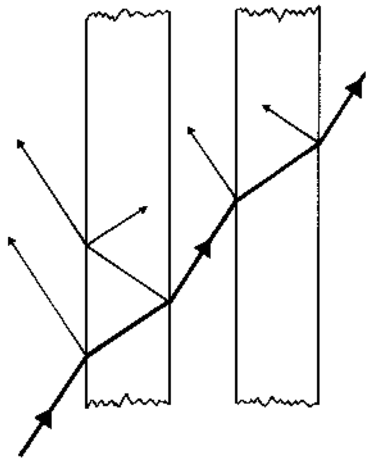

Figure 7.5. Multiple reflections by more than one sheet of glass. Light reflected from the first face at Brewster's angle is not bright but it is completely polarised; light refracted from this face meets the second face at Brewster's angle for the denser medium and the reflection is again fully polarised. The ongoing light (heavy line) is therefore enriched in light polarised at right angles—within the plane of the diagram. A second and further plates repeat the process so that the emergent beam is bright and, in principle, becomes progressively more polarised. But all the reflected light does not necessarily leave the system because some of it is reflected again as shown by the finer lines, and some of this 'unwanted light' can re-enter the onward path to degrade the final degree of polarisation.

bright—approaching 50% of the incident intensity. Many textbooks say a high degree of polarisation is quickly achieved, by as few as eight plates, and calculations of simple repeated subtraction would seem to support this.

But in practice things are rather more complicated and less effective. The main problem is that if the successive plates are close together, the light reflected from each face does not leave the system but is reflected again by the adjacent plate. It will also be reflected internally within each plate. Both processes may be repeated many times for each ray and can only be avoided by quite elaborate design. Proper analysis shows that even 16 plates in a simple stack at Brewster's angle can only achieve 74% polarisation. This theoretical performance is greatly degraded by dust or by imperfections on the glass surfaces. Adding more plates gives diminishing returns and begins to add serious loss due to absorption of the transmitted rays. Indeed a simple stack of thin glass plates does not even give the greatest polarisation at Brewster's angle but at a much higher, near-grazing angle of incidence, as noted by Brewster himself in 1831. For most purposes, therefore, a plain stack of plates is not a practical solution despite its apparent simplicity. Nevertheless a sophisticated modern version can be made by building a layer of say 25 very thin films between the faces of two prisms; by adjusting the thickness of the films, all less than a wavelength, it is possible to achieve a high degree of polarisation up to 98%, at least over a narrow range of wavelengths.

Iridescent natural materials, such as some butterfly and beetle colours, some fish scales and feathers, and the mother of pearl in shells, are composed of multiple microscopic layers of material whose very many internal reflections interfere to produce different colours in different directions. The gemstone opal gives similar effects from a structure composed of an array of microscopic spheres of silica. As might be expected, the reflected coloured lights from these materials are sometimes quite strongly polarised, as can be seen when they are examined through a rotated polaroid. Most of the bright glints of hoar frost sparkling in sunshine are also strongly polarised in a direction depending on the angle of view; the few exceptions are presumably reflecting well away from Brewster's angle and so remain bright when seen through a rotating polar.

Malus himself found that reflections from the surface of water are strongly polarised in just the same way as for shiny solids, with a Brewster angle of 53°. This accounts for the usefulness of polaroid sunglasses. It is seldom that the actual brightness of light is distressing to the eye but rather the glare: unwanted light coming from below. Much of this is horizontally polarised, especially when reflected from wet roads but also quite strongly from most kinds of dry ground. Polaroid sunglasses are vertically polarised and so they greatly reduce glare even when the line of sight is not very near Brewster's angle. (The downward looking parts of some insect eyes are sensitive only to vertically polarised light, presumably to achieve the same end when flying.) Polaroid glasses give a quite dramatic effect when one looks into still water, for reflections at the surface are reduced and at Brewster's angle are effectively abolished. One can then see clearly into the depths, with details of the bottom, weeds and fishes that are normally obscured by reflection of the sky or clouds. The water surface may seem to disappear

Figure 7.6. A sound in Bermuda photographed through a vertically orientated polaroid filter. The bather is sitting near the edge of the water which is very clear and quite still. When the polaroid suppresses surface reflections the water virtually disappears.

completely (figure 7.6) provided that there are no ripples.

The polarisation of light reflected from water is admirably exploited by the aquatic bug called the Water Boatman or Backswimmer (*Notonecta*). As its names suggest, this insect lies on its back at the surface of freshwater and rows itself around by means of greatly enlarged back legs (figure 7.7). But from time to time it flies off looking for a new pond or ditch. In 1935 it was noticed that just before plunging in, when less than a metre above the surface, the insect hesitates briefly and tilts itself upwards by nearly 20°. This was explained only in 1984 by careful examination of the insect's vision. The ventral facets of its compound eye each contain eight sensory cells of which two are sensitive to ultraviolet, one polarised vertically, the other horizontally. When swimming, these facets look up at the sky and would seem to be ideal polar analysers for sky compass orientation (chapter 6). But no facets of this kind look forwards—at all angles more than 35° from vertically below (figure 7.7) all the polarisation sensitive cells respond only to horizontal polarisation. In flight, these forward-looking facets

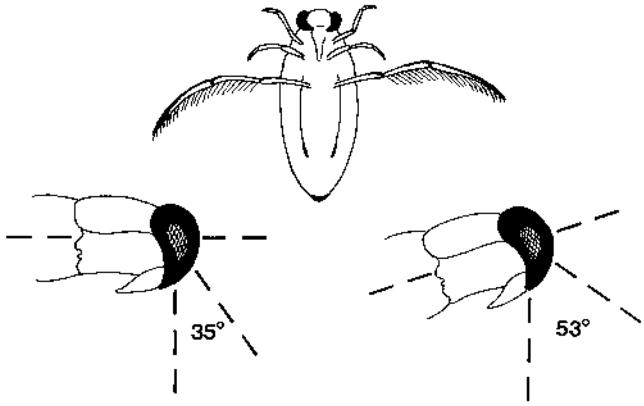

Figure 7.7. The Water boatman (*Notonecta*): top, swimming on its back; below, side views of the head; left, in normal flight posture; and right, tilted up by 28° before plunging into water.

would be ideal for detecting the polarised light reflected from standing water because light that is horizontally polarised is more likely to be seen if all the visual cells are maximally sensitive to light polarised in that direction, although they would not be able to tell that it is, in fact, polarised. But during the final plunge, the upward tilt brings some downward-looking, analysing facets just up to Brewster's angle. Maximum stimulation of some cells and loss of stimulus to the others would then confirm that the light does come from reflection off a liquid and the bug can safely complete its dive. In ingenious laboratory tests, bugs landed on upward-facing lamps but only if they emitted ultraviolet light that was polarised transversely to the line of approach, thus simulating light reflected from water.

Dragonflies also have downward-pointing facets able to analyse the polarisation of either ultraviolet or of blue light. As before, these probably serve to detect the presence of water. It has also been suggested that, as the dragonflies fly over an expanse of water, the reflected light from all sides is predominantly horizontally polarised and could provide an 'artificial horizon' to help in maintaining a proper flight path. Such cues can sometimes be misleading, however, for recently it has been found that some mayflies are attracted in very large numbers to mate and lay their eggs on asphalt road surfaces, which is, of course, disastrous

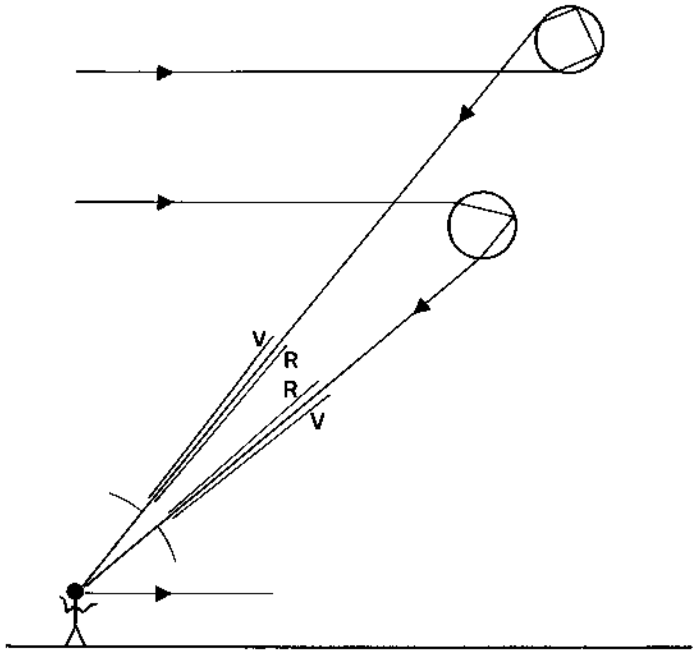

Figure 7.8. Two ray paths through raindrops that give rise to rainbows. The lower case involves a single reflection and gives the primary bow at 42° to the sun–antisun axis while the upper case involves two reflections and produces the secondary bow further out. In both cases the coloured rainbows are only chromatic fringes of larger areas of white reflective scattering which is strongly polarised in the tangential directions, around the bows.

for reproduction. It seems that roads not only resemble streams in their general shape, but even their reflected light is polarised to about the same degree as that from rippled water, which polarises light less effectively than a smooth surface.

Rainbows are another familiar source of strongly polarised light. It is often thought that rainbows result from the backscattering of sunlight by rain droplets, but actually the light is mainly returned by reflection within each drop. Figure 7.8 shows how light entering a spherical drop of water is first bent by refraction, then reflected from the back of the drop and finally refracted again as it leaves. Light can only be returned in this way up to an angle of about 42°, resulting in a disc of reflected light whose edge is 42° from the anti-sun point. This is seldom actually noticed although it shows clearly when viewed against a dark background (colour plate 25). The actual familiar rainbow is just a coloured fringe at the outer edge of this disc. It occurs because refraction allows the longer red waves to be returned at a slightly greater angle than the shorter blue and violet waves, thus forming a narrow spectrum, about 2° wide.

About 8° further out, light is again returned after being reflected, this time twice within each water drop. The inner edge of this band forms the secondary rainbow, about 3° wide and with the colours reversed—red on the inner side and blue–violet outwards. In both rainbows, the angles of reflection inside the drops happen to be close to Brewster's angle (37° or the cotangent of the refractive index for light within the denser medium) so that both kinds of rainbow are strongly polarised, the primary bow slightly more so (96%) than the secondary bow (90%). The direction of polarisation is tangential to the bows themselves, that is it runs around their curves, and this effect can easily be seen with a piece of polaroid. Segments of the bows themselves and the white regions bounded by them can be made to disappear when the polaroid is orientated in the radial direction.

When the sun is higher in the sky than 42°, primary bows can seldom be seen because they would have to be below the horizon, but bows do appear if the droplets are not falling rain but dew drops on a lawn, or the spray from a garden sprinkler or from a waterfall (colour plate 25). These rainbows are easier to observe than those produced by rain showers because they are generally less transitory and do not fade just as one is getting interested in making observations! There are many other atmospheric phenomena that give rise to colours in the sky and these are often polarised too. They are called haloes and arise from various kinds of ice crystals in high clouds; they are described in detail in the book by Greenler listed in the bibliography. Curious things happen to the polarisation of rainbows that are reflected by standing water and these are discussed in the book by Konnen, also listed there. Unfortunately both topics are too complex to go into here.

Photographers often use linear polarising filters on their cameras, either to suppress reflections or to obtain striking contrasts between sky and clouds (chapter 6). But they are often puzzled when catalogues offer filters of 'circular polaroid'. The reason is that many modern cameras have reflectors behind the lens that divert some light for automatic focusing or for automatic exposure control. These reflectors polarise

(*a*) (*b*) (*c*)

Figure 7.9. Light reflected from dark metals such as blue steel may be strongly polarised, especially at near grazing incidence—as if the refractive index were very high. (*a*) The left half, being lit here by vertically polarised light, is dark and unreflective. Other metals may show some degree of polarisation unless they are very shiny and reflect nearly all the incident light. Polarised reflection is also shown for a razor blade (*b*) and a blue hack-saw blade (*c*) using the polariscope of figure 1.4.

this light at least partially, so that a linear polariser on the lens will affect the readings as it is rotated. To avoid this, the back of the filter is covered by a quarter-wave retarder that changes the emerging light from plane to circular polarisation (see chapter 8). Because the light is now radially symmetrical, rotating this filter makes no difference to any reflections and automatic readings within the camera. The circular polaroid is actually fitted 'backwards', not in the way that would be needed to respond, as the name suggests, to circular polarisation of the incoming light. This is just one example of the problems that can arise by reflection within optical instruments; it is an effect that can easily give rise to false readings in a wide range of instruments unless proper precautions are taken in the design.

It is frequently stated that light reflected from metals is not polarised but once again reality is not quite so simple. Light reflected from dark metals such as tempered 'blue' steel may be very strongly polarised, especially at high angles of incidence (figure 7.9). Aluminium, copper and stainless steel also give quite strong polarised reflections at grazing angle (figure 7.10). It has also been long known that light that is emitted by white hot metals, either solid or molten, is strongly polarised when viewed at highly oblique angles. It was the absence of such polarisation in light from the 'edges' of the sun that showed it must be made of gas rather than solids. On the other hand a degree of polarisation in moonlight confirms that it shines by reflecting light from the sun.

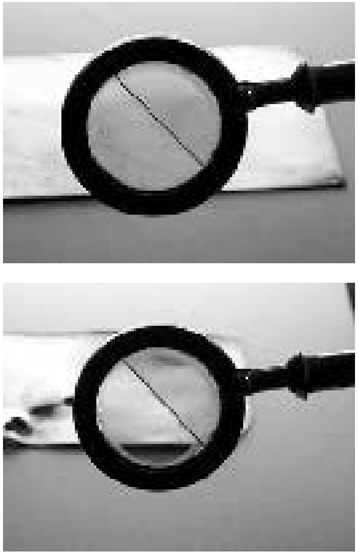

Figure 7.10. Light reflected by polished copper (bottom) is much more strongly polarised than light reflected from brass (top) which is brighter and more reflective overall. Both here and in figure 7.9, the polariscope has two pieces of polaroid each orientated at 45° to the line where they meet, so the reflected light is shown to be horizontally polarised.

Bright shiny metals reflect a very high proportion of the total incident light, so clearly this cannot be strongly polarised although there is a more subtle effect. Light vibrating in the direction normal to the surface (which would be suppressed by the Brewster effect with non-metals) suffers a phase change with respect to any components vibrating at right angles. So if the incident light is already polarised, it may become circularly or elliptically polarised after reflection (again see chapter 8 for further details). This effect will not be evident when examined with linear polaroid and is therefore often overlooked. Light reflected by a back-silvered glass mirror shows little effect because refraction by the glass limits the effective angle of incidence: even a grazing angle at the surface of the glass is reduced to a much lower angle of incidence on the silvered back (maximum about 41°, see figure 8.11).

A very interesting case is a crystal of germanium, a semiconductor that polarises light like a shiny non-conductor. Its refractive index has

Figure 7.11. Reflection on a piece of glass as in figure 7.1 but with pictures laid beneath the glass. Here it is seen that where the light is vertically polarised, and so is not reflected, the glass becomes 'transparent' and objects below it are no longer obscured by reflections. Such an effect might help fishing birds to see through the surface of water.

the extraordinarily high value of 4 so that Brewster's angle is 76° and complete polarisation occurs at an almost grazing angle. But the degree of reflection is about 40% which is almost metal-like since a polarised beam obviously cannot exceed 50% of the original unpolarised light.

The effect of polarisation can sometimes be seen without the aid of an artificial analyser. Colour plate 26 shows a lake called Bachalpsee above Grindelwald, Switzerland, photographed at dawn. The distinctive peaks of Schreckhorn and Finsteraarhorn show the view to the south-southeast (the latter bearing about 155°) and the shadows show the summer sun must be rising in the northeast over to the left. The striking feature is that the nearer part of the lake does not reflect the brilliant blue sky. The reason is that the clear sky 90° from the sun must be very strongly polarised vertically (see chapter 6); but the nearer water gives a line of view that approaches Brewster's angle at which only horizontally polarised light can be reflected. So the lake is acting as an analyser 'crossed' with the sky's polariser.

Another example is seen in colour plate 27, looking due north at sunset, as shown by shadows on the dome and minarets. The nearer part of the reflecting pool does not reflect the clear sky although the Taj Mahal itself is reflected perfectly because it is not a polariser. This beautiful effect is often seen in photographs where the view combines light from the side, a clear sky and still water in the near foreground. But are there any depictions of the effect in art? I would be most grateful for any information helping to identify a good example of the effect being noted by a landscape painter.

Finally one might speculate about the implications of polarised reflections for fishing birds. If, as now seems probable, some birds are able to respond selectively to the plane of polarisation, they might gain the advantages of polaroid glasses as modelled in figure 7.11. It would be interesting to see whether herons and kingfishers, for example, attack their prey at Brewster's angle of 53° where they would be able to see best into the water. Even if they do not respond directly to polarisation itself, they would still benefit by exploiting Brewster's angle at right angles to the sun when the sky is blue, as we can ourselves. The advantage would be especially great in early morning and late afternoon if birds faced north or south rather than in other directions. Simple observations of the behaviour of such birds might be very useful and interesting.