18

Refraction of Light

▶When light travels from one transparent material to another—say, from air to water—some interesting visual effects are created. Fish in an aquarium look bigger, and a tree that has fallen into a lake looks bent. Is it ever possible that the light cannot travel from one transparent material to another?

(See page 395 for the answer to this question.)

Refraction of light in the atmosphere causes the oval shape of the setting Sun.

WHEN light strikes a transparent material, it usually changes direction. This change accounts for many interesting effects such as the apparent distortion of objects and the beauty of an afternoon rainbow. This bending of light that occurs at the surface of a transparent object is called **refraction.**

Refraction can be studied by looking at the paths the light takes as the incident angle is varied, as shown in Figure 18-1. As in reflection, the angles are measured with respect to the normal to the surface. In this case the normal is extended into the material, and the angle of refraction is measured with respect to the extended normal. The amount of bending is zero when the angle of incidence is zero; that is, light incident along the normal to the surface is not bent. As the angle of incidence increases relative to the normal, the amount of bending increases; the angle of refraction differs more and more from the angle of incidence.

▶ Extended presentation available in the *Problem Solving* supplement

Index of Refraction

The amount of bending that occurs when light enters the material depends on the incident angle and an optical property of the material called the **index of refraction.** (We will refine the definition of the index of refraction in the next chapter.) A mathematical relationship can be written that predicts the refracted angle given the incident angle and the type of material. This rule, called *Snell's law,* is not as simple as the rule for reflection because it involves trigonometry. A simpler way to express the relationship is to construct a graph of the experimental data. Of course, although graphs are easier to use, they often have the disadvantage of being less general. In this case a graph has to be made for each substance. The graph in Figure 18-2 gives the angle of refraction in air, water, and glass for each angle of incidence in a vacuum. Although the curves for water and glass have similar shapes, light is refracted more on entering glass than water.

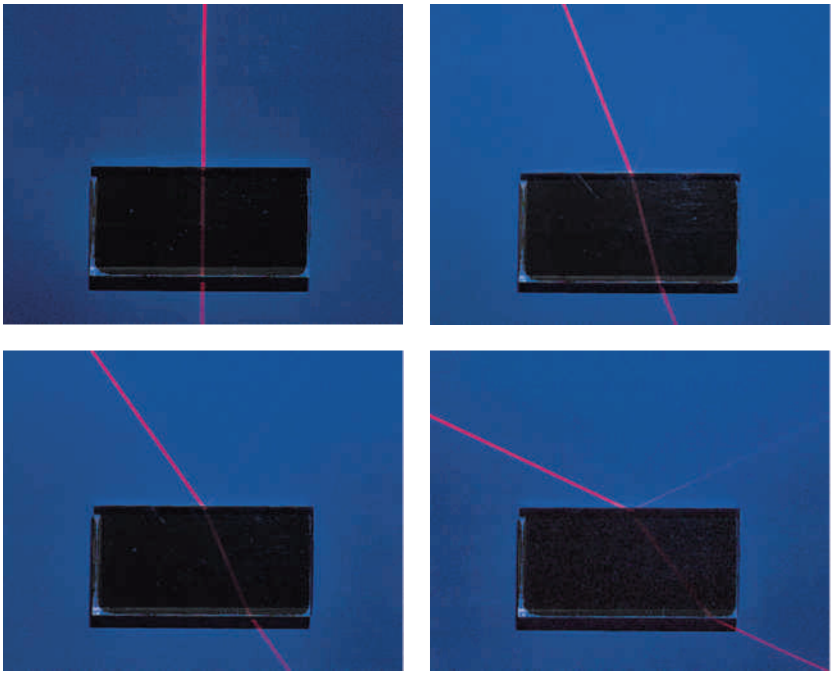


Figure 18-1 The amount of refraction depends on the angle of incidence. Notice that some of the incident light is reflected and some is refracted.

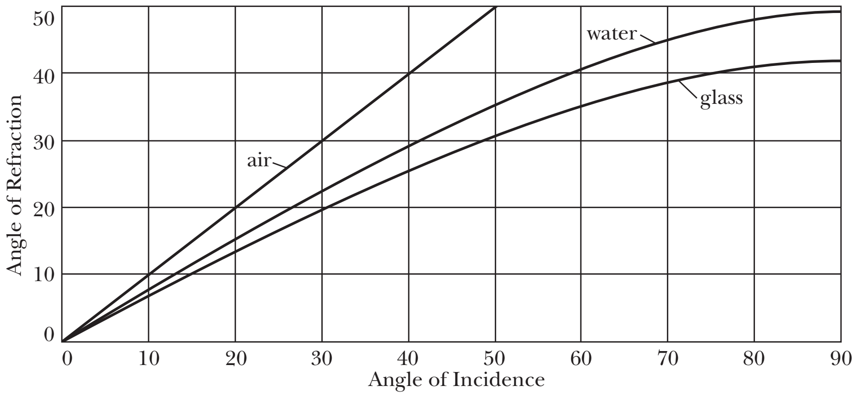


Figure 18-2 This graph shows the relationship between the angle of refraction and the angle of incidence for light entering air, water, and glass from a vacuum.

If no refraction takes place, the index of refraction is equal to 1. You can see from the graph that very little bending occurs when light goes from a vacuum into air; the index of refraction of air is only slightly greater than 1. Because the index of refraction of air is very close to 1, air and a vacuum are nearly equivalent. Therefore, we will use the graph in Figure 18-2 for light entering water or glass from either air or a vacuum. The index of refraction for water is 1.33; for different kinds of glass, it varies from 1.5 to 1.9. The curve for glass on the graph is drawn for an index of 1.5. The index of refraction for diamond is 2.42. A larger index of refraction means more bending for a given angle of incidence. For example, the graph indicates that light incident at 50 degrees (50°) has an angle of refraction of 31 degrees in glass and 35 degrees in water. Thus, the light is bent 19 degrees going into glass (index = 1.5) and only 15 degrees going into water (index = 1.33).

Are You On the Bus?

Q: What is the angle of refraction for light incident on glass at 30 degrees? How much does the ray bend?

A: The graph in Figure 18-2 gives an angle of refraction of approximately 20 degrees. Therefore, the ray bends 30 degrees − 20 degrees = 10 degrees from its original direction.

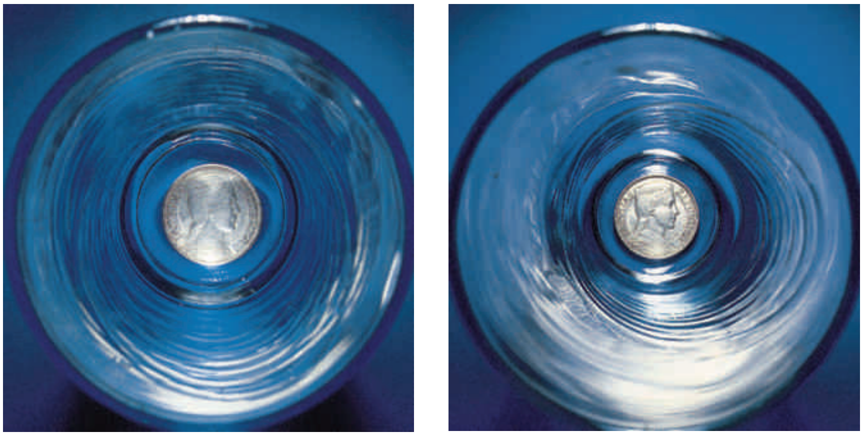
Light entering a transparent material from air bends *toward* the normal. What happens if light originates in the material and exits into the air? Experiments show that the paths of light rays are reversible. The photographs in Figure 18-1 can be interpreted as light inside the glass passing upward into the air. (If this were really the case, however, there would also be a faint reflected beam in the glass.) This example shows that when light moves from a material with a higher index of refraction to one with a lower index, the light leaving the material is bent *away from* the normal. Because of the reversibility of the rays, you can still use the graph in Figure 18-2 to find the angle of refraction; simply reverse the labels on the two axes.

Are You On the Bus?

Q: If a ray of light in water strikes the surface at an angle of incidence of 40 degrees, at what angle does it enter the air?

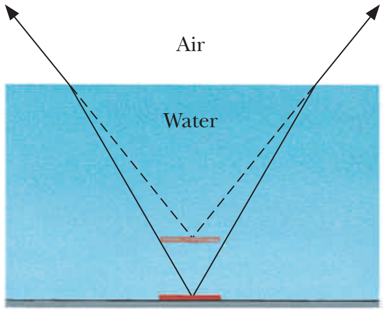
A: Locate the 40-degree angle on the *vertical axis* of the graph in Figure 18-2 and move sideways until you encounter the curve for water. Then, moving straight down to the horizontal axis, we obtain an angle of 58 degrees.

Figure 18-3 A straight pencil appears to be bent at the surface of the water.

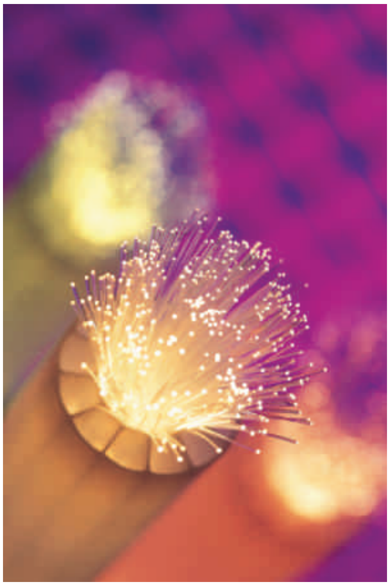


(a) (b)

Figure 18-4 A coin underwater (a) appears closer than an identical coin in air (b). (c) Some of the rays that produce the virtual image.



(c)



Strands of glass optical fibers are used to carry voice, video, and data signals in telecommunication networks. Typical fibers have diameters of 60 micrometers.

Another consequence of this reversibility is that light passing through a pane of glass that has parallel surfaces continues in its original direction after emerging. The glass has the effect of shifting the light sideways, as shown in Figure 18-1.

The refraction of light produces interesting optical effects. A straight object partially in water appears bent at the surface. The photograph of a pencil in Figure 18-3 illustrates this effect. Looking from the top, we see that the portion of the pencil in the water appears to be higher than it actually is.

This phenomenon can also be seen in the photographs of identical coins, one underwater [Figure 18-4(a)] and the other in air [Figure 18-4(b)]. Even though the coins are the same distance from the camera, the one underwater appears closer and larger. The drawing in Figure 18-4(c) shows some of the rays that produce this illusion. This effect also makes fish appear larger—although never as large as the unlucky fisherman would like you to believe.

Let's examine the reason for the coin's appearing larger when it is in the water. Is it because the image is closer, or is the image itself bigger? It is fairly straightforward to see that the increase in size is due to the image being closer. To see that the image hasn't increased in size, we need to remind ourselves that rays normal to the surface are not refracted. Therefore, if we use vertical rays to locate the images of all points on the rim of the coin, each image will be directly above the corresponding point on the rim. This means that the image has the same size as the coin.

Are You On the Bus?

Q: If you keep your stamp collection under thick pieces of glass for protection, will the stamps appear to have their normal sizes?

A: No. Just like the coin in water, the stamps appear to be closer and are therefore apparently larger in size.

Total Internal Reflection

In some situations, light can't pass between two substances even if they are both transparent. This occurs at large incident angles when the light strikes a material with a lower index of refraction, such as from glass into air, as shown at the lower surface in Figure 18-5. At small angles of incidence, both reflection and refraction take place. The refracted angle is larger than the incident angle as shown in Figure 18-5(a). As the incident angle increases, the refracted angle increases even faster. At a particular incident angle, the refracted angle reaches 90 degrees. Beyond this incident angle—called the **critical angle**—the light no longer leaves the material; the light is totally reflected as shown in Figure 18-5(b). This is called **total internal reflection.**

The critical angle can be found experimentally by increasing the incident angle and watching for the disappearance of the emerging ray. Because the graph in Figure 18-2 works for both directions, we can find the critical angle by looking for the angle of refraction for an incident angle of 90 degrees. The intersection of the curve with the right-hand edge of Figure 18-2 indicates that the critical angle for our glass is about 42 degrees. The critical angle for diamond is only 24 degrees.

This total internal reflection has many applications. For example, a 45-degree right prism can act as a mirror, as shown in Figure 18-6. If the incident angle of 45 degrees is greater than the critical angle, when the light beam hits the back surface, the beam is totally reflected. This reflecting surface has many advantages over ordinary mirrors. It doesn't have to be silvered, it is easier to protect than an external surface, and it is also more efficient for reflecting light.

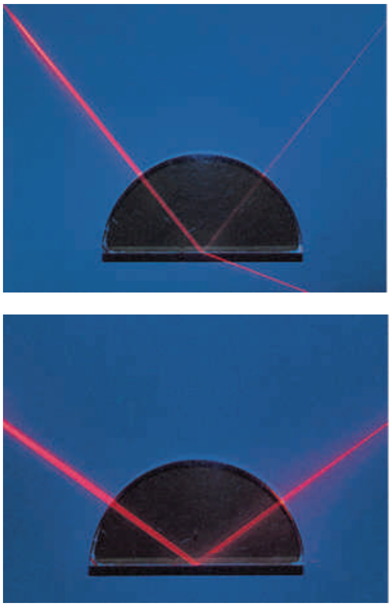


Figure 18-5 (a) Light traveling from glass into air at the lower surface bends away from the normal. (b) When the incident angle is larger than some critical angle, the light is totally reflected. None of the light passes through the surface.

Q: What is the critical angle for water?

A: The graph in Figure 18-2 shows that the angle of refraction in water never exceeds 49 degrees, so this is the critical angle.

Another application of this principle is to "pipe" light through long narrow fibers of solid plastic or glass, as shown in Figure 18-7. Light enters the fiber from one end. Once inside, the light doesn't escape out the side because the angle of incidence is always greater than the critical angle. The rays finally exit at the end of the fiber because there the incident angles are smaller than the critical angle. Fiber-optic applications are found in photography, medicine, telephone transmissions, and even decorative room lighting.

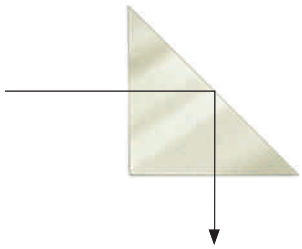


Figure 18-6 A prism acts as a flat mirror when the light is totally internally reflected.

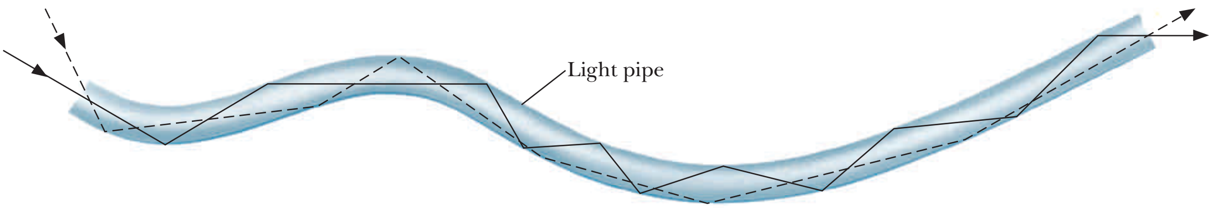


Figure 18-7 Light may be "piped" through solid plastic or glass rods using total internal reflection.

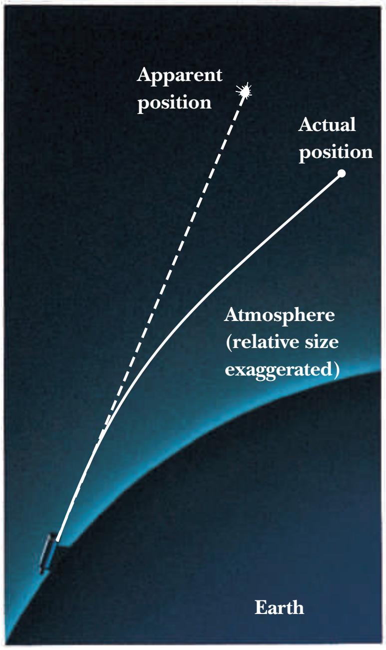


Figure 18-8 Atmospheric refraction changes the apparent positions of celestial objects, making them appear higher in the sky.

Atmospheric Refraction

We live at the bottom of an ocean of air. Light that reaches us travels through this air and is modified by it. Earth's atmosphere is not uniform. Under most conditions the atmosphere's density decreases with increasing altitude. As you may guess, the index of refraction depends on the density of a gas because the less dense the gas, the more like a vacuum it becomes. We therefore conclude that the index of refraction of the atmosphere gradually decreases the higher we go.

Refraction occurs whenever there is any change in the index of refraction. When there is an abrupt change, as at the surface of glass, the change in the direction of the light is abrupt. But when the change is gradual, the path of a light ray is a gentle curve. The gradual increase in the index of refraction as light travels into the lower atmosphere means that light from celestial objects such as the Sun, Moon, and stars bends toward the vertical. Figure 18-8 shows that this phenomenon makes the object appear higher in the sky than its actual position. Astronomers must correct for atmospheric refraction to get accurate positions of celestial objects.

This shift in position is zero when the object is directly overhead and increases as it moves toward the horizon. Atmospheric refraction is large enough that you can see the Sun and Moon before they rise and after they set. Of course, without knowing where the Sun and Moon should be, you are not able to detect this shift in position. You can, however, see distortions in their shapes when they are near the horizon, as shown in the photographs in Figure 18-9. Because the amount of refraction is larger closer to the horizon, the apparent change in position of the bottom of the Moon is larger than the change at the top. This results in a shortening of the diameter of the Moon in the vertical direction and gives the Moon an elliptical appearance.

There are other changes in the atmosphere's index of refraction. Because of the atmosphere's continual motion, there are momentary changes in the density of local regions. Stars get their twinkle from this variation. As the air moves, the index of refraction along the path of the star's light changes, and the star appears to change position slightly and to vary in brightness and color—that is, to twinkle. Planets do not twinkle as much because they are close enough to Earth to appear as tiny disks. Light from different parts of the disk averages out to produce a steadier image.

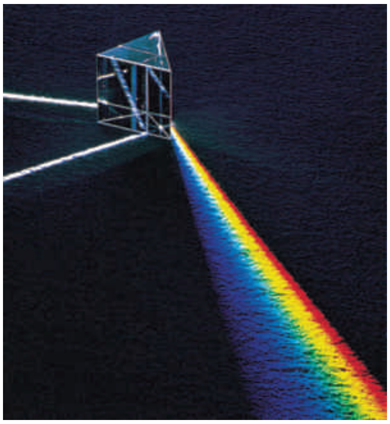
Images not available due to copyright restrictions

Dispersion

Although the ancients knew that jewels produced brilliant colors when sunlight shone on them, they were wrong about the origin of the colors. They thought the colors were part of the jewel. Newton used a prism to show that the colors don't come from jewels but rather from light itself—that the colors are already present in sunlight. When sunlight passes through a prism, the light refracts and is split up into a spectrum of colors ranging from red to violet, a phenomenon known as **dispersion** (Figure 18-10). To eliminate the idea that the prism somehow produced the colors, Newton did two experiments. He took one of the colors from a prism and passed it through a second prism, demonstrating that no new colors were produced. He also recombined the colors and obtained white light. His experiments showed conclusively that white light is a combination of all colors. The prism just spreads them out so that the individual colors can be seen.

The name ROY G. BIV is a handy mnemonic for remembering the order of the colors produced by a prism or those in the rainbow: red, orange, yellow, green, blue, indigo, and violet. (Indigo is included mostly for the mnemonic; people can seldom distinguish it from blue or violet.)

The light changes direction as it passes through the prism because of refraction at the faces of the prism. Dispersion tells us that the colors have slightly different indexes of refraction in glass. Violet light is refracted more than red and therefore has a larger index. ("Blue bends better" is an easy way of remembering this.) The brilliance of a diamond is due to the small critical angle for internal reflection and the separation of the colors due to the high amount of dispersion.



David Parker/Science Photo Library/ Photo Researchers, Inc.

Figure 18-10 A prism separates white light into the colors of the rainbow.

Rainbows

Sometimes after a rain shower, you get to see one of nature's most beautiful demonstrations of dispersion, a rainbow. Part of its appeal must be that it appears to come from thin air. There seems to be nothing there but empty sky.

In fact, rainbows result from the dispersion of sunlight by water droplets in the atmosphere. The dispersion that occurs as the light enters and leaves the droplet separates the colors that compose sunlight. You can verify this by making your own rainbow. Turn your back to the Sun and spray a fine mist of water from your garden hose in the direction opposite the Sun. Each color forms

David Cavagnaro/Visuals Unlimited

A rainbow formed in the spray from a sprinkler hose.

Figure 18-11 A rainbow's magic is that it seems to appear out of thin air. Notice the secondary rainbow on the right.

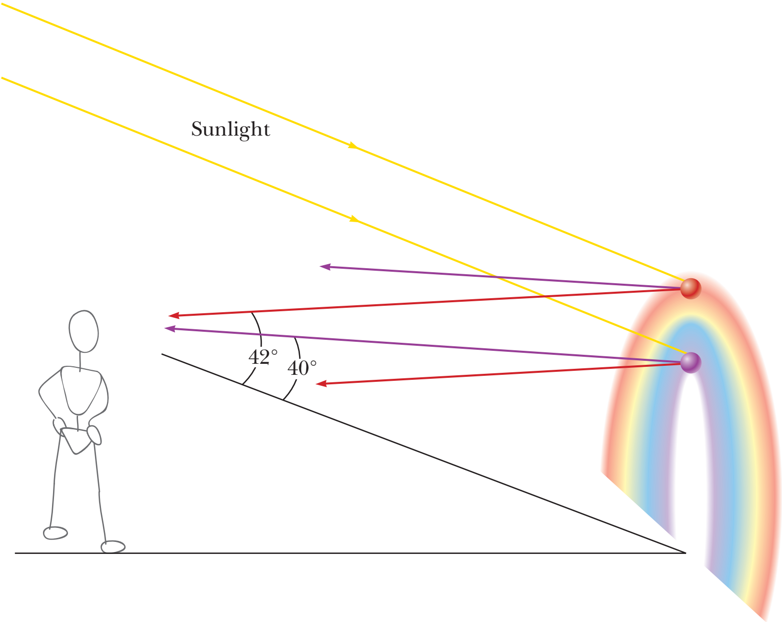


Figure 18-13 The color of each water droplet forming the rainbow depends on the viewing angle.

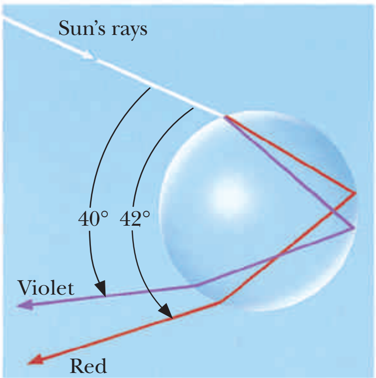


Figure 18-12 Dispersion of sunlight in a water droplet separates the sunlight into a spectrum of colors.

part of a circle about the point directly opposite the Sun (Figure 18-11). The angle to each of the droplets along the circle of a given color is the same. Red light forms the outer circle and violet light the inner one. Figure 18-12 shows the paths of the red and violet light. The other colors are spread out between these two according to the mnemonic ROY G. BIV. Each droplet disperses all colors. Your eyes, however, are only in position to see one color coming from a particular droplet. For instance, if the droplet is located such that a line from the Sun to the droplet and a line from your eyes to the droplet form an angle of 42 degrees, the droplet appears red (Figure 18-13). If this angle is 40 degrees, the droplet appears violet. Intermediate angles yield other colors.

Whether or not you believe there is a pot of gold at the end of the rainbow, you will never be able to get there to find out. As you move, the rainbow "moves." In your new position, different droplets produce the light you see as the rainbow.

FLAWED REASONING

A friend calls you at 8:00 a.m. and tells you to go outside and observe a beautiful rainbow in the east. **Would you hire this friend as a hiking guide?**

ANSWER Your friend has serious compass issues. The Sun comes up in the east. You see rainbows by looking away from the Sun. Indeed, the center of the rainbow will lie along a line passing through the Sun and your head. Therefore, at 8:00 a.m. you will see the rainbow in the west.

If you are willing to get wet, it is possible to see a complete circular rainbow. Near noon on a sunny day, spray the space around you with a fine mist. Looking down, you will find yourself in the center of a rainbow. A circular rainbow can sometimes be seen from an airplane.

If viewing conditions are good, you can see a secondary rainbow that is fainter and larger than the first (Figure 18-11). It is centered on the same point, but the colors appear in reverse order. This rainbow is produced by light that reflects twice inside the droplets.

Q: If you see a rainbow from an airplane, where do you expect to see the shadow of the airplane?

A: Because the center of the rainbow is always directly opposite the Sun, the shadow of the airplane will be at the center of the rainbow.

Halos

Sometimes a large halo can be seen surrounding the Sun or Moon. These halos and other effects, such as *sun dogs* and various arcs, are caused by the refraction of light by ice crystals in the atmosphere.

Atmospheric ice crystals have the shape of hexagonal prisms. Each one looks like a slice from a wooden pencil that has a hexagonal cross section. Light hitting the crystal is scattered in many different directions, depending on the angle of incidence and which face it enters and exits. Light entering and exiting alternate faces, as shown in Figure 18-14, has a minimum angle of scatter of 22 degrees. Although light is scattered at other angles, most of the light concentrates near this angle.

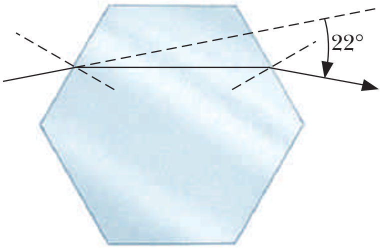


Figure 18-14 Light passing through alternate surfaces of a hexagonal ice crystal changes direction by at least 22 degrees.

To see a ray of light that has been scattered by 22 degrees, you must look in a direction 22 degrees away from the Sun. Light scattering this way from crystals randomly oriented in the atmosphere forms a 22-degree halo around the Sun, as shown in Figure 18-15. The random nature of the orientations ensures that at any place along the halo there will be crystals that scatter light into your eyes. Dispersion in the ice crystals produces the colors in the halo.

Occasionally one also sees "ghost" suns located on each side of the Sun at the same height as the Sun, as seen in Figure 18-15. Ice crystals that have vertically oriented axes produce these *sun dogs*. These crystals can refract light into your eyes only when they are located along or just outside the halo's circle at the same altitude as the Sun.

An even larger but dimmer halo at 46 degrees exists but is less frequently seen. It is formed by light passing through one end and one side of the crystals. Other effects are produced by light scattering through other combinations of faces in crystals with particular orientations.

Courtesy of Robert Greenler

Figure 18-15 A photograph of the 22-degree halo and its associated sun dogs taken with a fisheye lens. A building was used to block out the Sun's direct rays.

Lenses

When light enters a material with entrance and exit surfaces that are not parallel, unlike a pane of glass, the direction of the light beam changes. Two prisms and a rectangular block can be used to focus light, as shown in Figure 18-16. However, most other rays passing through this combination would not be focused at the same point. The focusing can be improved by using a larger number of blocks or by shaping a piece of glass to form a lens.

We see the world through lenses. This is true even for those of us who don't wear glasses, because the lenses in our eyes focus images on our retinas. Other lenses extend our view of the universe—microscopes for the very small and telescopes for the very distant.

Although many lens shapes exist, they can all be put into one of two groups: those that converge light and those that diverge light. If the lens is thicker at

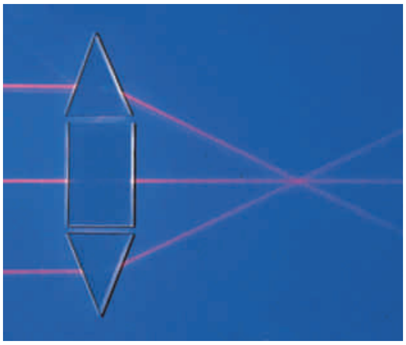


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Figure 18-16 Two prisms and a rectangular block form a primitive lens.

its center than at its edge, as in Figure 18-17(a), it is a converging lens. If it is thinner at the center, as in Figure 18-17(b), it is a diverging lens.

Q: Lenses in eyeglasses are made with one convex surface and one concave surface. How can you tell if the lenses are converging or diverging?

A: Check to see if they are thicker at the center than at the edges. If they are thicker at the center, they are converging.

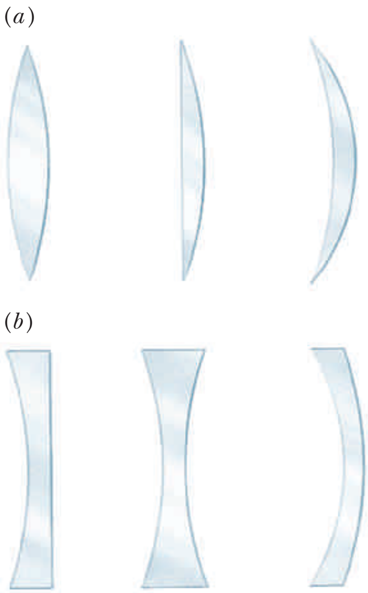

Figure 18-17 (a) Converging lenses are thicker at the middle. (b) Diverging lenses are thinner at the middle.

Lenses have two focal points—one on each side. A converging lens focuses incoming light that is parallel to its **optic axis** at a point on the other side of the lens known as the *principal* **focal point** (Figure 18-18). The distance from the center of the lens to the focal point is called the **focal length.** We can find the other focal point by reversing the direction of the light and bringing it in from the right-hand side of the lens. The light then focuses at a point on the left-hand side of the lens that we refer to as the "other" focal point in drawing ray diagrams.

For a diverging lens, incoming light that is parallel to the optic axis appears to diverge from a point on the same side of the lens (Figure 18-19). This point is known as the *principal focal point,* and the focal point on the other side is known as the "other" one. You can show by experiment that the two focal points are the same distance from the center of the lens if the lens is thin. A lens is considered to be thin if its thickness is very much less than its focal length.

The shorter the focal length, the "stronger" the lens; that is, the lens focuses light parallel to the optic axis at a point closer to the lens.

Images Produced by Lenses

The same ray-diagramming techniques used for curved mirrors in the previous chapter will help us locate the images formed by lenses. Again, three of the rays are easily drawn without measuring angles. The intersection of any two determines the location of the image. Figure 18-20 shows the three rays.

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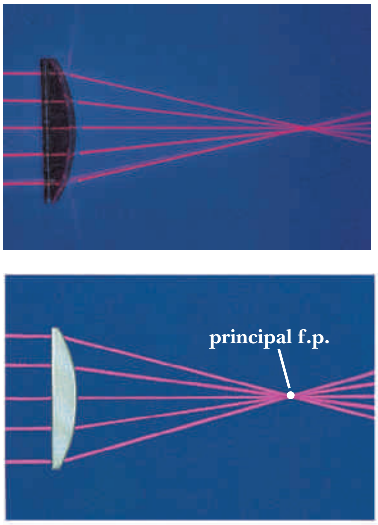

Figure 18-18 Light parallel to the optic axis of a converging lens is focused at the principal focal point.

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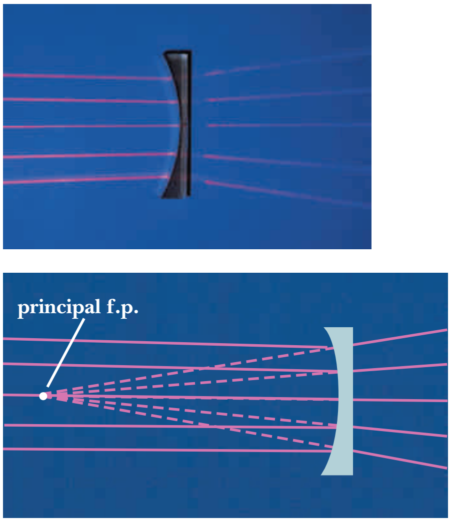


Figure 18-19 Light parallel to the optic axis of a diverging lens appears to come from the principal focal point.

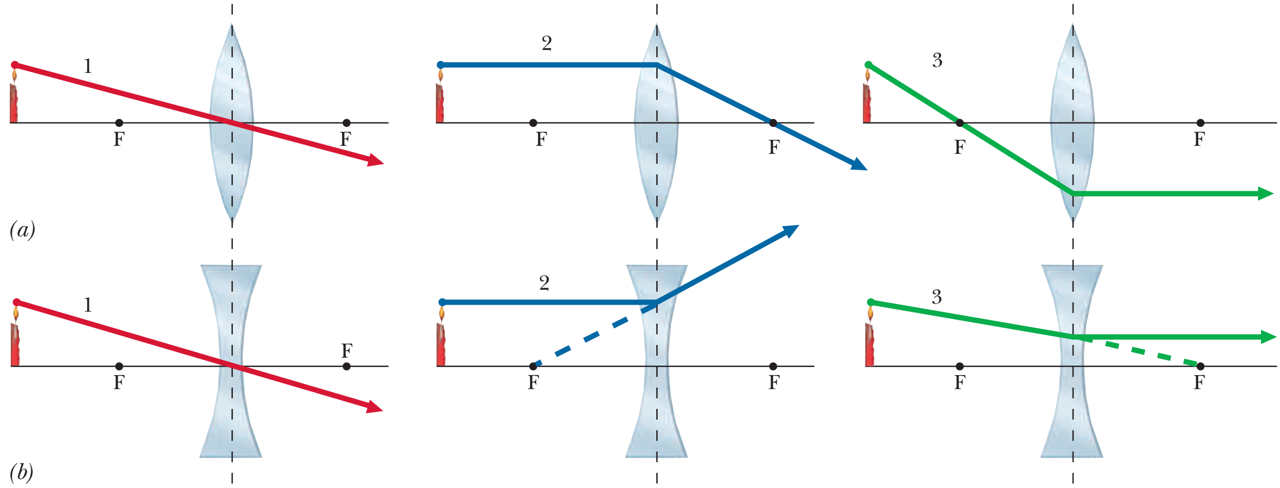


Figure 18-20 The three rays used in drawing ray diagrams for (a) converging and (b) diverging lenses.

First, a ray passing through the center of the lens continues without deflection. Second, for a converging lens, a ray parallel to the optic axis passes through the principal focal point. Third, a ray coming from the direction of the other focal point leaves the lens parallel to the optic axis [Figure 18-20(a)]. (The optic axis passes through the center of the lens and both focal points.) Notice that the second and third rays are opposites of each other. For a diverging lens, the second ray comes in parallel to the optic axis and leaves as if it came from the principal focal point, and the third ray heads toward the other focal point and leaves parallel to the optic axis [Figure 18-20(b)].

These rays are similar to the ones used for mirrors. There are two main differences: the first ray passes through the center of the lens and not the center of the sphere as it did for mirrors, and there are now two focal points instead of one. We can still give abbreviated versions of these rules (the words in parentheses refer to diverging lenses).

1. Through center—continues
2. Parallel to optic axis—through (from) principal focal point
3. Through (toward) other focal point—parallel to optic axis

◀ rays for lenses

These rules assume that the lens is thin. The first rule neglects the offset that takes place when a light ray passes through parallel surfaces of glass at other than normal incidence (see Figure 18-1). For the purposes of drawing these rays, the bending of the light is assumed to take place at a plane perpendicular to the optic axis and through the center of the lens. A vertical dashed line indicates this plane.

We can apply these rays to locate the image of a candle that is located on the optic axis outside the focal point of a converging lens. The ray diagram in Figure 18-21 shows that the image is located on the other side of the lens and is real and inverted. (See the previous chapter for a discussion of the types of image.) Whether the image is magnified depends on how far it is from the focal point. As the candle is moved away from the lens, the image moves closer to the principal focal point and gets smaller.

If the candle is moved inside the focal point, as illustrated in Figure 18-22, the image appears on the same side of the lens. This is the arrangement that is used when a converging lens is used as a magnifying glass. The lens is positioned such that the object is inside the focal point, producing an image that is virtual, erect, and magnified.

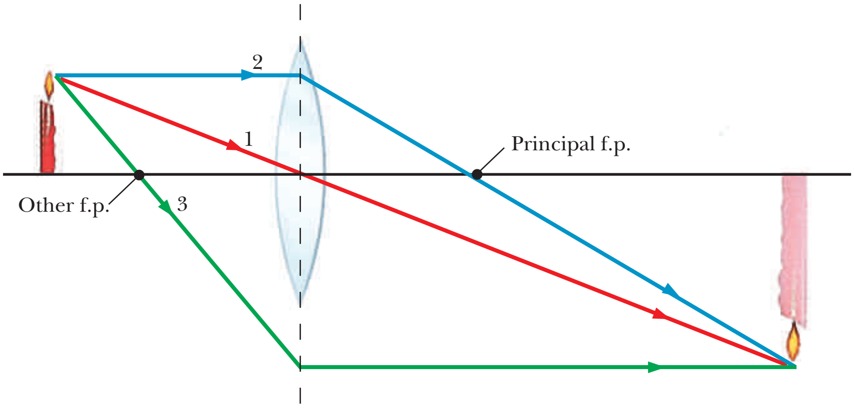


Figure 18-21 The image formed by a candle located outside the focal point of a converging lens is real and inverted and may be magnified or reduced in size.

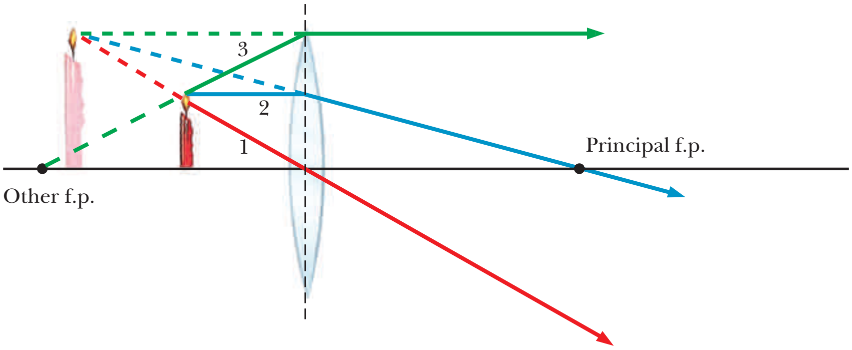


Figure 18-22 The image formed by a candle located inside the focal length of a converging lens is virtual, erect, and magnified.

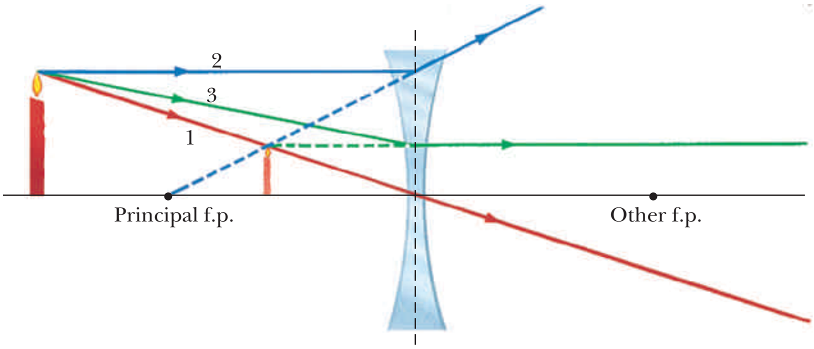


Figure 18-23 The image formed by a diverging lens is virtual, erect, and reduced in size.

A diverging lens always produces a virtual image, as shown in Figure 18-23. The image changes location and size as the object is moved, but the image remains erect and virtual.

Q: Is the lens used in a slide projector converging or diverging?

A: It must be converging because it forms a real image on the screen.

Notice that one of the rays in Figure 18-21 does not pass through the lens. This isn't a problem because there are many other rays that do pass through the lens to form the image. Ray diagramming is just a geometric construction that allows you to locate images, a process that can be illustrated with an illu-

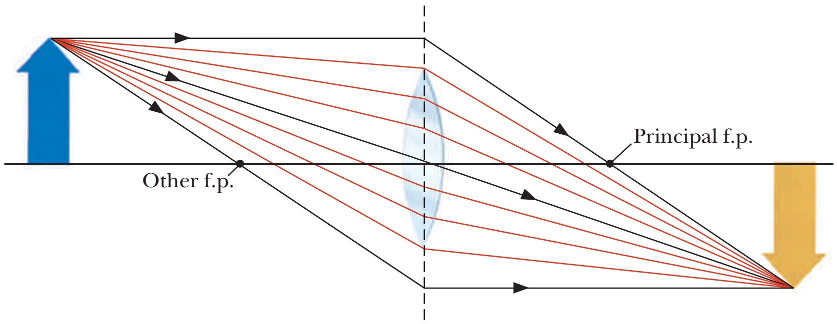


Figure 18-24 The orange rays form the image. The black ones are used because they are easy to draw.

minated arrow and a large-diameter lens, as drawn in Figure 18-24. A piece of paper at the image's location allows the image to be easily seen. If the lens is then covered with a piece of cardboard with a hole in it, the image is still in the same location, is the same size, and is in focus. The light rays from the arrow that form the image are those that pass through the hole. The image is not as bright because less light now forms the image. The orange lines illustrate the paths of some of the other rays.

FLAWED REASONING

The following question appears on the final exam: "Three long light filaments are used to make a letter Y that is placed in front of a large converging lens such that it creates a real image on the other side of the lens. The meeting point of the three filaments lies on the optic axis of the lens. A piece of cardboard is then used to cover up the bottom half of the lens. Describe what happens to the image of the Y."

Three students give their answers:

Jacob: "The cardboard will block the light from the lower filament, so the image will appear as a letter V."

Emily: "The real image formed by a converging lens is inverted. The image would now appear to be an upside-down letter V."

Michael: "The image is inverted, so the light from the lower filament must pass through the top half of the lens and the light from the upper two filaments will be blocked by the cardboard. The image will appear as the letter I."

All three students have answered incorrectly. **Find the flaws in their reasoning.**

ANSWER A point source of light sends light to all parts of the lens's surface. This light converges at a single point on the other side of the lens (the image location). Covering half the lens blocks half the light, but the other half still forms an image at the same location. The three long filaments can be thought of as a collection of many point sources. They still form the same image (an upside-down Y). The image will be dimmer because half the light is blocked.

Cameras

We saw in the last chapter that pinhole cameras produce sharp images if the pinhole is very small. The amount of light striking the film, however, is quite small. Very long exposure times are needed, which means that the objects in the scene must be stationary. The amount of light reaching the film can be substantially increased (and the exposure time substantially reduced) by using a converging lens instead of a pinhole.

The essential features of a simple camera are shown in Figure 18-25. This camera has a single lens at a fixed distance from the film. The distance is chosen so that the real images of faraway objects are formed at, or at least near, the film. These cameras are usually not very good for taking close-up shots, such as portraits, because the images are formed beyond the film and are therefore out of focus at the film. More expensive cameras have an adjustment that moves the lens relative to the film to position (focus) the image on the film.

Q: If the focal length of the lens in a simple camera is 50 millimeters, how far is it from the lens to the film for a subject that is very far from the camera?

A: If the objects are effectively at infinity, the light from each point will be focused at a distance equal to the focal length. Thus, the film should be about 50 millimeters from the center of the lens.

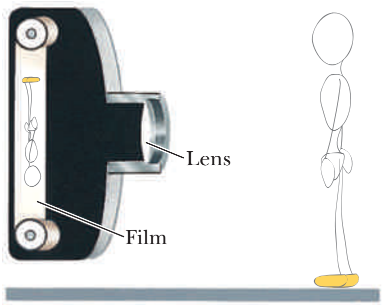


Figure 18-25 The essential features of a simple camera.

Ideally, all light striking the lens from a given point on the object should be focused to a given point on the film. However, real lenses have a number of defects, or **aberrations,** so that light is not focused to a point but is spread out over some region of space.

A lens cannot focus light from a white object to a sharp point because of dispersion. A converging lens focuses violet light at a point closer to the lens than it does red light. This chromatic aberration produces images with colored fringes. Because the effect is reversed for diverging lenses and the amount of dispersion varies with material, lens designers minimize chromatic aberration by combining converging and diverging lenses made of different types of glass.

A spherical lens (or a spherical mirror, for that matter) does not focus all light parallel to the optic axis to a sharp point. Light farther from the optic axis is focused at a point closer to the lens than light near the optic axis. Using a combination of lenses usually corrects this spherical aberration; using a diaphragm to decrease the effective diameter of the lens also reduces it. Although this sharpens the image, it also reduces the amount of light striking the film. New techniques for reducing spherical aberration by grinding lenses with nonspherical surfaces and by making lenses in which the index of refraction of the glass changes with the distance from the optic axis have been developed.

Our Eyes

Gerald F. Wheeler

The retina of a human eye.

Leonardo da Vinci stated in the 15th century that the lens of an eye forms an image inside the eye that is transmitted to the brain. He believed that this image must be upright. It was a century before it was shown that he was half right: the lens forms an image inside the eye, but the image is upside down. The inverted nature of the image was demonstrated by removing the back of an excised animal eye and viewing the image. The inverted world received by our retinas is interpreted as right-side up by our eye–brain system. The essential features of this remarkable optical instrument include the cornea, the lens, and some fluids, which act collectively as a converging lens to form real, inverted images on the retina (Figure 18-26).

When you look at a distant object, nearby objects are out of focus. Only distant objects form sharp images on the surface of the retina. The nearby objects form images that would be behind the retina, and the images on the retina are therefore fuzzy. This phenomenon occurs because the locations of images of objects at various distances depend on the distances between the lens and the objects and on the focal length of the lens. The lens in the eye changes its shape and thus its focal length to accommodate the different distances.

Opticians measure the strength of lenses in diopters. The lens strength in *diopters* is equal to the reciprocal of the focal length measured in meters. For example, a lens with a focal length of 0.2 meter is a 5-diopter lens. In this case a larger diopter value means that the lens is stronger. Converging lenses have positive diopters, and diverging lenses have negative diopters. Diopters have the advantage that two lenses placed together have a diopter value equal to the sum of the two individual ones.

In the relaxed eye of a young adult who does not wear corrective lenses, all the transparent materials have a total "power" of +60 diopters. Most of the refraction (+40 diopters) is due to the outer element of the eye, the cornea, but the relaxed lens contributes +20 diopters.

The eye can vary the strength of the lens from a relaxed value of +20 diopters to a maximum of +24 diopters. When the relaxed eye views a distant object, the +60 diopters produce an image at 1.7 centimeters (0.7 inch), which is the distance to the retina in a normal eye. The additional +4 diopters allow the eye to view objects as near as 25 centimeters (10 inches) and still produce sharp images on the retina.

The ability of the eye to vary the focal length of the lens decreases with age as the elasticity of the lens decreases. A 10-year-old eye may be able to focus as close as 7 centimeters (+74 diopters), but a 60-year-old eye may not be able to focus any closer than 200 centimeters ($6\frac{1}{2}$ feet). An older person often wears bifocals when the eyes lose their ability to vary the focal length.

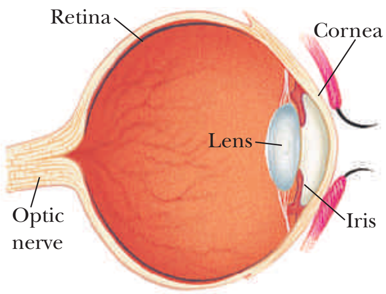


Figure 18-26 Schematic drawing of the human eye.

	Sphere	Cylinder	Axis
R	−6.50	+3.25	089
L	−5.75	+2.75	074
R	+2.00		
L	+2.00	Bifocals	

The prescription for your author's eyeglasses. The spherical and cylindrical corrections are given in diopters. Axis is the number of degrees the axis of the cylinder is rotated from the vertical. The bifocal correction is added to the others.

WORKING IT OUT *Diopters*

A converging lens of focal length 25 cm is placed next to a diverging lens of length 20 cm. What is the effective focal length for this combination? Is it diverging or converging?

A lens with a shorter focal length is more effective in bending the light; it is a "stronger" lens. The strength of the lens is therefore given by the inverse of the focal length, measured in diopters. The strength of the converging lens is

$$d_1 = \frac{1}{0.25\ \text{m}} = +4\ \text{diopters}$$

The strength of the diverging lens is

$$d_2 = -\frac{1}{0.20\ \text{m}} = -5\ \text{diopters}$$

where the negative sign indicates that it is spreading the light rather than collecting it. The combined strength of the two lenses is given by the sum of the diopters:

$$d_{total} = d_1 + d_2 = +4\ \text{diopters} - 5\ \text{diopters} = -1\ \text{diopter}$$

The effective focal length is the inverse of d_{total}, or −1 m. The two lenses combined could be replaced by a single diverging lens with focal length of 1 m.

The amount of light entering the eye is regulated by the size of the pupil. As with the ear, the range of intensities that can be viewed by the eye is very large. From the faintest star that can be seen on a dark, clear night to bright sunlight is a range of intensity of approximately 10^{10}.

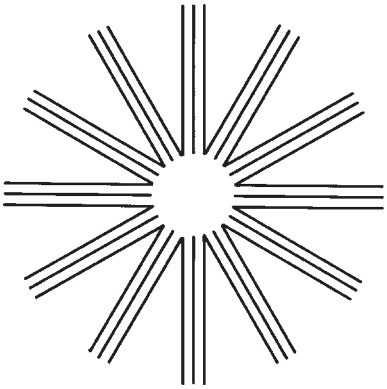


Figure 18-27 A test pattern for astigmatism. If you see some lines blurred while other lines are sharp and dark, you have some astigmatism.

Another common visual defect is *astigmatism.* When some of the refracting surfaces are not spherical, the image of a point is spread out into a line. Use the pattern in Figure 18-27 to check for astigmatism in your eyes. Lines along the direction in which images of point sources are spread remain sharp and dark, but the others become blurred. Are your two eyes the same?

Magnifiers

It has been known since the early 17th century that refraction could bend light to magnify objects. The invention of the telescope and microscope produced images of regions of the universe that until then had been unexplored. Galileo used the newly discovered telescope to see Jupiter's moons and the details of our Moon's surface. English scientist Robert Hooke spent hours peering into another unexplored world with the aid of the new microscope.

The size of the image on the retina depends on the object's physical size and on its distance away. The image of a dime held at arm's length is much larger than that of the Moon. What really matters is the angular size of the object—that is, the angle formed by lines from your eye to opposite sides of the object. The angular size of an object can be greatly increased by bringing it closer to your eye. However, if you bring it closer than about 25 centimeters (10 inches), your eye can no longer focus on it, and its image is blurred. You can get both an increased angular size and a sharp image by using a converging lens as a magnifying glass. When the object is located just inside the focal point of the lens, the image is virtual and erect and has nearly the same angular size as the object. Moreover, as shown in Figure 18-28, the image is now far enough away that the eye can focus on it and see it clearly.

An even higher magnification can be achieved by using two converging lenses to form a compound microscope, as shown in Figure 18-29. The object is located just outside the focal point of the objective lens. This lens forms a real image that is magnified in size. The eyepiece then works like a magnifying glass to further increase the angular size of this image.

Figure 18-28 A candle viewed (a) at a distance of 25 centimeters and (b) through a magnifying glass.

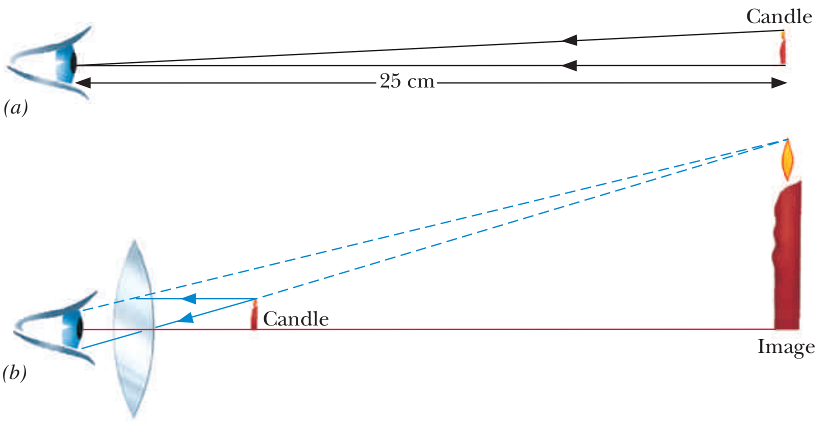
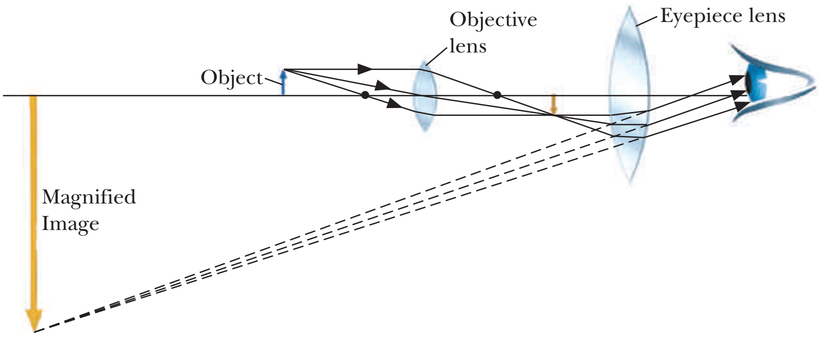


Figure 18-29 Schematic of a compound microscope.



Everyday Physics | *Eyeglasses*

Our optical system is quite amazing. The lens in our eye can change its shape, altering its focal length to place the image on the retina. Sometimes, however, the eye is too long or too short, and the images are formed in front of or behind the retina. When the eye is too long, the images of distant objects are formed in front of the retina, as shown in Figure A. Such a person has *myopia* (nearsightedness) and can see things that are close but has trouble seeing distant objects. When the eye is too short, the person has *hyperopia* (farsightedness) and has trouble seeing close objects. Distant objects can be imaged on the retina, but close objects form images behind the retina (Figure B).

Our knowledge of light and refraction allows us to devise instruments—eyeglasses—that correct these deficiencies. The nearsighted person wears glasses with diverging lenses to see distant objects (Figure A). The farsighted person's sight is corrected with converging lenses (Figure B).

Even people with perfect vision early in life lose some of the lens's range, particularly the ability to shorten the focal length. These people have trouble creating a focused image on their retina for objects that are close. Many older people wear bifocals when their eyes lose the ability to shorten the focal length. The upper portion of the lens is used for distant viewing; the lower portion is used for close work or reading. When people work at intermediate distances such as looking at computer screens, they sometimes wear trifocals.

The difficulty of making glasses to correct vision is increased when a person has astigmatism. This occurs when some of the refracting surfaces are not spherical and the image of a point is spread out into a line. This visual defect is corrected by adding a cylindrical curvature to the spherical curvature of the lens. You can check your (or a friend's) glasses for correction for astigmatism by looking through them in the normal way but holding the glasses at a distance from your head. When you rotate the lens about a horizontal axis, you will see background distortion if the lens has an astigmatic correction.

Many people wear contact lenses to correct their vision. The use of contact lenses has created some interesting challenges in correcting for astigmatism and the need to wear bifocals. When correcting for astigmatism, the cylindrical correction must have the correct orientation. Contact lenses can be weighted at one place on the edge to keep the lens oriented correctly.

People who need bifocals can sometimes be fitted with different corrections in each eye; one eye is used for close vision and the other is used for distant vision. The eye–brain system switches from one eye to the other as the situation demands.

Finally, a medical procedure uses laser technology to correct nearsightedness. In this procedure, the laser is used to make radial cuts in the cornea of the eye to reduce its curvature.

1. Explain how diverging lenses can be used to correct for nearsightedness.
2. Why do your contact lenses need to be weighted more heavily on one side if you have astigmatism?

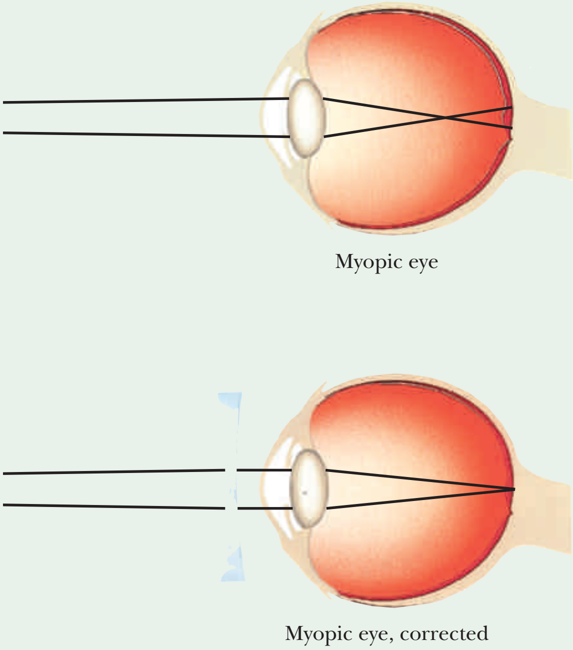


Figure A The myopic eye forms the images of distant objects in front of the retina. This is corrected with diverging lenses.

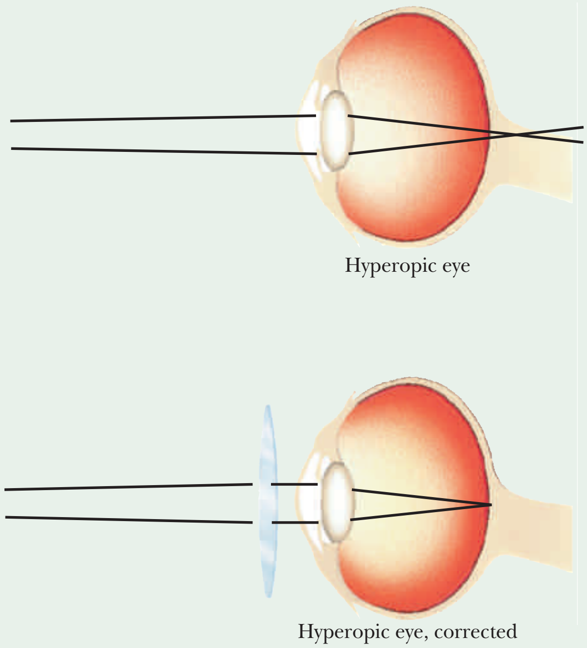


Figure B The hyperopic eye forms images of close objects in back of the retina. This is corrected with converging lenses.

Telescopes

There are many varieties of telescope. A simple one using two converging lenses is known as a **refracting telescope,** or refractor. Figure 18-30 shows that this type of telescope has the same construction as a compound microscope except that now the object is far beyond the focal point of the objective lens. Like the microscope, the refractor's objective lens produces a real, inverted image. Although the image is much smaller than the object, it is much closer to the eye. The eyepiece acts as a magnifying glass to greatly increase the angular size of the image. The magnification of a telescope is equal to the ratio of the focal lengths of the objective lens and the eyepiece. To get high magnification, the focal length of the objective lens needs to be quite long.

Binoculars were designed to provide a long path length in a relatively short instrument. The diagram in Figure 18-31 shows that this is accomplished by using the internal reflections in two prisms to fold the path.

Large-diameter telescopes are desirable because they gather a lot of light, allowing us to see very faint objects or to shorten the exposure time for taking pictures. The problem, however, is making a large-diameter glass lens. It is difficult, if not impossible, to make a piece of glass of good enough quality. Also, a lens of this diameter is so thick that it sags under its own weight. Therefore, most large telescopes are constructed with concave mirrors as objectives and

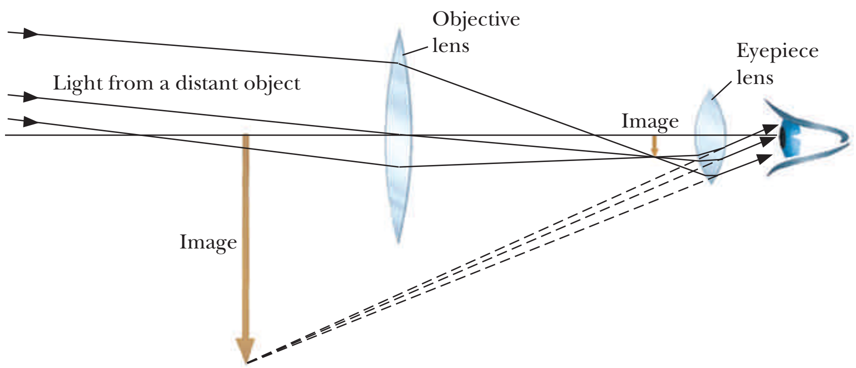


Figure 18-30 Schematic of an astronomical telescope.

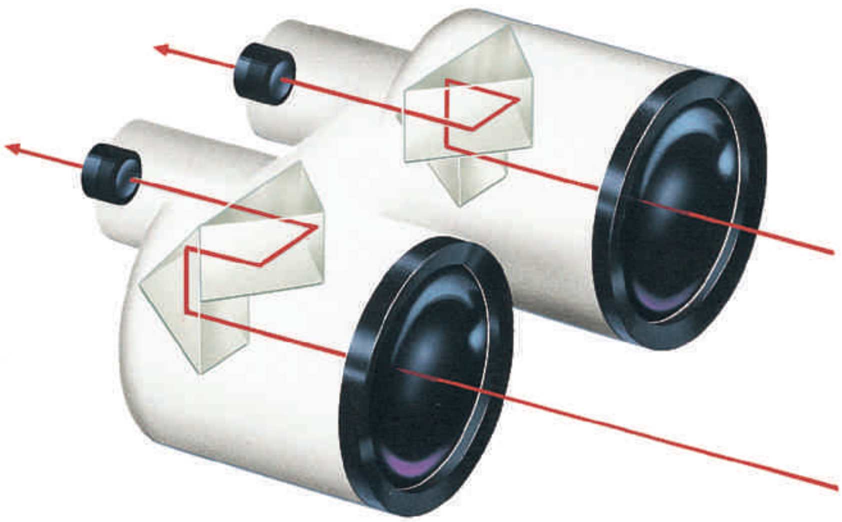


Figure 18-31 Schematic of prism binoculars.

are known as **reflecting telescopes,** or reflectors. The use of a concave mirror to focus the incoming light has several advantages: the construction of a mirror requires grinding and polishing only one surface rather than two; a mirror can be supported from behind; and, finally, mirrors do not have the problem of chromatic aberration. Figure 18-32 illustrates several designs for reflecting telescopes.

The world's largest refractor has a diameter of 1 meter (40 inches), whereas the largest reflector has a diameter of 6 meters (236 inches). This is just about the limit for a telescope with a single objective mirror; the costs and manufacturing difficulties are not worth the gains. Telescope makers have recently built telescopes in which the images from many smaller mirrors are combined to increase the light-gathering capabilities.

Summary

When light strikes a transparent material, part of it reflects and part refracts. The amount of refraction depends on the incident angle and the index of refraction of the material. Light entering a material of higher index of refraction bends toward the normal. Because the refraction of light is a reversible process, light entering a material with a smaller index of refraction bends away from the normal. For light in a material with a larger index of refraction, total internal reflection occurs whenever the angle of incidence exceeds the critical angle.

The refraction of light at flat surfaces causes objects in or behind materials of higher indexes of refraction to appear closer, and therefore larger. The apparent locations of celestial objects are changed by refraction in the atmosphere.

White light is separated into a spectrum of colors because the colors have different indexes of refraction, a phenomenon known as dispersion. Rainbows

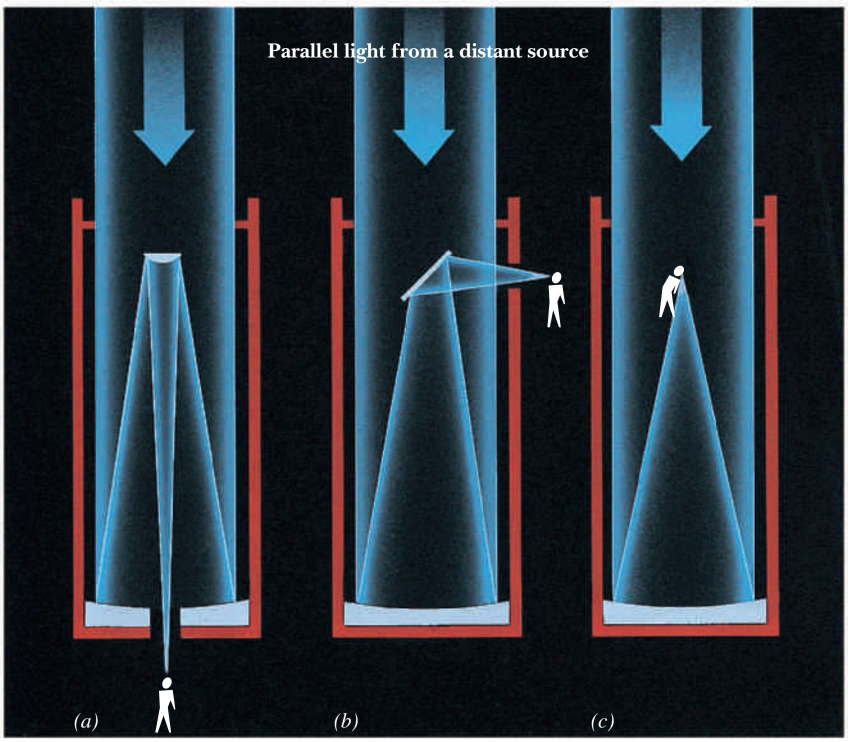


Figure 18-32 Schematics of (a) a Cassegrain reflector, (b) a Newtonian reflector, and (c) a prime-focus telescope.

Everyday Physics | *The Hubble Space Telescope*

At a cost of $1.6 billion, the Hubble Space Telescope was placed in an orbit 575 kilometers (357 miles) above Earth by the space shuttle *Discovery* in April 1990. Its mission is to provide astronomers with observations of the universe without the disturbances caused by Earth's atmosphere. The atmosphere absorbs most of the radiation reaching us from space, except for two broad bands in the radio region and around the visible region. A variety of experiments were planned that ranged from viewing distant, faint objects to accurately measuring the positions of stars. The design specifications indicated that the Hubble Space Telescope would be able to see objects seven times as far away as what could be observed from Earth's surface.

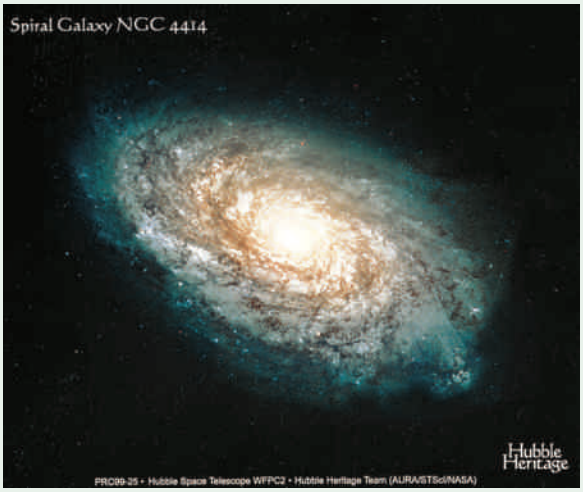
However, these experiments were seriously hampered by a defect in the telescope's primary mirror. Although the error in its shape was only 0.002 millimeter (about one-fortieth the thickness of a human hair) at the edge of the 2.4-meter-diameter mirror, it caused light from the edge of the mirror to focus 38 millimeters beyond light from the center. This left the telescope with an optical defect—spherical aberration—that created fuzzy halos around images of stars, and blurred images of extended objects such as galaxies and giant clouds of gas and dust. Only 15% of the light from a star was focused into the central spot compared to the design value of 70%. However, because this type of aberration is well known, computer enhancement was used to sharpen images of brighter objects, producing some rather remarkable views and some very good science, but the technique did not work for faint objects.

Fortunately, the Hubble Space Telescope was designed to be serviced by the space shuttles, and new optics were designed to compensate for the error. In December 1993 the space shuttle *Endeavour* docked with the Hubble Space Telescope to repair the optics and replace a number of mechanical and electrical components that had failed or required scheduled replacement. The repairs required five spacewalks involving two astronauts each. The total repair mission had a cost of $700 million. The repaired Hubble Space Telescope is able to see much farther into space.

1. Why is a space-based telescope superior to an Earth-based one?
2. In what ways did spherical aberration affect the initial images formed by the Hubble Space Telescope?

NASA

The Hubble Space Telescope.



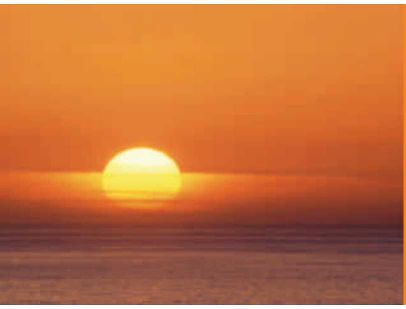
NASA

Careful study of images of this spiral galaxy (NGC 4414) taken by the Hubble Space Telescope allowed astronomers to determine that it is 60 million light-years from Earth.

are formed by dispersion in water droplets. Each color forms part of a circle about the point directly opposite the Sun. Halos are caused by the refraction of sunlight in ice crystals.

Ray diagrams can be used to locate the images formed by lenses. The rays are summarized by the following rules: (1) through center—continues; (2) parallel to optic axis—through (from) principal focal point; and (3) through (toward) other focal point—parallel to optic axis.

Cameras and our eyes contain converging lenses that produce real, inverted images. Converging lenses can be used as magnifiers of objects located inside the focal points. Lenses can be combined to make microscopes and telescopes.



CHAPTER 18 *Revisited*

The most obvious consequence of the passage of light between two transparent materials is that the direction of the light changes at the interface. This may produce virtual images that are closer, making the fish look bigger and the tree look bent. It is possible for light to get "trapped" if it is in the material with the larger index of refraction and if the angle of incidence is larger than the critical angle.

Key Terms

aberration A defect in a mirror or lens causing light rays from a single point to fail to focus at a single point in space.

critical angle The minimum angle of incidence for total internal reflection to occur.

dispersion The spreading of light into a spectrum of colors.

focal length The distance from the center of a lens to its focal point.

focal point The location at which a lens focuses rays parallel to the optic axis or from which such rays appear to diverge.

index of refraction An optical property of a substance that determines how much light bends on entering or leaving it.

optic axis A line passing through the center of a lens and both focal points.

reflecting telescope A type of telescope using a mirror as the objective.

refracting telescope A type of telescope using a lens as the objective.

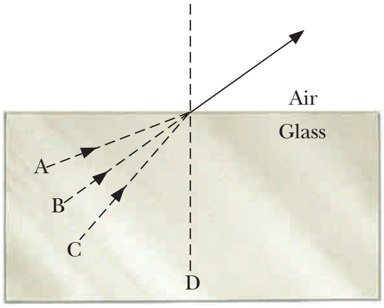
refraction The bending of light that occurs at the interface between transparent media.

total internal reflection A phenomenon that occurs when the angle of incidence of light traveling from a material with a higher index of refraction into one with a lower index of refraction exceeds the critical angle.

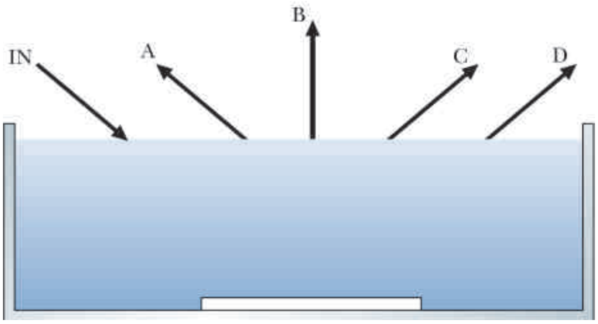
Questions and exercises are paired so that most odd-numbered are followed by a similar even-numbered.
Blue-numbered questions and exercises are answered in Appendix B.
indicates more challenging questions and exercises.
WebAssign Many Conceptual Questions and Exercises for this chapter may be assigned online at WebAssign.

Conceptual Questions

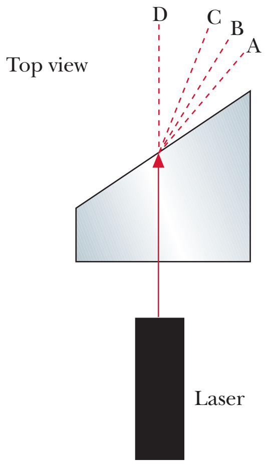
1. A narrow beam of light emerges from a block of glass in the direction shown in the following figure. Which arrow best represents the path of the beam within the glass?



2. A mirror is lying on the bottom of a fish tank that is filled with water. If IN represents a light ray incident on the top of the water, which possibility in the following figure best represents the outgoing ray?



3. You place a waterproof laser and a glass prism flat on the bottom of an empty aquarium, as shown in the following figure. The light leaving the prism follows path B. If you filled the aquarium with water, which path would the light leaving the prism now follow?



4. Figure 18-2 shows the refraction curves for air, water, and glass. If we were to draw the curve for diamond, would it appear above or below the curve for glass? Why?
5. Why do clear streams look so shallow?
6. Suppose you are lying on the bottom of a swimming pool looking up at a ball that is suspended 1 meter above the surface of the water. Does the ball appear to be closer, farther away, or still 1 meter above the surface? Explain.
7. Is the critical angle greater at a water–air surface or a glass–air surface?
8. For what range of incident angles is light totally reflected at a water–air surface?
9. Telephone companies are using "light pipes" to carry telephone signals between various locations. Why does the light stay in the pipe?
10. There is a limit to how much a fiber-optic cable can be bent before light "leaks" out because bending the pipe allows light to strike the surface at angles less than the critical angle. If you were laying fiber-optic cable under water instead of in air, would this be a greater or lesser problem? Why?
11. The distance from Earth to Mars varies from 48 million miles to 141 million miles as the two planets orbit the Sun. At which distance would Mars appear to twinkle more? Why?
12. We observe stars twinkling when viewed from Earth, but astronauts in a space shuttle do not observe this. Why?
13. As you look toward the west, you see two stars one above the other with a 5-degree separation. As the two stars move closer to the western horizon, will their apparent separation increase, decrease, or stay the same? Why?
14. In the absence of an atmosphere, a star moves across the sky from horizon to horizon at a constant speed. How does the star appear to move in the presence of an atmosphere?
15. How is the time of sunrise affected by atmospheric refraction?
16. How does the presence of an atmosphere affect the length of day and night?
17. How does the refraction of light in the atmosphere affect the appearance of the Sun or Moon as it approaches the horizon?
18. During a total lunar eclipse, the Moon lies entirely within Earth's umbra and yet is still faintly visible. If Earth lacked an atmosphere, the Moon would not be visible at

all. Explain how Earth's atmosphere allows the Moon to be seen during an eclipse.

19. You are trying to spearfish from a boat, and you spy a fish about 2 meters from the boat. Should you aim high, low, or directly at the fish? Why?

20. If you were going to send a beam of light to the Moon when it is just above the horizon, would you aim high, low, or directly at the Moon? Explain.

21. Does a beam of white light experience dispersion as a result of reflecting from a mirror? Explain.

22. Why is a diamond more brilliant than a clear piece of glass having the same shape?

23. A fiber-optic cable is used to transmit yellow light. At one sharp bend, the incident angle is exactly at the critical angle for yellow light. If the pipe were bent any more, the yellow light would "leak" out. If the cable were used with blue light, would this bend be a problem? What if it were used with red light? Explain.

24. While transmitting white light down a fiber-optic cable, you bend the cable too much in one place, and some of the light "leaks" out. Which is the first color of light to "leak" out?

25. If your line of sight to a water droplet makes an angle of 41 degrees with the direction of the sunlight, what color would the raindrop appear to be?

26. You are looking at a rainbow from the ground floor of an apartment building and notice that a kite is hovering right in the green portion. If you were to go up to the second floor, would you be likely to see the kite hovering in the red portion or the blue portion of the rainbow? Explain.

27. Why is a shadow of your head always in the center of a rainbow?

28. If you were flying in an airplane and saw a rainbow at noon, what shape would it be, and where would you be looking?

29. At what time of day might you expect to see the top of a rainbow set below the horizon? In what direction would you look to see it?

30. At what time of day and in what direction would you look to see the top of a rainbow rise above the horizon?

31. To produce a hologram, a narrow beam of laser light must be spread out enough to expose the surface of a piece of film. What type of lens would accomplish this? Explain your reasoning.

32. What type of lens would be helpful in starting a campfire? Why?

33. You find a converging lens in the storeroom and wish to determine its focal length. Describe how you could use two lasers to accomplish this.

34. You place a laser at the principal focus of a converging lens and aim the beam toward any part of the lens. Describe the beam's path after passing through the lens.

35. You find a diverging lens in the storeroom and wish to determine its focal length. Describe how you could use two lasers to accomplish this.

36. You wish to use a diverging lens to redirect the light from six lasers to produce beams that are parallel to the optic axis of the lens. How should you aim the lasers to accomplish this?

37. What type of lens would you use to construct an overhead projector? Explain your reasoning.

38. Can a prism be used to form an image? Explain.

39. Where does a ray arriving parallel to the optic axis of a converging lens go after passing through the lens?

40. What path does a ray take after passing through a converging lens if it passes through a focal point before it enters the lens?

41. A converging lens is used to form a sharp image of a candle. What effect does covering the upper half of the lens with paper have on the image?

42. How does covering all but the center of a lens affect the image of an object?

43. Two converging lenses with identical shapes are made from glasses with different indexes of refraction. Which one has the shorter focal length? Why?

44. You are building a device in which the dimensions of a diverging lens cannot be changed. On testing the device, however, you discover that the focal length of your lens is too short. You decide to fix this problem by grinding a lens of identical shape from different glass. Should you use a glass with a larger or a smaller index of refraction? Why?

45. Consider the image of a candle as shown in Figure 18-21. Explain why you would not be able to see the image if your eye were located to the left of the image location.

46. Consider the image of a candle as shown in Figure 18-21. To clearly see the image, should you locate your eye at the image location or to the right of the image location? Explain.

47. What kind of image is formed on the retina of an eye?

48. How might you convince a friend that the image formed by a camera is a real image?

49. What is the purpose of the pupil in the eye?

50. What is the purpose of a diaphragm in a camera?

51. Why does a telescope that uses a mirror to focus the light not exhibit chromatic aberration whereas a telescope that uses a lens to focus the light does?

52. You measure the focal length of a converging lens by finding the crossing point of parallel beams of red laser light. If you measure the focal length using lasers that emit green light, would the measured value be greater than, less than, or the same as before? Why?

53. Are reading glasses used by older people converging or diverging? Explain.

54. Without glasses, the light entering our eyes comes directly from the object. With glasses, the light comes from the image formed by the glasses. Is this image real or virtual? Explain.

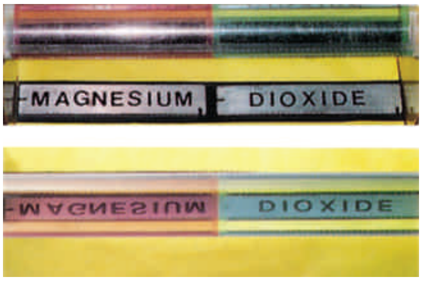
55. When a person has cataract surgery, the lens of the eye is removed and replaced with a plastic one. Would you expect this lens to be converging or diverging? Explain.

56. Stamp and coin collectors often wear special glasses that allow them to see the details of the stamps and coins. Are the lenses in these glasses converging or diverging? Why?

57. The ray diagram for a magnifying glass is shown in Figure 18-22. As the object is moved toward the focal point, the direction of emerging ray 2 does not change, whereas the direction of emerging ray 1 does. By looking at where these rays now intersect, determine whether the image gets larger or smaller as the object is moved closer to the focal point.

58. If the magnifying lens in Figure 18-22 were replaced with a lens of shorter focal length, the direction of emerging ray 1 would not change, whereas the direction of emerging ray 2 would. By looking at where these rays would now intersect, determine whether the magnification would be increased or decreased.

59. The figure shows the words MAGNESIUM DIOXIDE viewed through a solid plastic rod. Why does MAGNESIUM appear upside down, while DIOXIDE appears right-side up?



60. When a single converging lens is used to focus white light, the image has a colored fringe due to chromatic aberration. Describe the changes in the color of the fringe as a screen is moved through the focal point.

Exercises

61. If light in air is incident at 30°, at what angle is it refracted in water? In glass?

62. Light in air is incident on a surface at an angle of 60°. What is its angle of refraction in glass? In water?

63. You are spearfishing in waist-deep water when you spot a fish that appears to be down at a 45° angle. You recognize that the light coming from the fish to your eye has been refracted and you must therefore aim at some angle below the apparent direction to the fish. What is this angle?

64. Light from the bottom of a swimming pool is incident on the surface at an angle of 30°. What is the angle of refraction?

65. Use Figure 18-2 to estimate the critical angle for glass with an index of refraction of 1.6.

66. Use Figure 18-2 to estimate the angle of refraction for light in air incident at 50° to the surface of glass with an index of refraction of 1.6.

67. A prism made of glass with an index of refraction of 1.5 has the shape of an equilateral triangle. A light ray is incident on one face at an angle of 48°. Use a protractor and Figure 18-2 to find the path through the prism and out an adjacent side. What is the exit angle?

68. A prism made of plastic with an index of refraction of 1.33 has the shape of a cube. A light ray is incident on one face at an angle of 70°. Use a protractor and Figure 18-2 to find the path through the prism and out an adjacent side. What is the exit angle?

69. You are scuba diving below a fishing pier. You look up and see a fishing pole that appears to be 2 m above the surface of the water. Use a ray diagram to show that the pole is actually closer to the surface of the water.

70. Using data from Figure 18-2 to determine the exact angles, redraw Figure 18-4(c) to locate the image of something sitting on the bottom of a pond. Use your scale diagram and a ruler to show that an object in water appears to be about $\frac{3}{4}$ as deep as it actually is. (Note that the index of refraction for water is $\frac{4}{3}$.)

71. An object is located midway between the other focal point and the center of a converging lens. Draw a ray diagram showing how you locate the image. Estimate the magnification of the image from your diagram.

72. Use a ray diagram to find the location and magnification of the image of an object located three focal lengths from a converging lens.

73. Use a ray diagram to locate the image of an arrow placed 60 cm from a diverging lens with a focal length of 30 cm.

74. The focal length of a converging lens is 30 cm. Use a ray diagram to locate the image of an object placed 60 cm from the center of this lens.

75. Over what range of positions can an object be located so that the image produced by a converging lens is real and smaller than the object?

76. Over what range of positions can an object be located so that the image produced by a converging lens is real and magnified?

77. In Figure 18-21 a weakly diverging lens is inserted at the principal focal point of the converging lens. Use a ray diagram to show that this results in the real image being shifted to the right.

78. Use ray diagrams to show that a diverging lens cannot produce a magnified image of an object.

79. Draw a ray diagram to locate the image of an object placed inside the focal point of a diverging lens. Is the image real or virtual? Erect or inverted? Magnified or reduced in size? Explain.

80. What is the location of the image of an object placed at the focal point of a diverging lens? Is the image real or virtual? Erect or inverted? Magnified or reduced in size? Explain.

81. How many diopters are there for a converging lens with a focal length of 0.4 m?

82. If a lens has a focal length of 25 cm, how many diopters does it have?

83. A converging lens of focal length 20 cm is placed next to a converging lens of focal length 50 cm. What is the effective focal length for this combination?

84. What focal-length lens would you need to place next to a converging lens of focal length 25 cm to create an effective focal length of 20 cm for the combination?

85. A converging lens of focal length 50 cm is placed next to a diverging lens of length 25 cm. What is the effective focal length for this combination? Is it diverging or converging?

86. You ordered a converging lens of focal length 2 m, but the company delivered a lens whose focal length was only 1 m. You don't have time to wait for a replacement, so you decide to correct the problem by placing a diverging lens next to the lens they sent you. What must the focal length be for this diverging lens?