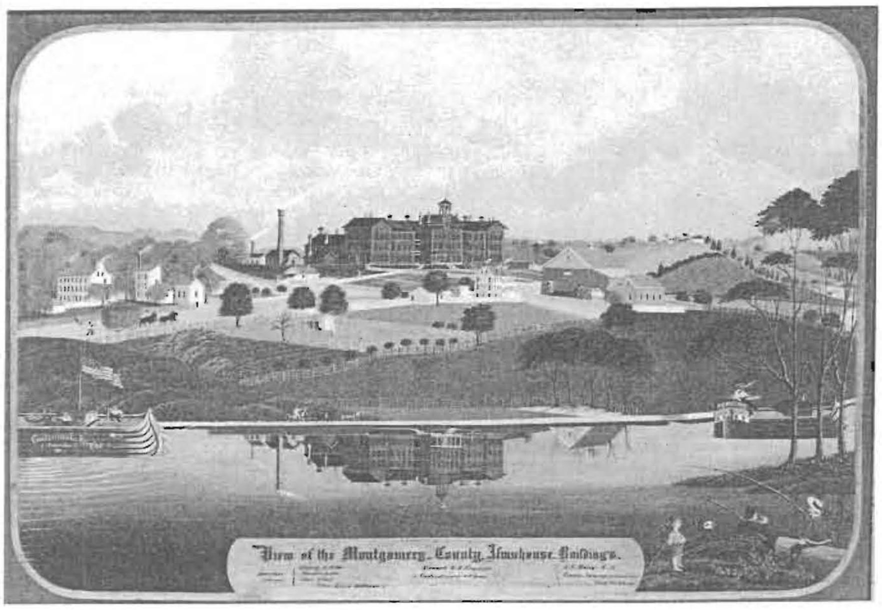


FIGURE 2.22

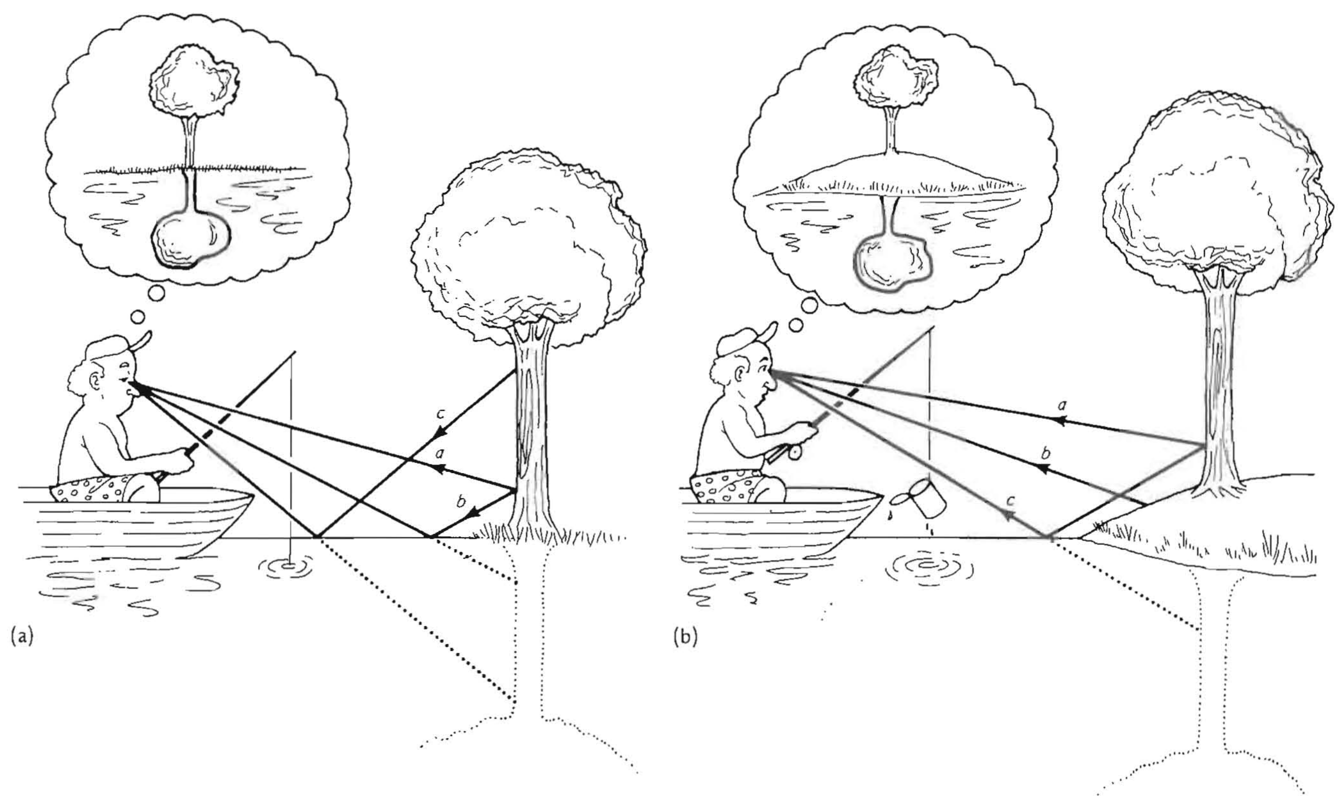
Charles C. Hofmann, "The Montgomery County Almshouse." The difference between direct view and reflection is drawn accurately and is a little more obvious than in Figure 2.21.

FIGURE 2.23

(a) A tree at the very edge of the lake has a nearly symmetrical reflection. **(b)** Here the objects in the scene are at different distances, and the reflection looks different than the direct view.

sometimes there is a difference, which is important in making a drawing or painting of a reflection look realistic (Fig. 2.22).

Suppose you look at a tree standing right at the edge of a lake (Fig. 2.23a). As your eye scans down from the top, you see the tree, and then just below the lowest ray from the tree (ray *a*), you see a ray from the bottom of the tree that was reflected by the water (ray *b*). If you look lower you see the ray reflected from the middle, and lower still you see the rays from the top of the tree (ray *c*). Thus, you see both the tree and an inverted (upside-down) image of the tree, symmetrical as most people expect of reflections (the closer your eye to the water, the more symmetrical). But suppose now the tree is up on a hill (Fig. 2.23b) instead of at the water's edge. Now as you look down, you first see the direct rays from the tree (ray *a*), then the direct rays from the hillside (ray *b*). You do not, however, see any reflected rays from the hillside because they are blocked by the bottom of the hill-



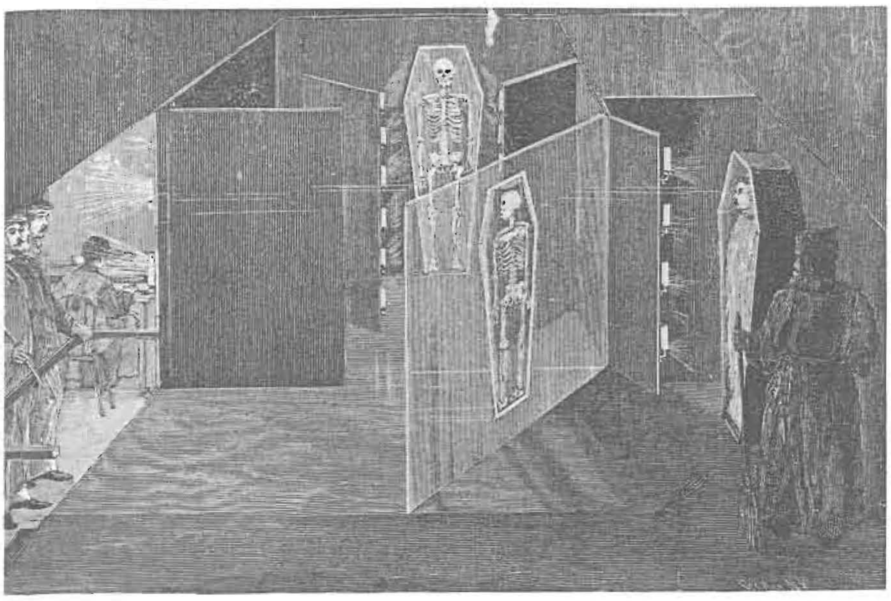


FIGURE 2.29

The Cabaret du Neant.

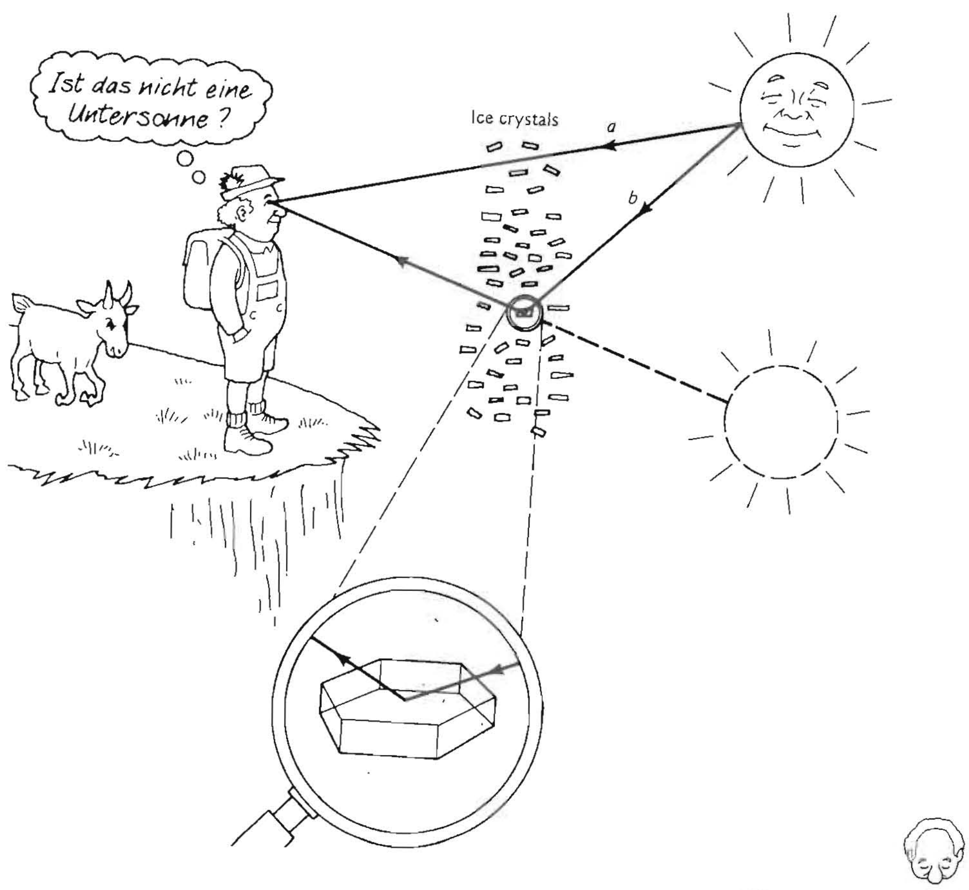


FIGURE 2.30

A sub sun is formed when sunlight reflects from the horizontal surfaces of ice crystals. The magnifying glass shows a single crystal.

2.28). If originally light A, beside the friend's head, is turned on and the other light is off, the viewer can only see her friend's head. You then gradually dim light A and simultaneously gradually turn on light B, beside the skull, and the viewer sees her friend's head turn into a skull.

The nineteenth-century Cabaret du Neant (Fig. 2.29) was a glorious elaboration of this trick, featuring coffins and other lugubrious paraphernalia, the proprietor of this "cabaret" providing the appropriate funereal words to create a properly sepulchral atmosphere. Nowadays, the technique is used less morbidly in various fun houses and amusement parks, and even in museum exhibits.

*A. Sub suns and sun pillars

Reflections from ice crystals in the atmosphere cause some infrequent but striking phenomena. When water freezes in the atmosphere it may freeze in a variety of forms, depending upon the conditions—how cold the air is, how suddenly it got cold, etc. A form that concerns us here is a special, very symmetrical kind of crystal, a flat-plate, hexagonal crystal (Fig. 2.30). When these fall through the atmosphere, their large, hexagonal faces tend to become horizontal—the crystals fall flat, just as a dead leaf does when it falls from a tree. If you are lucky enough, there will be a cloud of these essentially horizontal small ice crystals, which can serve as reflecting surfaces. If you then are on a mountain, or in an airplane, so that you are above these crystals, you may be able to see two "suns." One is due to the direct rays from the sun (ray *a*) while the other (the **sub sun**) is due to reflections by the ice crystals below you (ray *b*). The sub sun is less bright and fuzzier than the sun because not all the rays are reflected and because not all the crystals are horizontal (Fig. 2.31). If there are other clouds that block out the direct ray, you may appears to be the color of the low sky. The light from the front of the wave *(b)* is reflected almost perpendicularly and therefore is weaker. If the overhead sky is not too bright you also see light coming from within the water—either light that penetrates from the back of the wave or that is scattered from the depths of the water *(c)*. The subtle changes in the colors as the wave moves and the lighting changes provide a key part of the wonder of wave-watching.

TRY IT

FOR SECTION 2.4
Magic with mirrors

Although true magicians are sworn to secrecy, we will reveal the principles of some very old mirror tricks so you can try to construct them or variations on them. For a simple device that will allow you to pull a rabbit out of an apparently empty box, you'll need a cardboard box, a mirror, and a rabbit (or whatever you care to make appear). Figure 2.26 gives the design. Looking in the front flap, the viewer sees the bottom of the box, and its reflection in the mirror. The reflection should look like the back of the box, so the box appears empty. The deception works best if the inside of the box has a pattern, designed so that the edges of the mirror don't stand out. Shadows may be a problem—a broad light source or lots of lights in the room works best. You first open both flaps to show that the box is empty. The top flap must be opened symmetrically with the front flap so that the viewer believes that the front flap's reflection is actually the back flap, and that she can see right through the box. (Place your two hands symmetrically, one on each flap.) Do not allow the viewer to look in the top opening. You then close the front flap, reach in the top flap, and pull the rabbit from the "empty" box.

The nineteenth-century Talking Head (Fig. 2.27) was a variation on this theme. It consisted of a woman whose head protruded through a hole in a table, but whose body was concealed with a 45° mirror that showed the side of the stage, designed to look like the back of the stage. The head could talk, answer questions, and so on, while appearing to sit on a plate, unconnected to a body.

Half-silvered mirrors can be used to turn objects into one another, but, since the amount of reflected light increases as the angle of reflection increases, a 45° piece of window glass works well enough for many tricks. You'll need a large box, a piece of window glass large enough to fit diagonally across it, and two lights, preferably with dimmer switches (Fig.

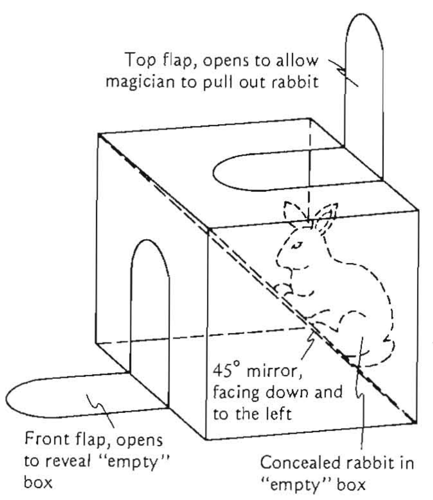


FIGURE 2.26

Design for a magic box. The box should have two flaps that can be separately opened or closed. A mirror fits across the diagonal of the box, facing down toward the front flap. A mirror tile, sold in hardware stores, works well. The rabbit is concealed above the mirror and thus is not visible from the front opening.

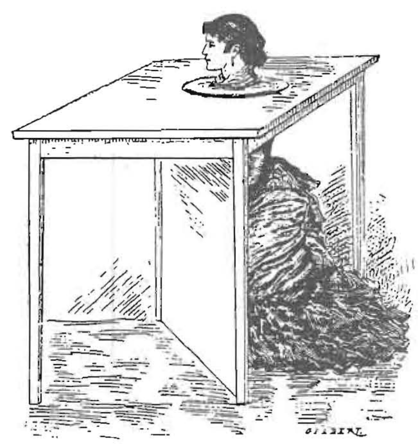


FIGURE 2.27

The Talking Head illusion.

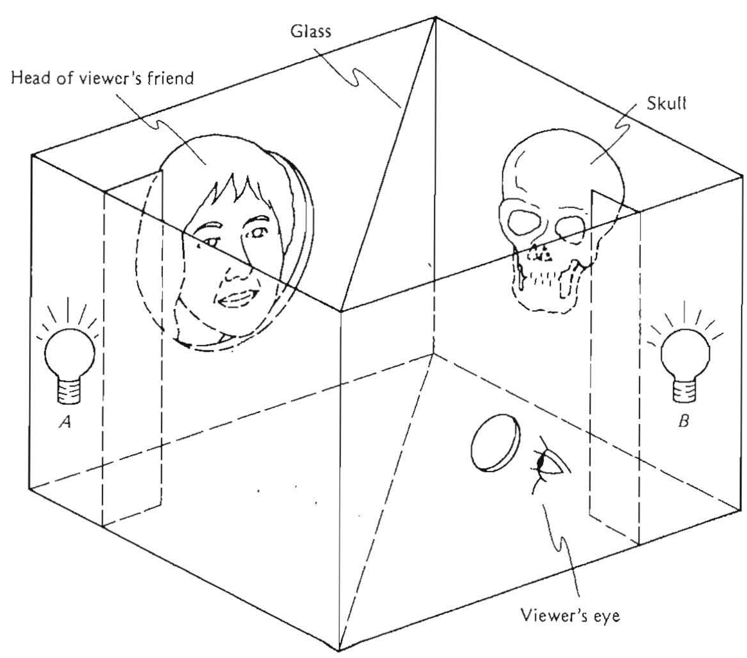


FIGURE 2.28

Design for a machine to turn a friend's head into a skull. The box has an opening in the front through which the viewer looks. There is another opening directly opposite, in the back behind the glass, through which the viewer's friend inserts his head. To the side a skull is carefully placed, so that its reflection in the glass appears in the same place, to the viewer, as her friend's head.

FIGURE 2.31

Photograph of a sub sun. (The sun itself is above, as the reflection on the airplane wing indicates.)

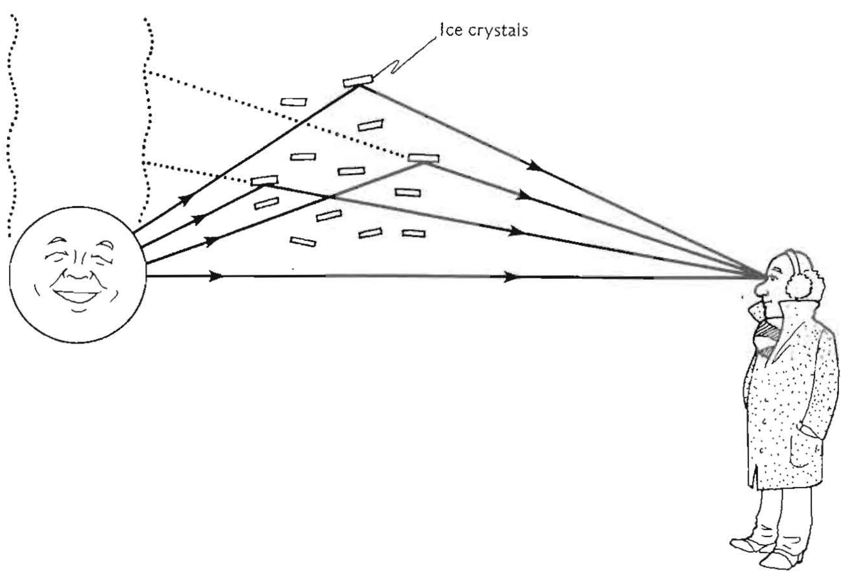
see only the sub sun. The sub sun moves with you as your airplane moves around (much as the distant moon appears to move with you as you drive a car—Sec. 8.4) and vanishes suddenly when you pass the ice crystals. It might easily be inferred to be a UFO (unidentified by those who fail to identify it).

The ***sun pillar*** comes about when ice crystals provide reflecting surfaces that are not exactly horizontal—each crystal is tilted by a slightly different amount. These surfaces can be the almost horizontal hexagonal faces of the flat crystals of Figure 2.30. Alternatively, they can be side faces of long, hexagonal, pencil-shaped crystals (as in Fig. 2.74), which tend to fall with their axes close to horizontal. In either case, there are many nearly horizontal reflecting surfaces, and you can get reflections at a variety of angles, depending on the tilt of the reflecting crystal. If there are enough ice crystals, there will be some at various heights that are just at the right angle to reflect the sunlight into your eyes. You then see light coming from all these heights, that is, a pillar of light—the sun pillar (Fig. 2.32). The pillar may be either above or below the sun, but is most often seen when the sun is low and the pillar extends above it (Fig. 2.33).

One often sees a similar effect, without any ice crystals, when the sun or moon is low over a body of water. Here, the role of the nearly horizontal ice crystals is played by the ripples in the surface of the water, and the pillar appears as a swath of light across the water (Fig. 2.34).

FIGURE 2.32

A sun pillar can be seen when the ice crystals are not all exactly horizontal.



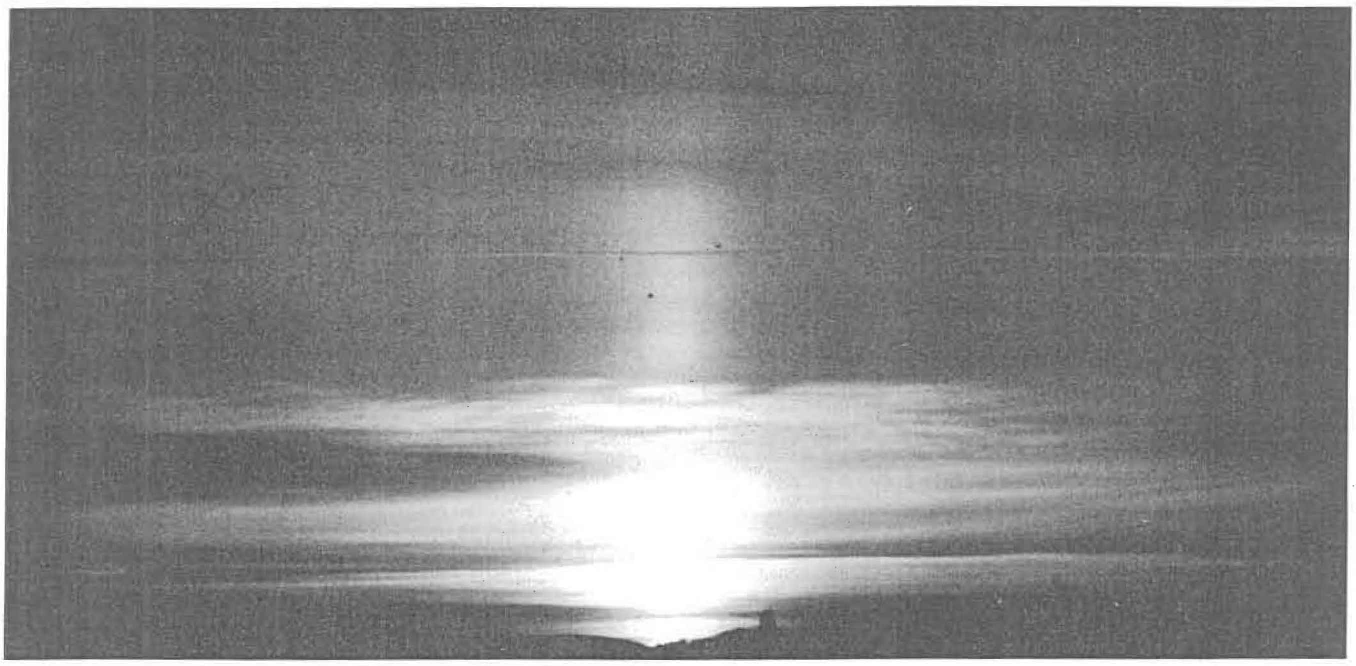


FIGURE 2.33

The setting sun, with a sun pillar above it. (The horizontal line is a thin cloud layer.)

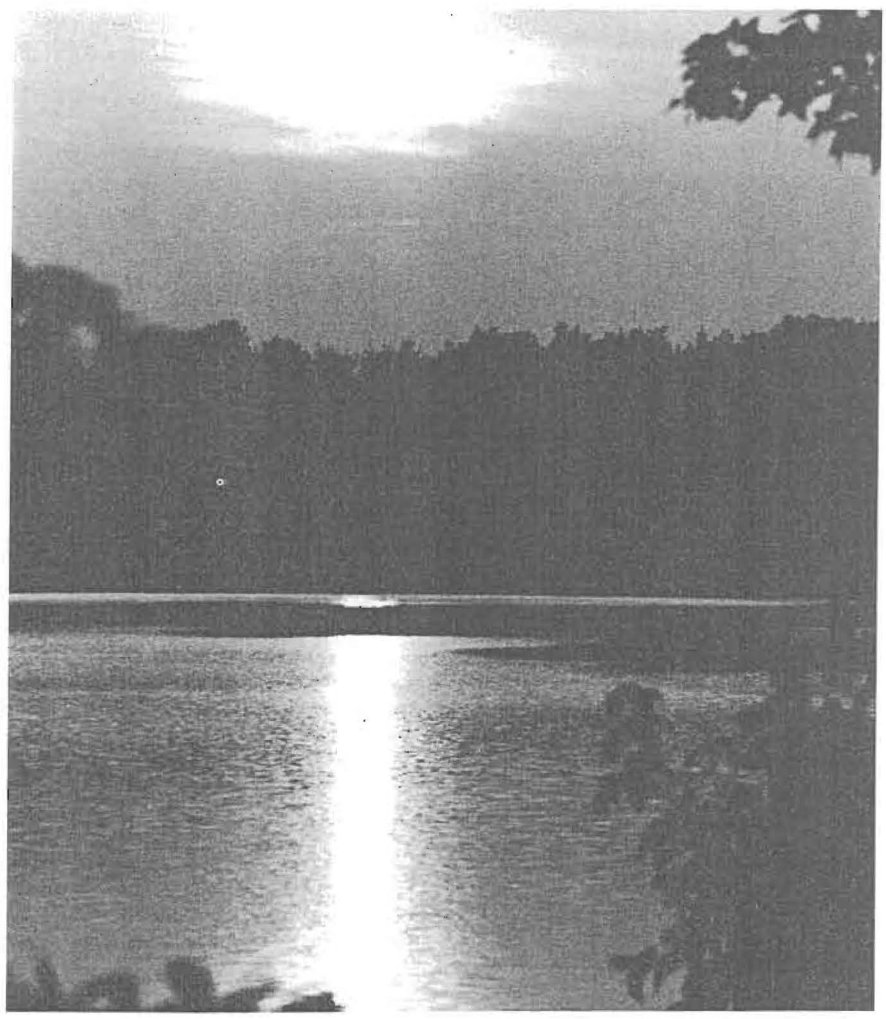


FIGURE 2.34

Mood photographs of sunsets over a lake usually show a "sun pillar" on the rippled water.

B. Diffuse reflection

We have been talking about reflections from *smooth* surfaces, such as polished metal, glass, or water—so-called ***specular**** reflections. However, if the surface is rough, like that of most cloth, we get a smeared-out reflection. Light is reflected in many directions from a rough surface, so it does not produce a "mirror image," but just an overall brightness of the surface. For example, the surface of this paper when greatly magnified is shown in Figure 2.35. The result of the reflections from all the irregularities is a ***diffuse*** reflection (Fig. 2.36), where the reflected light goes in all directions. Most surfaces are rough on a small scale, and that is very useful to us, because otherwise we would have trouble seeing them. For example, the light from your car headlights hits the diffusely reflecting road surface and is scattered all around, some of it back to your eye, so you see the road (Fig. 2.37a). In the rain, however, the road is covered by a smooth surface of water, which gives a specular reflection, sending light away from your eye (Fig. 2.37b). This is why headlights are less helpful in the rain, and why some paint for road markings contains tiny spheres that reflect light back. Note that the eye treats diffuse reflection (and even specular reflections from very small mirrors) like scattering: it assumes, correctly, that the object is located where the diffuse reflection occurred, rather than farther back along the extended ray, as it does for specular reflections from mirrors. (The driver of the car in Fig. 2.37a "sees" the road at point *a*, whereas the man in Fig. 2.19 tends to "see" the image behind the mirror, rather than the mirror itself; see Fig. 2.38.)

*Latin *speculum*, mirror.

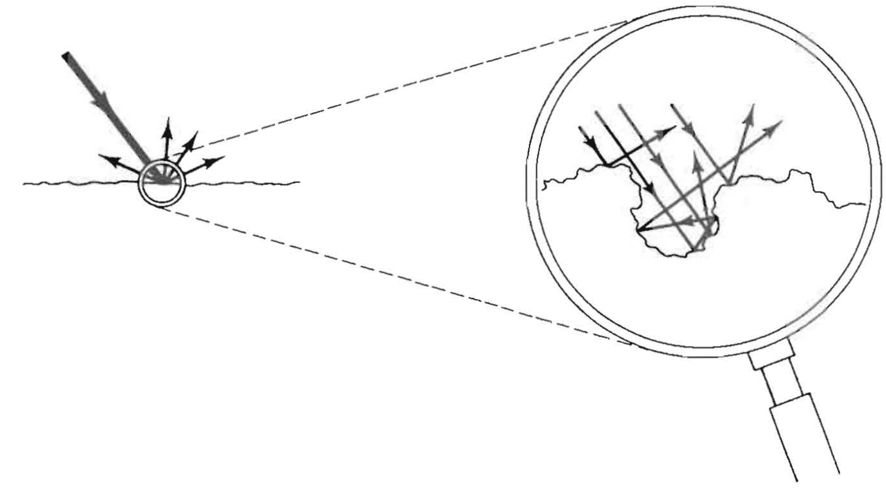


FIGURE 2.36

Diffuse reflection of a beam of light from a rough surface.

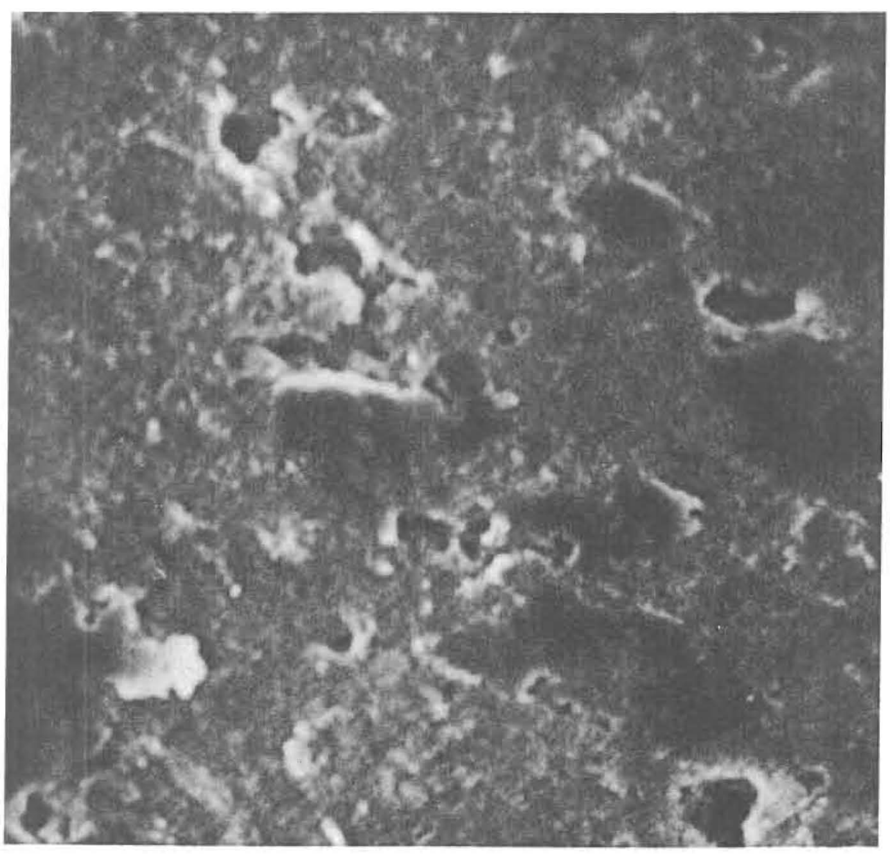
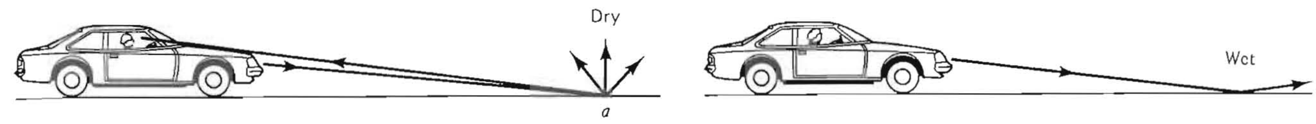


FIGURE 2.35

Scanning electron microscope view of the coated paper used in this book. The actual size of the pictured region is about 50 μm.

C. Multiple reflections

A light beam that has been reflected from one mirror is just as good as any other light beam, so there is no reason why it cannot be reflected again. And again, and again. . . . You may have seen this effect in a barber shop or a hall of mirrors, where you are between two mirrors that face each other on opposite walls. Looking into one mirror you



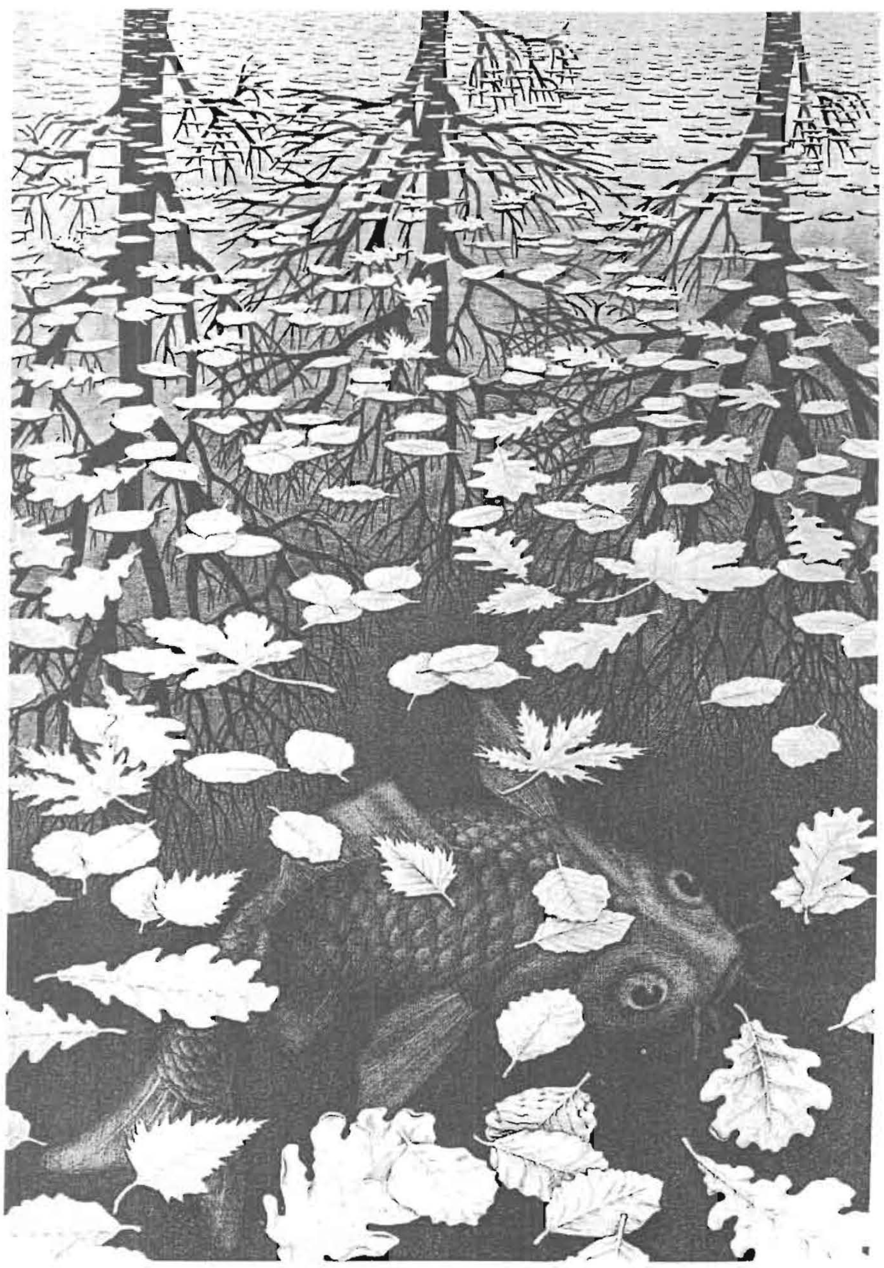
(a) (b)

FIGURE 2.37

(a) Diffuse reflection of headlights by a dry road makes the road easily visible. **(b)** More nearly specular reflection by a wet road makes the road hard to see.

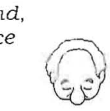
FIGURE 2.38

M. C. Escher, "Three Worlds." We see the trees by reflection, the leaves by scattering (or diffuse reflection), and (at a steeper angle) the fish by refraction.



see an "endless" series of images as each mirror produces a reflection of you, and then a reflection of your reflection in the other mirror (the back of your head), and then a reflection of the reflection of your reflection, etc., on and on. An ancient Chinese philosopher used this as an example of the meaning of infinity. Of course, the reflections are not really infinite, for several reasons: (1) often the mirrors are not quite parallel, so each image is a little off from the previous one, and the sequence of images "curves" away so you don't see all of them, (2) the mirrors do not reflect quite all the light, so each successive image gets a little darker, and the infinite end of the series fades out, (3) as John Barth wrote in "Lost in the Funhouse": "In the funhouse mirror-room you can't see yourself go on forever because no matter how you stand, your head gets in the way. Even if you had a glass periscope, the image of your eye would cover up the thing you really wanted to see," and (4) seeing an infinite number of images would mean an infinite number of reflections, hence an infinite path for the light, which it cannot cover in a finite time. In *The Third Policeman*, Flann O'Brien describes the fictional scientist de Selby, who carried this last idea a bit too far:

> *. . . he constructed the familiar arrangement of parallel mirrors, each reflecting diminishing images of an interposed object indefinitely. The interposed object in this case was de Selby's own face and this he claims to have studied backwards through an infinity of reflections by means of 'a powerful glass'. What he states to have seen through his glass is astonishing. He claims to have noticed a growing youthfulness in the reflections of his face according as they receded, the most distant of them—too tiny to be visible to the naked eye—being the face of a beardless boy of twelve, and, to use his own words, 'a countenance of singular beauty and nobility'.*



If the mirrors are not parallel but at some angle to each other, an incident ray will be reflected just a few times. For example, if the mirrors are perpendicular to each other, you get just two reflections (Fig. 2.39). The interesting thing about these perpendicular mirrors is this: no matter what the direction of incidence, the light always is reflected back into that *same* direction (at least for light in the plane of the paper). No matter from where you look into the corner, you always see yourself. Such a corner mirror does not "reverse right and left," so if you pull your left ear, the image pulls his or her left ear (see the TRY IT).

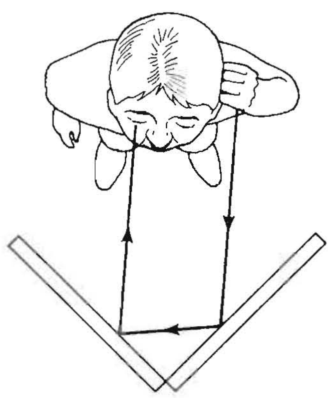


FIGURE 2.39

A corner mirror, made from two plane mirrors.

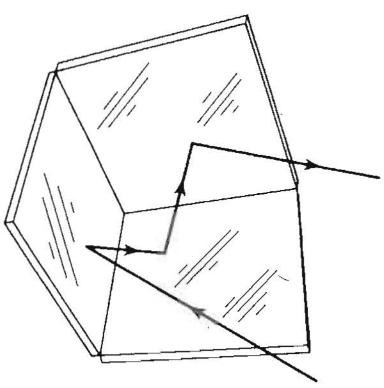
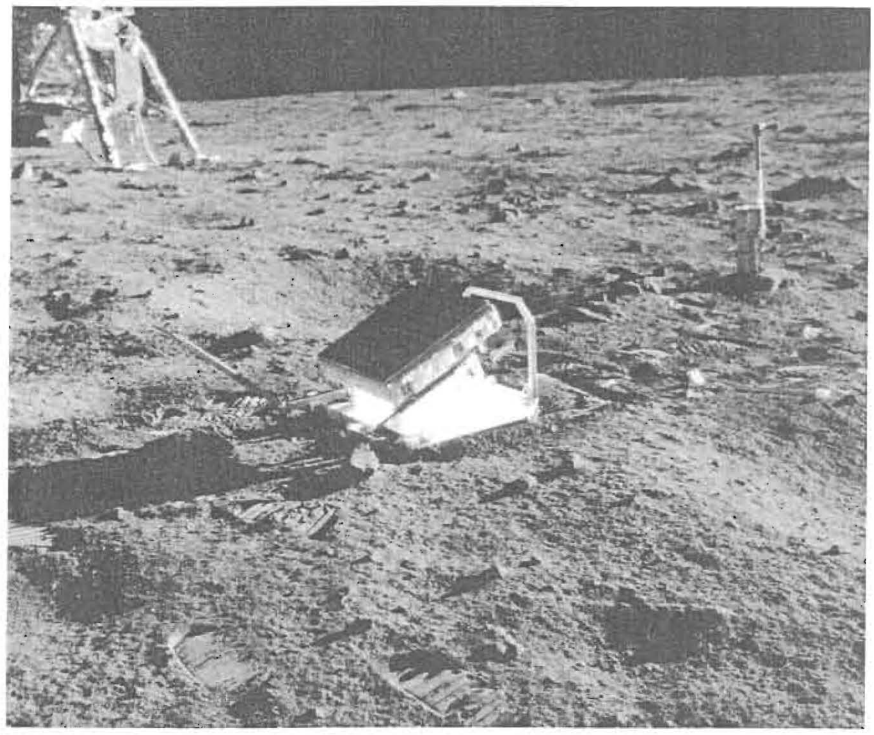
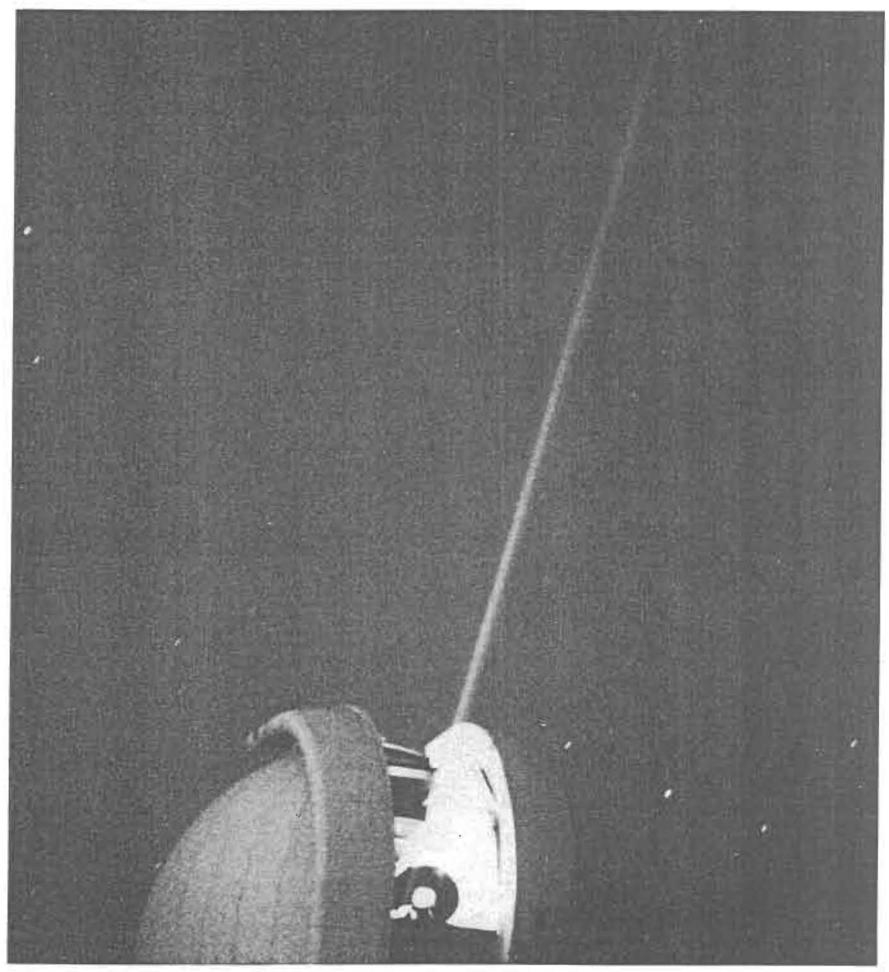


FIGURE 2.40

A corner reflector, made from three plane mirrors.





If we want a device to ***retroreflect**** all rays, whether in the plane of the paper or not, we need a third perpendicular mirror. This arrangement (Fig. 2.40) is called a ***corner reflector.*** It reflects any beam back in the direction it came from. This can be useful for anything that you want to be very visible in light from automobile headlights (e.g., highway signs, bicycles, joggers). Look closely at a bike or car reflector to see the many small "corners." (These are most easily seen after removing the opaque backing.) Corner reflectors are used on buoys at sea to reflect radar back to the transmitting ship. Corner reflectors were placed on the moon by astronauts so that a laser beam from the earth could be reflected back to the earth (Fig. 2.41). The astronauts could not be expected to align a single mirror precisely enough to reflect the beam to a particular spot on earth, but with a set of corner reflectors there was considerable leeway in the alignment. (The point of bouncing a laser beam back was to measure the transit time and hence monitor very precisely—to a few centimeters!—the earth-moon distance.)

Since most mirrors have a glass surface covering the reflecting silver, you can also get several reflections from one mirror. Most of the light is reflected from the silver, but some is reflected from the front glass surface. At normal incidence

*Latin *retro*, backward.

FIGURE 2.41

(a) Array of corner reflectors placed on the moon. Note that they look black—they reflect the black sky behind the camera; the sun is to the right (note shadows), and the moon has no atmosphere to scatter the sunlight (hence the black sky). **(b)** Telescope at McDonald Observatory, Mt. Locke, Texas, being used "backward" to send a laser beam to the corner reflector on the moon. Note that stars have become short streaks due to the long exposure necessary to make the laser beam visible, even though the beam was made narrower than normal to make it sufficiently bright to be photographed.

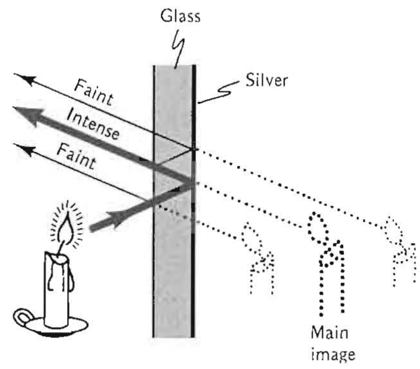


FIGURE 2.42

A single mirror can form several images of a candle. If both the candle and the viewer's eye are held close to the glass surface, the better glass reflectivity at grazing incidence makes the extra images brighter.

the glass reflection is weak (4%), but at grazing incidence ($\theta_i \approx 90°$) it is comparable to that from the silver. Further, the light reflected from the silver can be partially reflected back to the silver by the front glass surface, so a sequence of images can be obtained somewhat like those from the two parallel barbershop mirrors, but of much more rapidly decreasing brightness. Using a match or a candle as a light source in front of a mirror in an otherwise dark room (Fig. 2.42), you may be able to see three or four images of the candle (Fig. 2.43).

A nice example of multiple reflections is the nineteenth-century toy "X-ray Machine" (Fig. 2.44). You can "see through" any coin with this four-mirror device. A simpler device, using only two mirrors, is the periscope,* which allows one to see over obstacles or around corners. Multiple reflections are commonly used in light devices of modern kinetic art and light shows (Fig. 2.45). Often the reflections are off crumpled aluminum foil, so you don't see images but rather patterns of light that may change as the system rotates.

**Peri*, Greek prefix meaning around, about. To make a periscope, see the TRY IT.

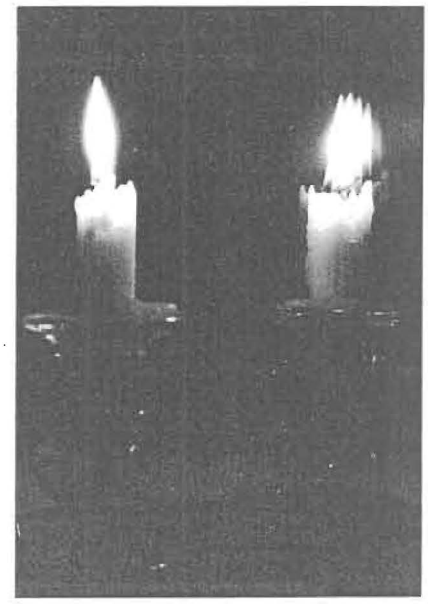


FIGURE 2.43

A candle and its multiple reflected images.

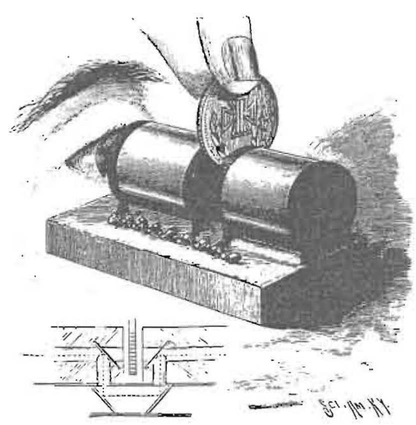


FIGURE 2.44

A toy "X-ray Machine." The diagram reveals the secret.

One needn't have specular reflections to have multiple reflections. Diffuse reflections are primarily responsible for the subtle lighting, shading, and coloring captured by artists. Leonardo da Vinci advised painters to notice these reflections carefully, and "show in your portraits how the reflection of the garments' colors tints the neighboring flesh. . . ."

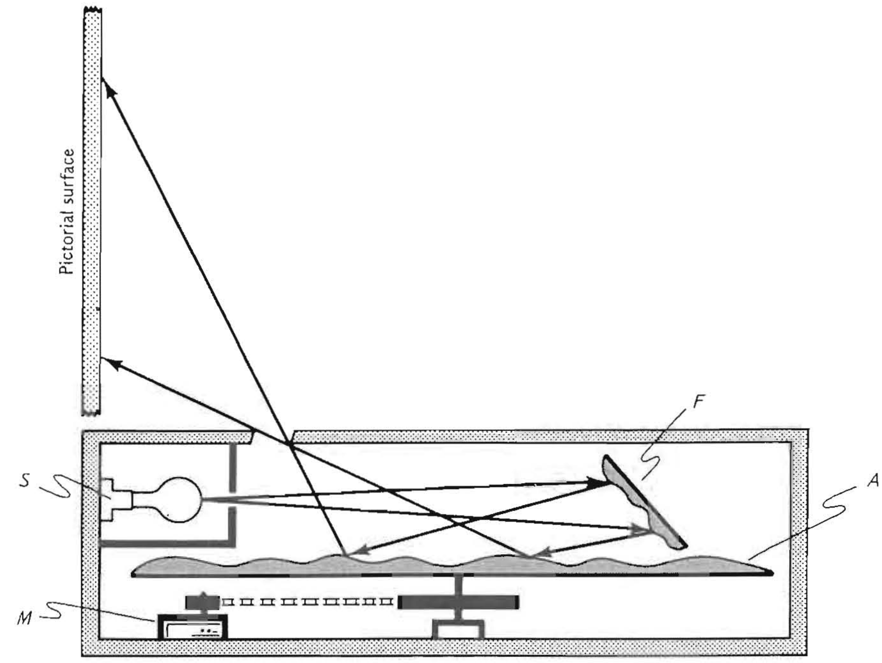


FIGURE 2.45

The "Kinoptic System" by Valerios Cabutsis. Light from source *S* is reflected by fixed mirror *F* onto crumpled aluminum foil *A*. As motor *M* rotates foil, the pattern of light on the screen changes.

TRY IT

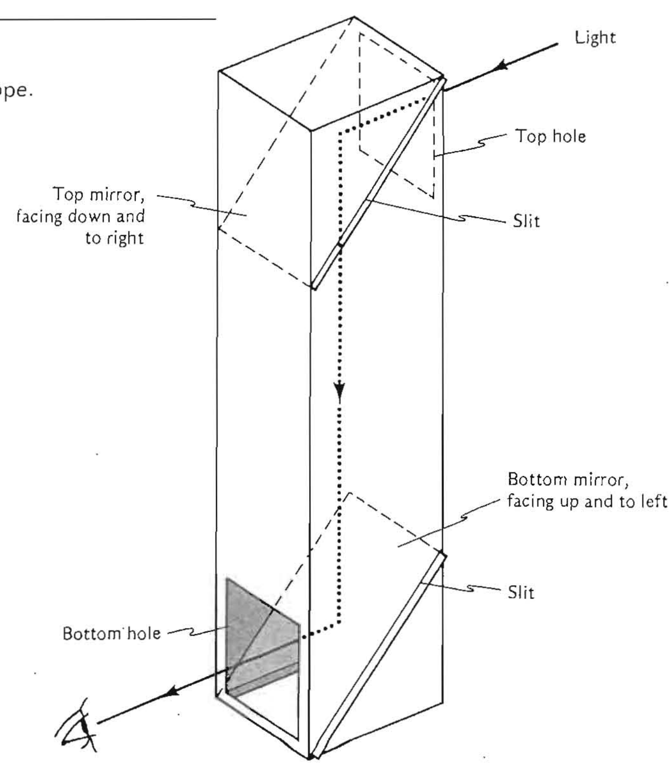
FOR SECTION 2.4C
Fun with two small mirrors

Two small pocket mirrors (preferably rectangular, without frames) will enable you to demonstrate several of the ideas discussed in this section. Hold the two mirrors at a right angle, and look at your reflection (Fig. 2.39). (You can be sure that the two mirrors are actually perpendicular to each other by adjusting the angle between the mirrors until your face looks normal.) Move your head a bit, and see if you can avoid looking into your own eyes. Close one eye and see which eye closes in the reflected image. Turn your head slightly to one side. Which way does the reflected image turn? Is this what you are used to seeing in a single mirror? Draw light rays to explain the difference. (If you place an object, such as your thumb, between the two perpendicular mirrors, you'll see more than one reflected thumb. The number of thumbs will increase as you make the angle between the mirrors smaller—see Sec. 3.2B.)

The same two mirrors can be used to construct a **periscope**. *These devices, popularized in World War II submarine movies, allow you to see around corners or over obstacles. To make a periscope, you will need a cardboard tube. Make one of square cross section (Fig. 2.46) or use a mailing tube. The size of the tube must be such that the mirrors will fit in as shown in the figure. Slits cut at 45° in one side of the tube will enable you to get the mirrors in. The mirrors should be held in place with tape (or chewing gum), and the entire tube (including the top and bottom) should be taped shut to eliminate stray light. Two holes, on opposite sides of the tube, one in front of each mirror, should be cut in the tube.*

FIGURE 2.46

Design for a periscope.



2.5 REFRACTION

We've mentioned that whenever there is a change of medium and an associated change in the speed of light, some of the light is reflected and some of it is transmitted. The transmitted beam usually does not continue to travel in exactly the same direction as the incident beam. This bending of the transmitted beam at the interface between two media is called ***refraction**** (Fig. 2.47).

To find out *why* the lightbeam is bent, we must go beyond geometrical optics and again consider waves. The key idea is that light travels more slowly in a denser medium than in a less dense medium (Sec. 1.3A). In glass it travels at about $\frac{2}{3}$ the speed it has in air. Now consider a wavefront of a beam (e.g., a crest of the wave) headed toward the glass (Fig. 2.48). A wavefront that starts out at *AA'* will get to *BB'* after some little time, traveling with the speed of light in air. At that moment the left end of the wavefront, near *B*, enters the glass.

*Latin *re-fringere*, break away. The light path has a break in its direction.

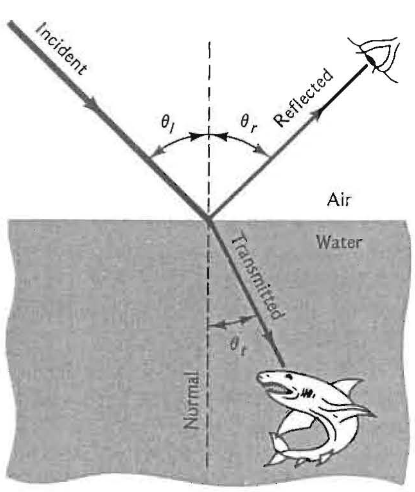


FIGURE 2.47

A beam incident on a transparent medium is split into a reflected and a transmitted (refracted) beam.

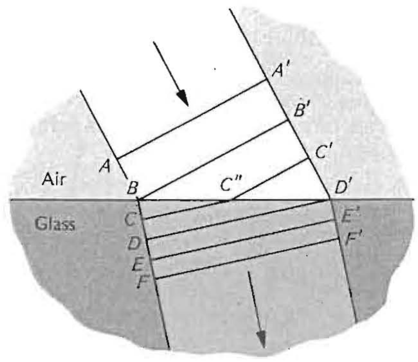


FIGURE 2.48

The wavefronts of a beam entering a slower medium explain why the beam refracts.

During the time the right end (near *B'*) moves the distance $\overline{B'C'}$ in air, the left end, moving more slowly in the glass, moves only the smaller distance $\overline{BC}$. The wavefront then looks like *CC''C'*. As the right end continues to move at the faster (air) speed to *D'*, the left end moves at the slower (glass) speed to *D*. Finally, the entire wavefront is in the glass and moves at the slower speed from *DD'* to *EE'* and beyond.

Thus, the edge of the wavefront that first hits the glass slows down, and the beam pivots about the edge, like a wagon pivoting around the wheel that is stuck in the mud. (Remember that the beam moves perpendicularly to the wavefront.) Hence the angle θ_t of the transmitted beam is *less* than the incident angle θ_i. That is, the beam is bent toward the normal at the surface. If *CC'* and *DD'* are successive crests, you can see that the wavelength (the distance between successive crests) is smaller in glass than in air, as it should be.

Had we sent the beam in the opposite direction, out of the glass, the diagram would be the same except the arrows would be reversed, and we would interchange the names "incident" and "transmitted." The first part of the wavefront to break free of the glass would speed up in the air, and the beam would pivot to the left, *away* from the perpendicular to the surface. So we find that:

Light going from fast medium to slow bends toward the normal, and light going from slow medium to fast bends away from the normal.

This is a qualitative statement of the ***law of refraction,*** also known as ***Snell's law.***

The mathematical form of Snell's law (Appendix B), relating θ_i and θ_t, depends on the ratio of the two speeds of light in the two substances that form the refracting interface (air and glass in our example). Since only this ratio is important, we often specify the speed of light in a medium by comparing it to *c*, the speed of light in vacuum. So, if v is the speed of light in some material, we define the medium's ***index of refraction*** *n* by:

$$n = \frac{c}{v}$$

Thus the larger v is, the smaller n is. In vacuum v equals c, so n equals 1. For all other media, v is always less than c, so n is greater than 1. The index of refraction is a measure of the density of the medium, as far as the behavior of light is concerned. Using it avoids the unwieldly large numbers associated with the speed of light (Table 2.4).

TABLE 2.4 Approximate index of refraction for various media

Medium	*Index of refraction*
Vacuum	1 (exactly)
Air	1.0003
Water	1.33
Glass	1.5
Diamond	2.4

We can now restate Snell's law qualitatively thus:

Light going from small *n* to large *n* is bent toward the normal. Light going from large *n* to small *n* is bent away from the normal.

(Of course if the light is going *along* the normal, it is not bent at all.) Table 2.5 gives an idea how much the beam is bent.

As an example of refraction, suppose we look at a fish in water (Fig. 2.49). The light coming from the fish at *A* was bent at the surface, away from the normal since n_{water} is greater than n_{air}. But the eye always assumes that the light has traveled in a straight line, so it looks as if the fish is at *B*. If you stick your spear in at *B*, you will likely miss the fish. For the same reason, a partially submerged straight stick looks bent—and therefore looks, correctly, as if it missed the fish and went to *C* instead (Fig. 2.50). This is of course not a refraction of the *stick*, but rather a consequence of refraction of the *light* we use to look at the stick.

FIGURE 2.49

Refraction makes underwater objects appear to be where they aren't.

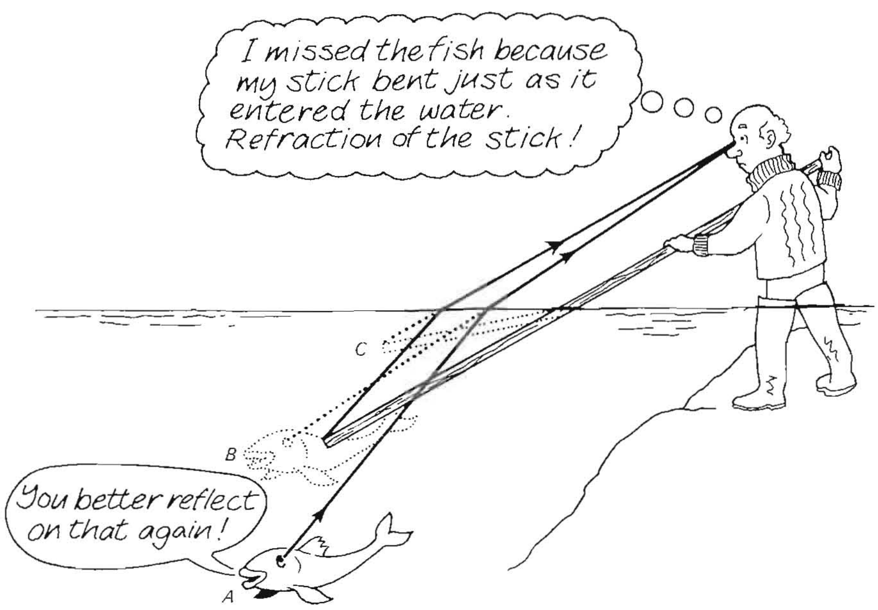


FIGURE 2.50

A pen appears bent when half immersed in water. (Notice the reflection on the surface of the water of the upper part of the pen.)

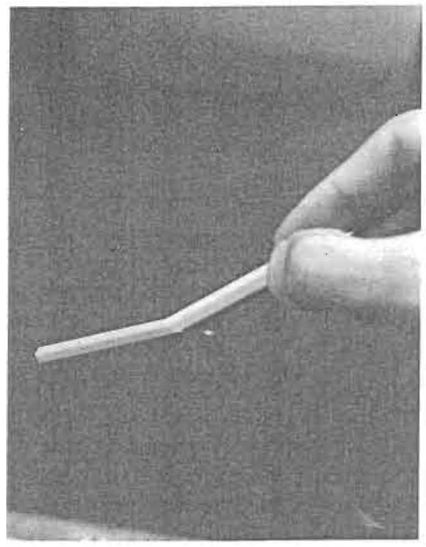


TABLE 2.5 Angle of transmission, θ_t, for various angles of incidence, θ_i, and various media

From	*To*	θ_i = 15°	30°	45°	60°	75°	89°
Air	Water	11°	22°	32°	41°	47°	49°
Air	Glass	10°	19°	28°	35°	40°	42°
Air	Diamond	6°	12°	16°	20°	23°	24°
Glass	Water	17°	34°	53°	78°	—	—
Glass	Air	23°	49°	—	—	—	—

See Sec. 2.5A for a discussion of the blank entries.

If there are ripples in the water, there will be a different amount of bending at each part of the surface and the fish may appear broken up, or you may even see several fish. A piece of glass made with many facets can, similarly, result in many images when you look through it, as described by John Webster in 1612 in "The White Devil":

I have seen a pair of spectacles fashioned with such perspective art, that lay down but one twelve pence o'th'board, 'twill appear as if there were twenty; now should you wear a pair of these spectacles, and see your wife tying her shoe, you would imagine twenty hands were taking up of your wife's clothes, and this would put you into a horrible causeless fury. (Fig. 2.51.)

As another example, refraction in a thick-walled beer glass makes the walls look very thin, so you think you're getting more beer (Fig. 2.52).

A. Total internal reflection

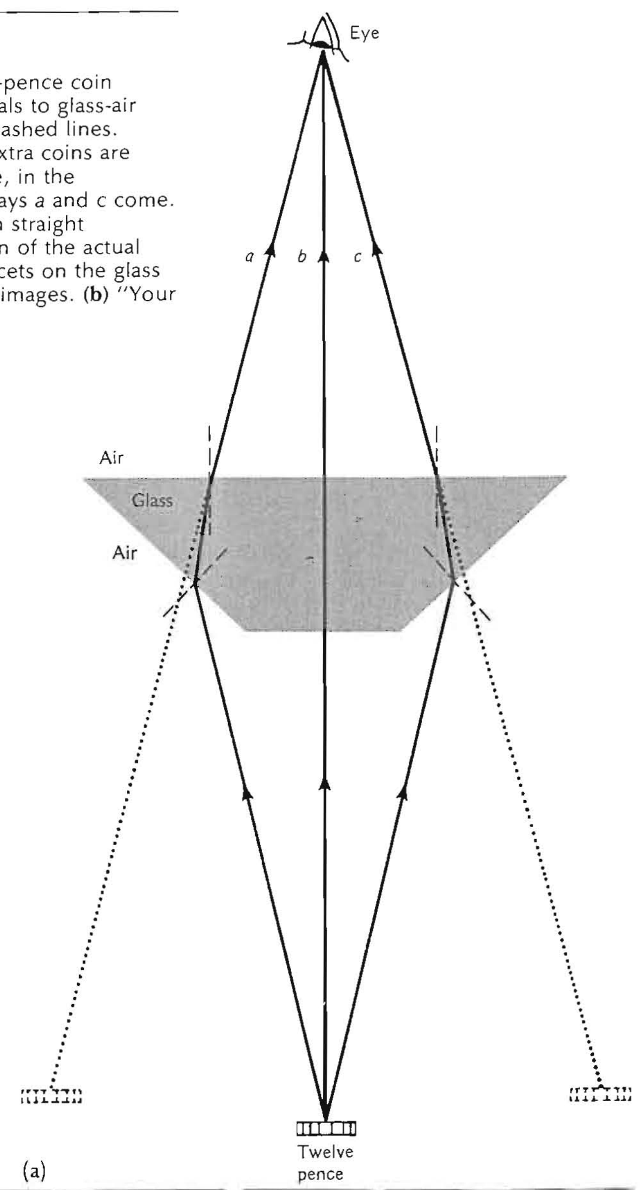
Notice that some entries are blank in Table 2.5. The reason is that a beam that is trying to enter a faster

FIGURE 2.52

Mug shot shows deception. Not only is there hardly any beer in the foam—which nonetheless reflects a lot of light—but the beer seems to go all the way to the side of the mug, not showing the thick wall. In the photograph, refraction in the lower half of the mug has been reduced by placing the mug in water. (Because *some* refraction occurs at the glass-water surface, the walls still look thinner than they are.)

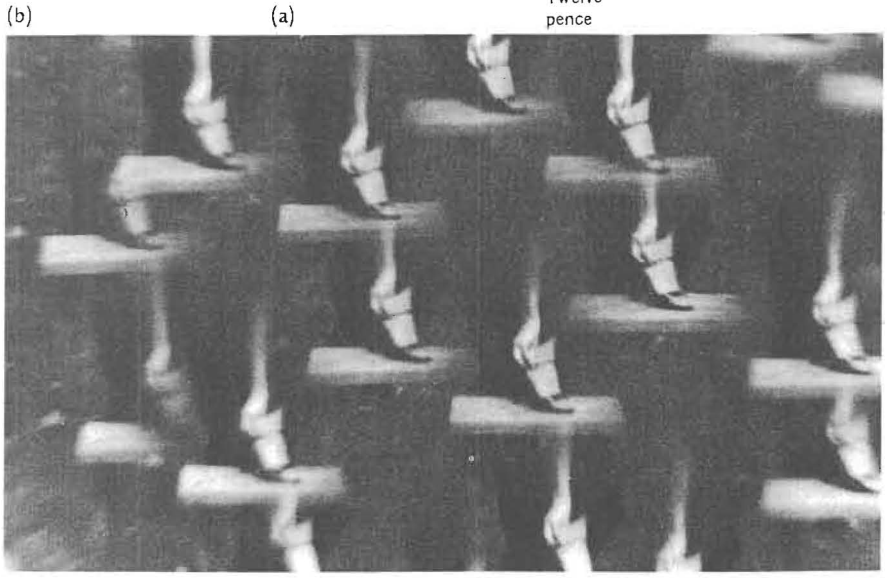
FIGURE 2.51

(a) Wherein one twelve-pence coin appears as three. Normals to glass-air surfaces are shown as dashed lines. Apparent positions of extra coins are shown in dotted outline, in the directions from which rays *a* and *c* come. The eye also sees a coin straight through, in the direction of the actual coin, via ray *b*. More facets on the glass may produce still more images. **(b)** "Your wife tying her shoes."



(a)

(b)



medium (smaller n) at a larger angle of incidence would have to be bent away from the normal to more than 90°. But that is impossible; the transmitted beam cannot bend more than 90° from the normal and still stay in the faster medium. Light, therefore, gives up the idea of transmission—nothing is transmitted, and everything is reflected. This is called ***total internal reflection.*** It only occurs at sufficiently large θ_i at the inside (internally) of a dense medium (larger n) bordered by a less dense medium (smaller n). Of course the law of reflection, $\theta_r = \theta_i$, holds for this as for all reflections. The angle of incidence where total internal reflection first happens is called the ***critical angle,*** θ_c. From Table 2.5 you can see that the critical angle for glass in air is somewhere between 30° and 45°—actually it is about 42°. So any light hitting a glass-air surface, from the glass side at more than 42° to the normal, is totally reflected (Fig. 2.53).

PONDER

Why isn't there a critical angle for light passing from air into water?

A simple place to see total internal reflection is in a fish tank or swimming pool. The light from the fish in Fig. 2.54 is totally reflected at the top surface of the water, and the swimmer sees the fish's reflection there. Similarly, the fish sees the swimmer's reflection there. If the fish looks up at less than the critical angle, she sees out the top, but everything above the water, down to the horizon, is compressed into the angles between straight up and the critical angle (Fig. 2.55). Below the critical angle the view suddenly shifts to a reflection. It is like seeing the world squeezed together through a hole in a mirror (distorted by ripples).

Total internal reflection is used in some optical instruments to reflect a beam by 90° using a prism cut at 45° (Fig. 2.56). Several of these are used in prism binoculars to increase the path length between the

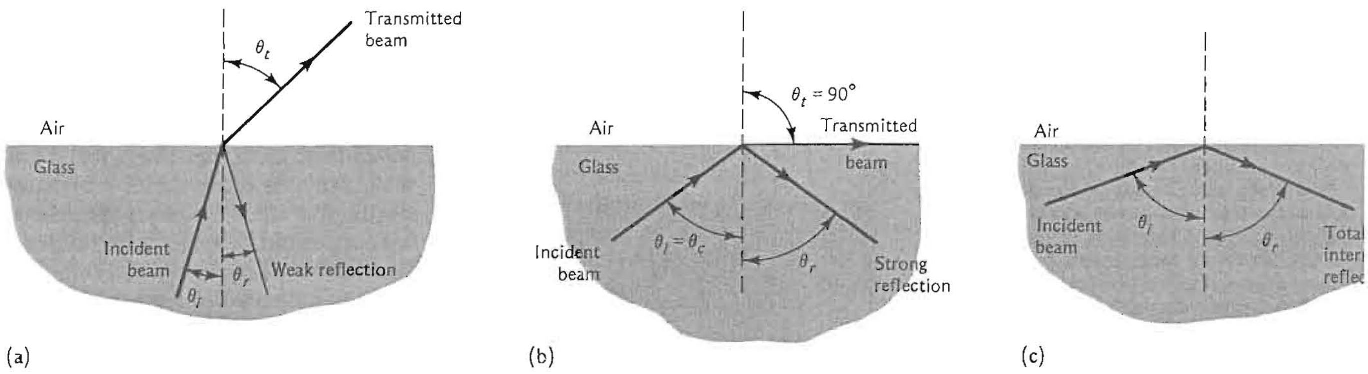


FIGURE 2.53

Reflected and transmitted beams when incident angle is **(a)** smaller than the critical angle, **(b)** equal to the critical angle, **(c)** larger than the critical angle.

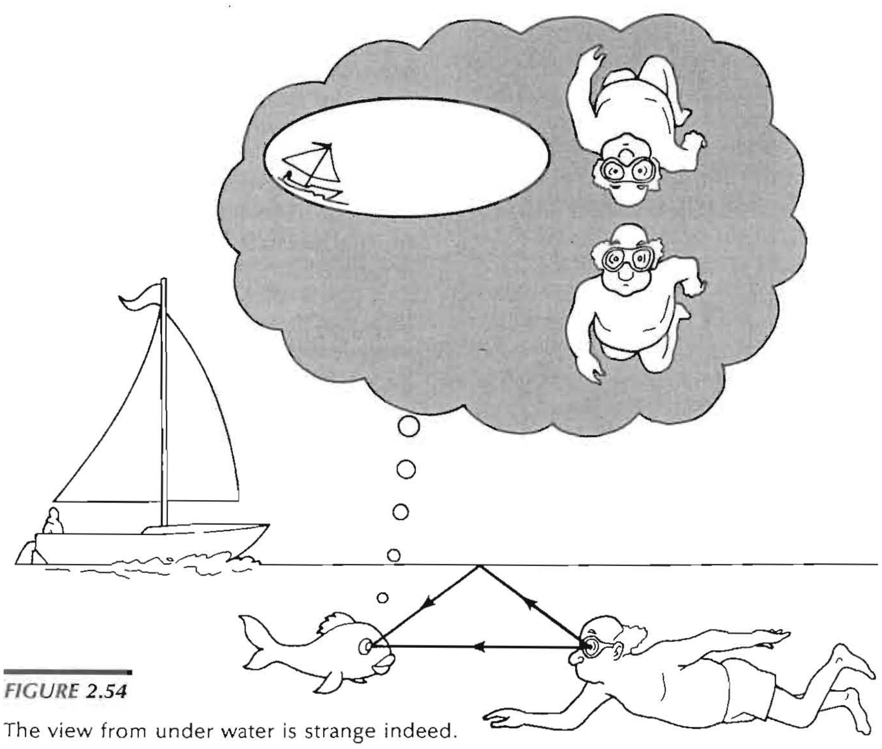


FIGURE 2.54

The view from under water is strange indeed.

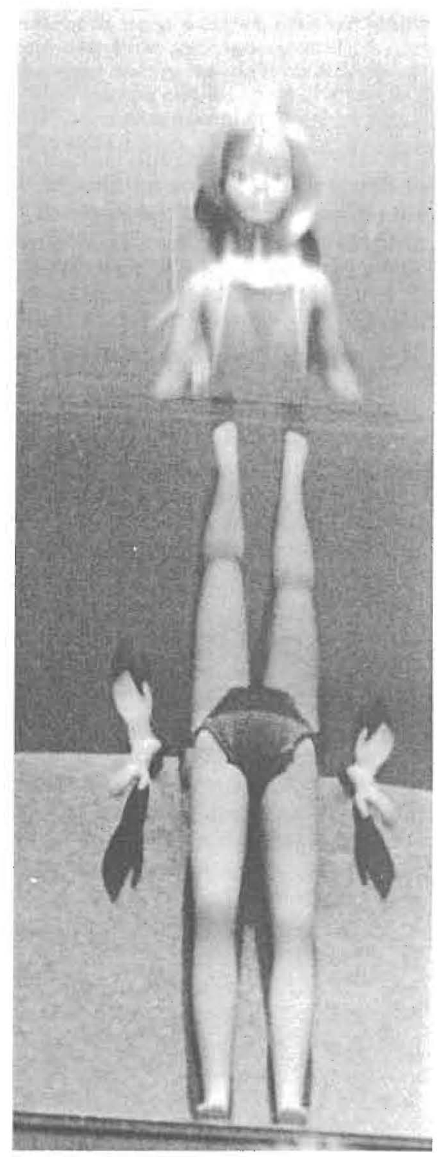


FIGURE 2.55

An underwater photograph of a doll standing in water, showing both direct and reflected views of her legs and hands.

FIGURE 2.56

Use of the total internal reflection to change the direction of a light beam, **(a)** by 90° ($\theta_i = \theta_r = 45°$), **(b)** by 180° using a Porro prism. **(c)** Two Porro prisms as used in binoculars (actually, they would be touching).