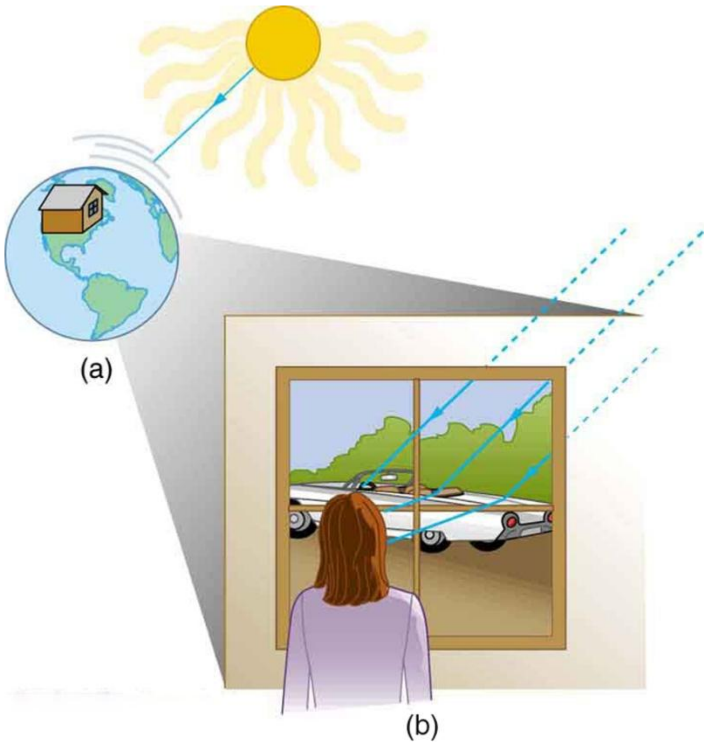
# FIGURE 25.1

Image seen as a result of reflection of light on a plane smooth surface. (credit: NASA Goddard Photo and Video, via Flickr)

# FIGURE 25.2

Double Rainbow over the bay of Pocitos in Montevideo, Uruguay. (credit: Madrax, Wikimedia Commons)

# FIGURE 25.3

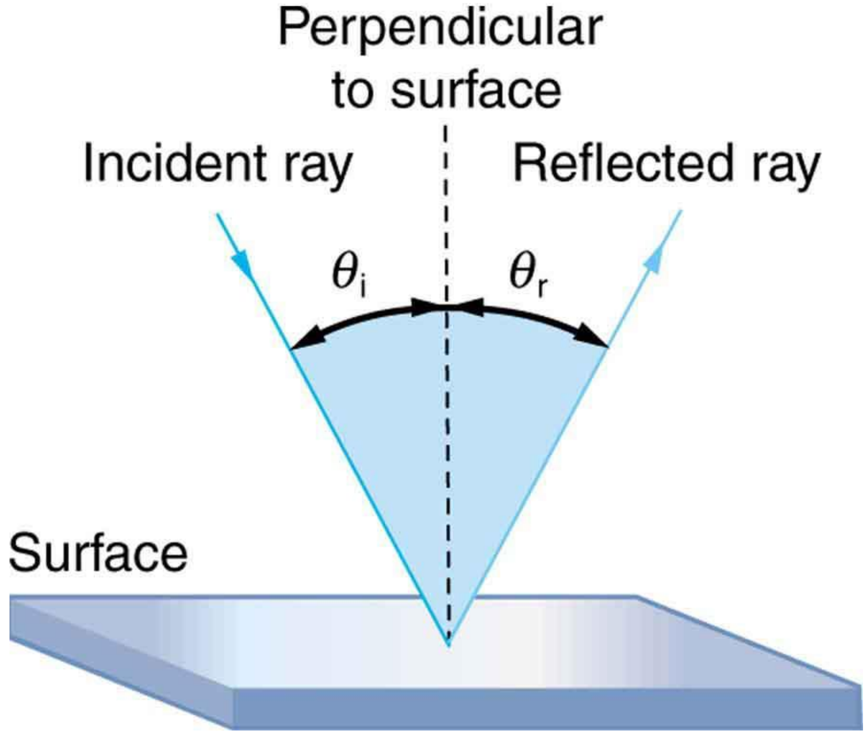



Three methods for light to travel from a source to another location.

(a) Light reaches the upper atmosphere of Earth traveling through empty space directly from the source.

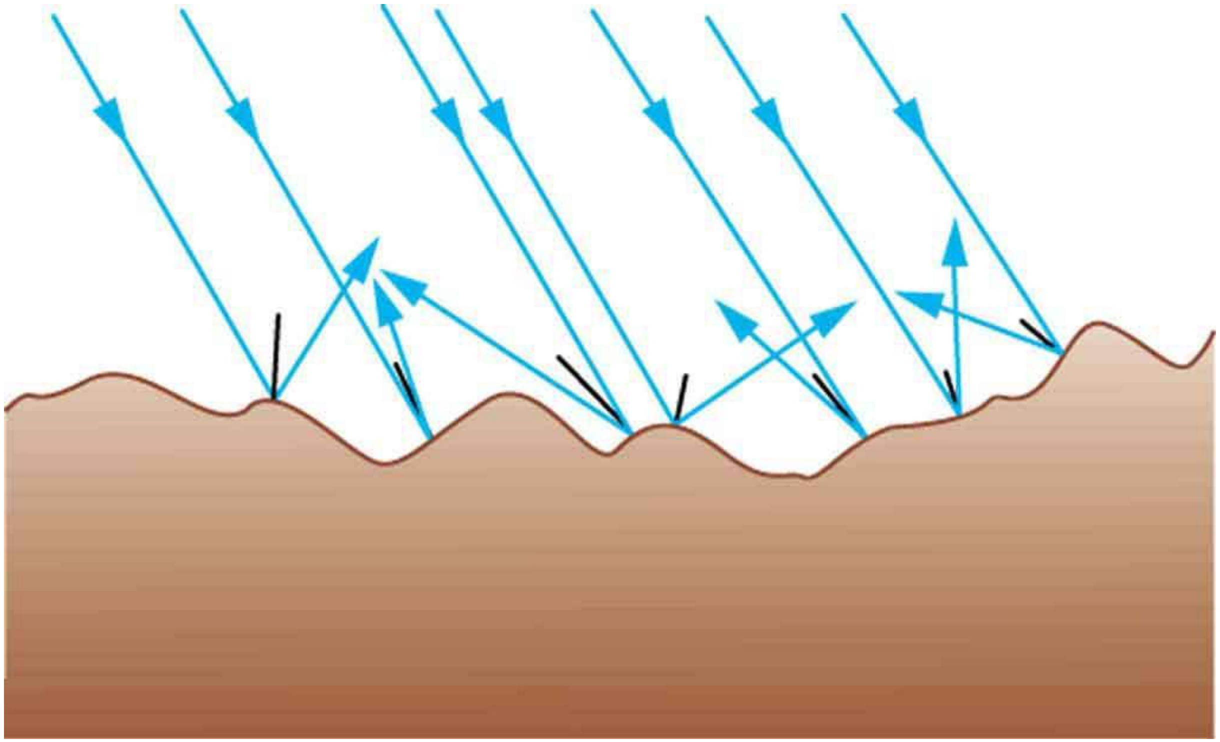
(b) Light can reach a person in one of two ways. It can travel through media like air and glass. It can also reflect from an object like a mirror. In the situations shown here, light interacts with objects large enough that it travels in straight lines, like a ray.

# FIGURE 25.4



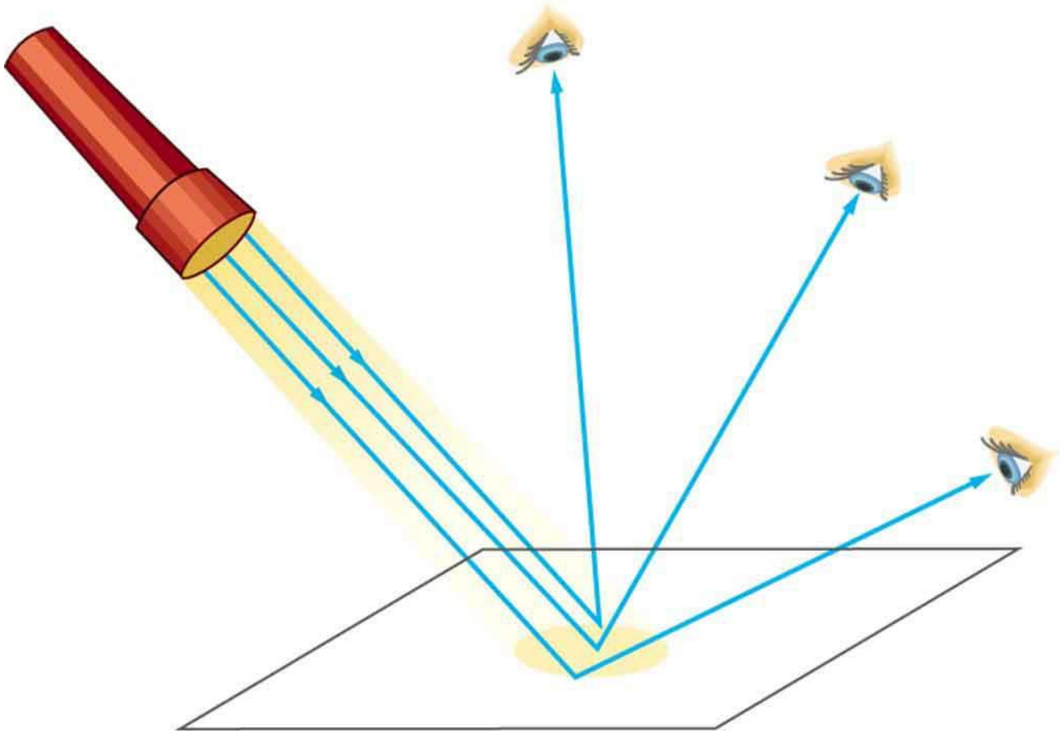

The law of reflection states that the angle of reflection equals the angle of incidence—$\theta_r = \theta_i$ . The angles are measured relative to the perpendicular to the surface at the point where the ray strikes the surface.

# FIGURE 25.5



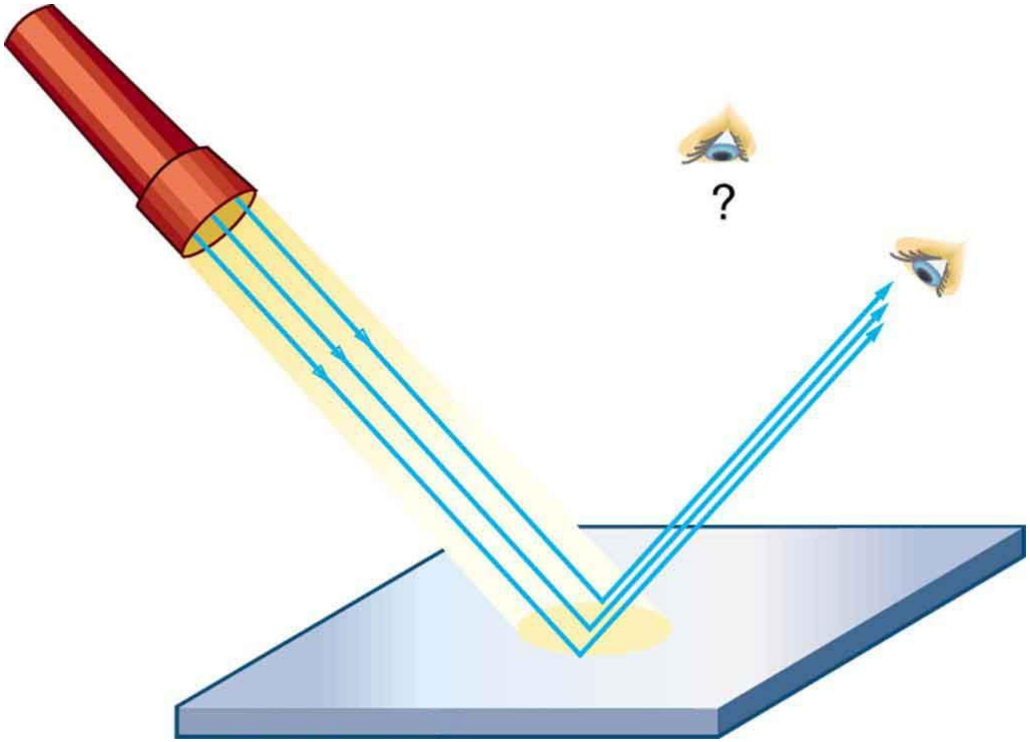
Light is diffused when it reflects from a rough surface. Here many parallel rays are incident, but they are reflected at many different angles since the surface is rough.

# FIGURE 25.6



When a sheet of paper is illuminated with many parallel incident rays, it can be seen at many different angles, because its surface is rough and diffuses the light.

# FIGURE 25.7

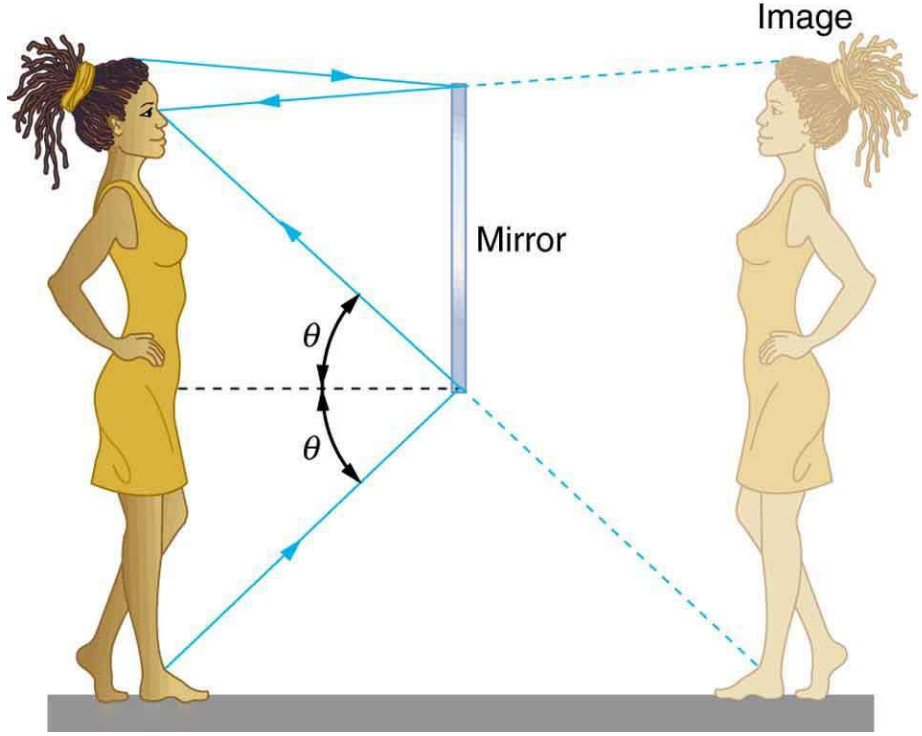



A mirror illuminated by many parallel rays reflects them in only one direction, since its surface is very smooth. Only the observer at a particular angle will see the reflected light.

# FIGURE 25.8

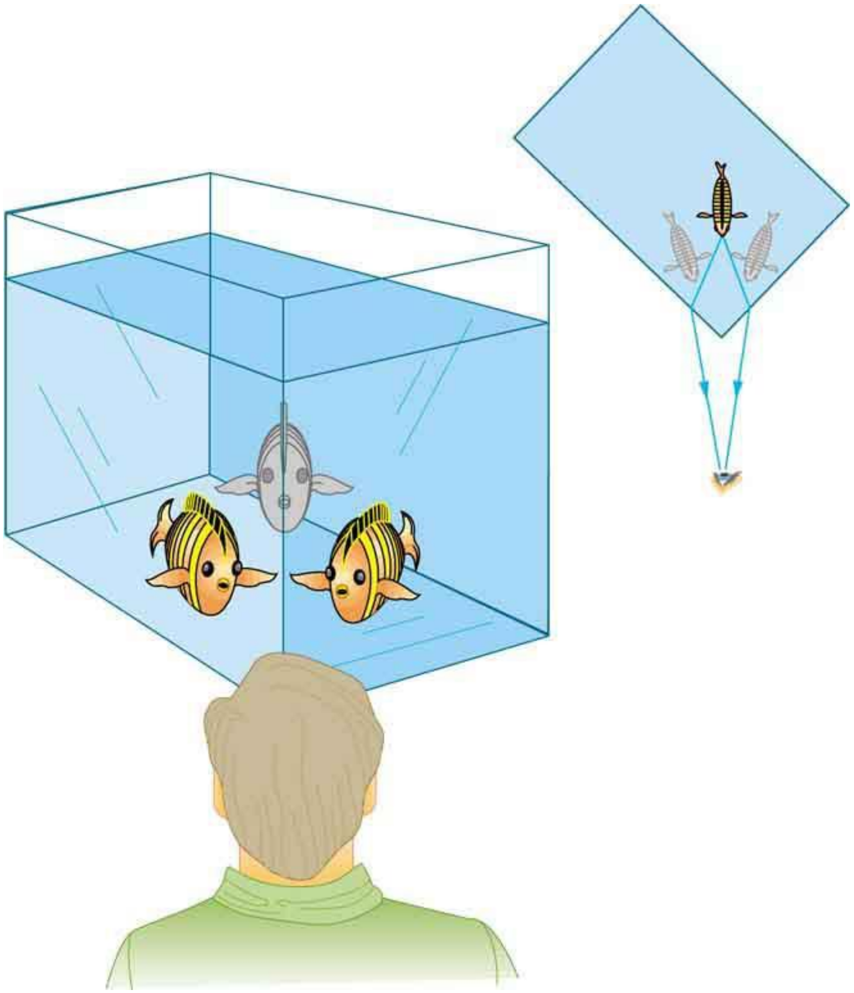
Moonlight is spread out when it is reflected by the lake, since the surface is shiny but uneven. (credit: Diego Torres Silvestre, Flickr)

# FIGURE 25.9




Our image in a mirror is behind the mirror. The two rays shown are those that strike the mirror at just the correct angles to be reflected into the eyes of the person. The image appears to be in the direction the rays are coming from when they enter the eyes.

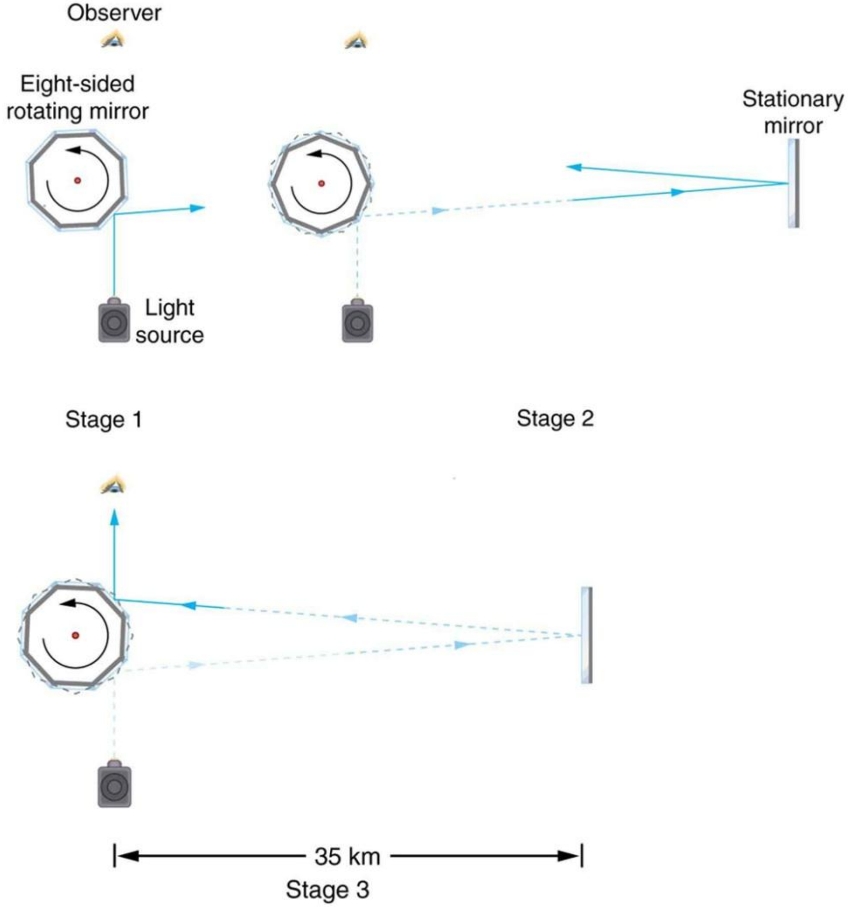
# FIGURE 25.10



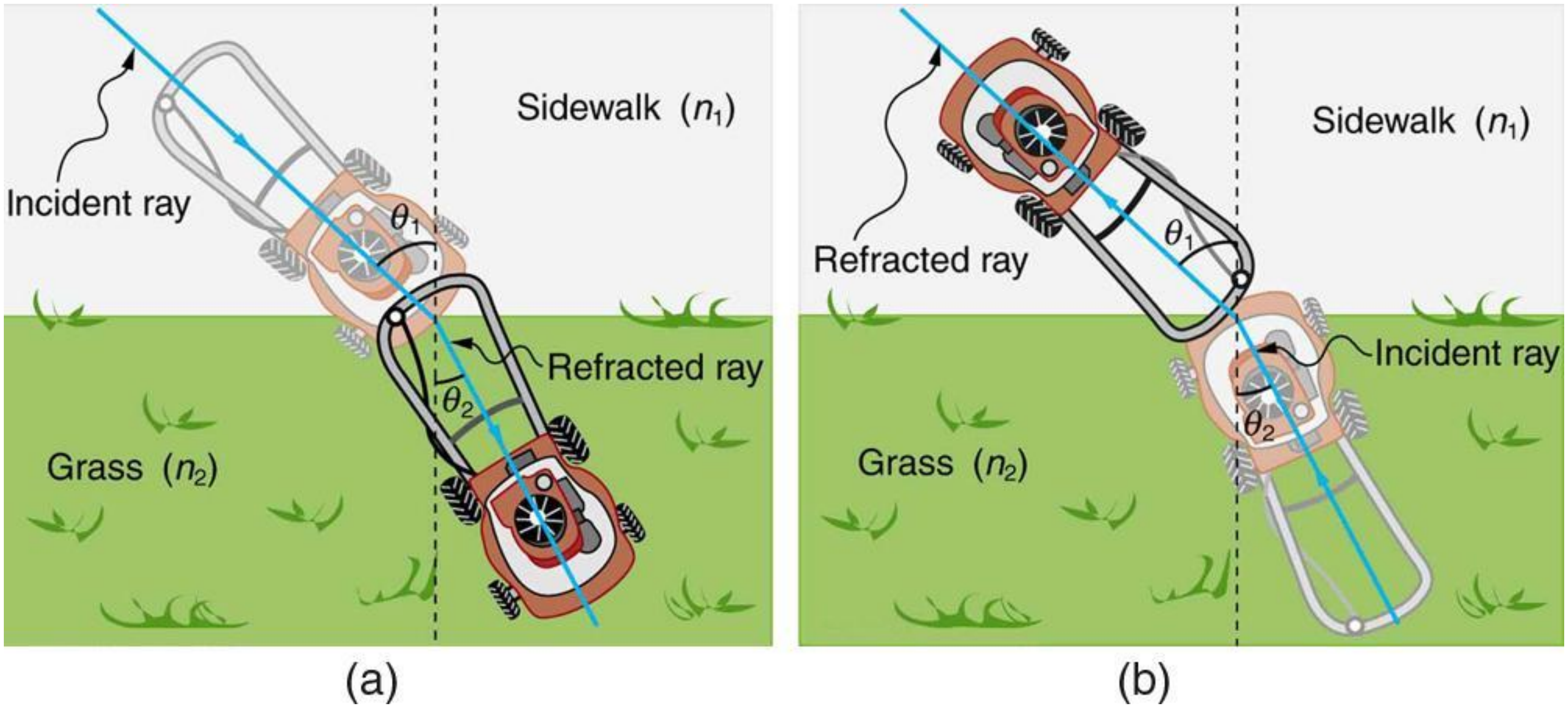
Looking at the fish tank as shown, we can see the same fish in two different locations, because light changes directions when it passes from water to air. In this case, the light can reach the observer by two different paths, and so the fish seems to be in two different places. This bending of light is called refraction and is responsible for many optical phenomena.

# FIGURE 25.11

A schematic of early apparatus used by Michelson and others to determine the speed of light. As the mirrors rotate, the reflected ray is only briefly directed at the stationary mirror. The returning ray will be reflected into the observer's eye only if the next mirror has rotated into the correct position just as the ray returns. By measuring the correct rotation rate, the time for the round trip can be measured and the speed of light calculated. Michelson’s calculated value of the speed of light was only 0.04% different from the value used today.



# FIGURE 25.12

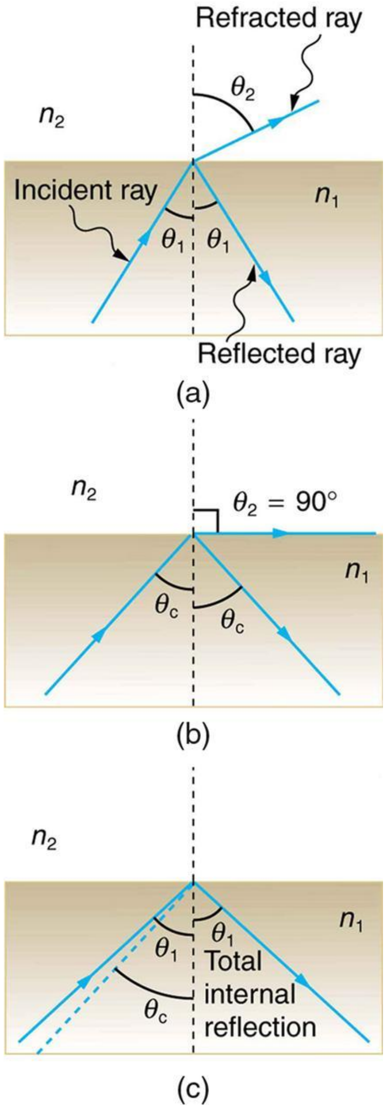



The change in direction of a light ray depends on how the speed of light changes when it crosses from one medium to another. The speed of light is greater in medium 1 than in medium 2 in the situations shown here.

(a) A ray of light moves closer to the perpendicular when it slows down. This is analogous to what happens when a lawn mower goes from a footpath to grass.

(b) A ray of light moves away from the perpendicular when it speeds up. This is analogous to what happens when a lawn mower goes from grass to footpath. The paths are exactly reversible.

# FIGURE 25.13

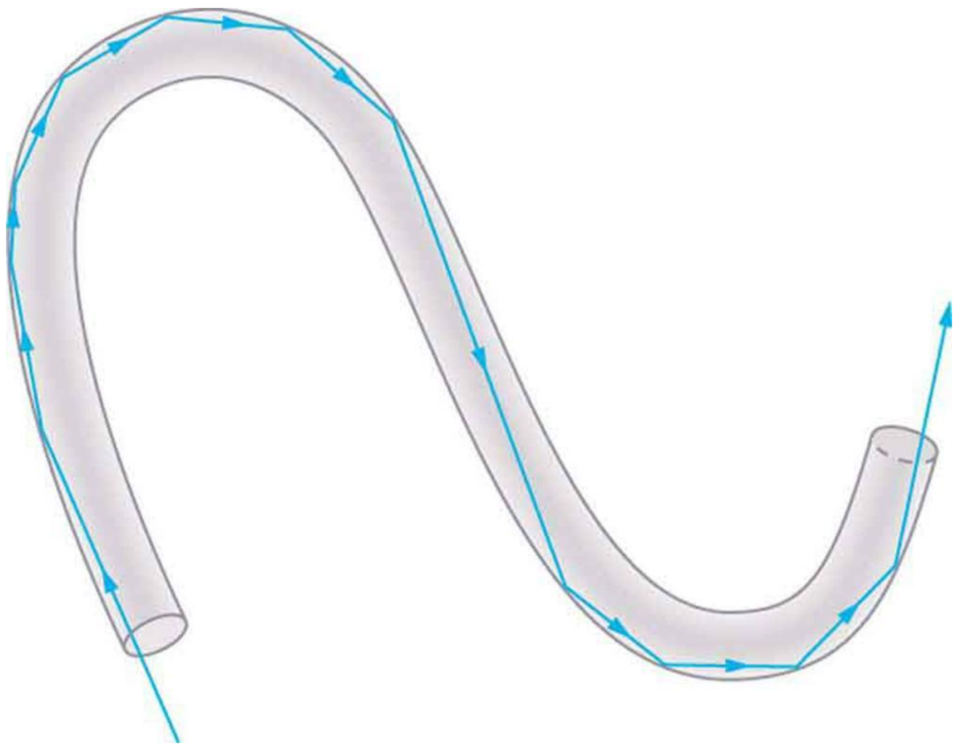



(a) A ray of light crosses a boundary where the speed of light increases and the index of refraction decreases. That is, $n_2 < n_1$. The ray bends away from the perpendicular.

(b) The critical angle $\theta_c$ is the one for which the angle of refraction is .

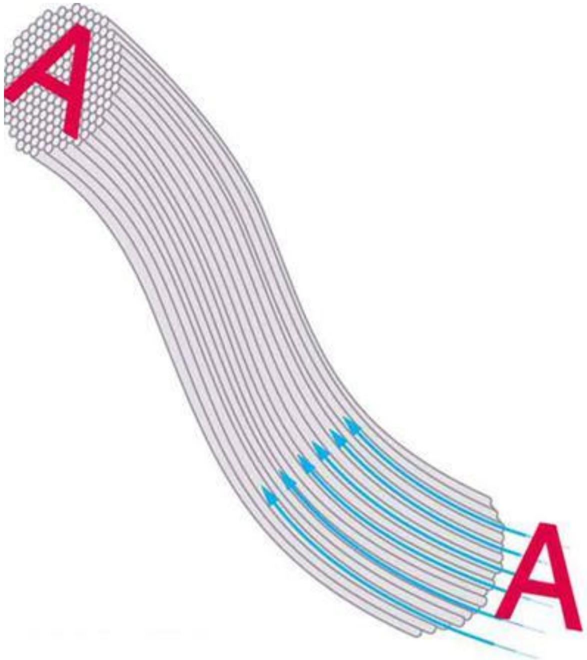
(c) Total internal reflection occurs when the incident angle is greater than the critical angle.

# FIGURE 25.14

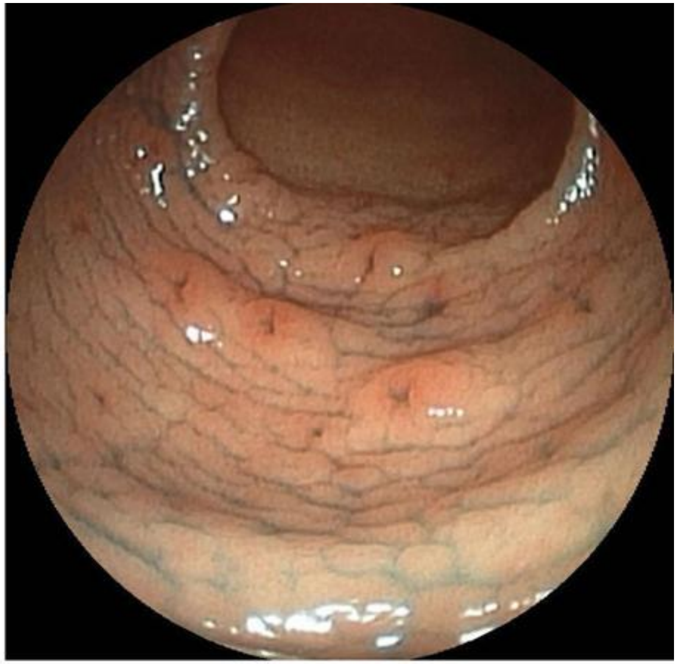


Light entering a thin fiber may strike the inside surface at large or grazing angles and is completely reflected if these angles exceed the critical angle. Such rays continue down the fiber, even following it around corners, since the angles of reflection and incidence remain large.

# FIGURE 25.15




(a)



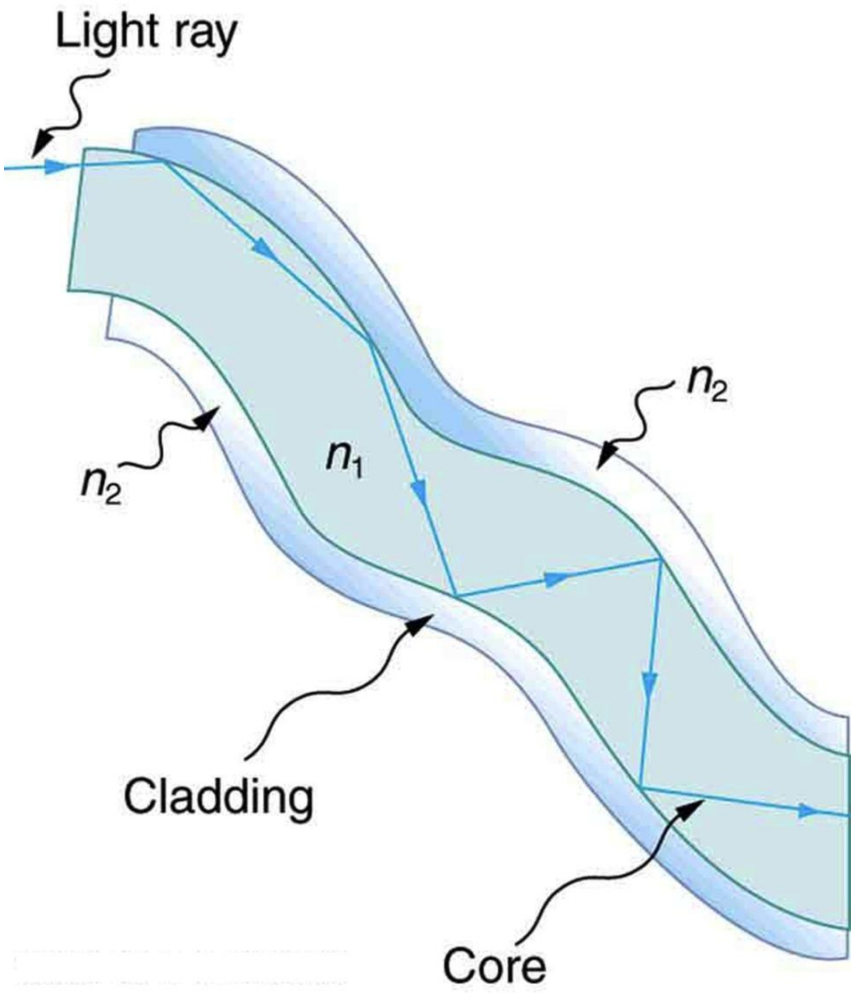
(b)

(a) An image is transmitted by a bundle of fibers that have fixed neighbors.

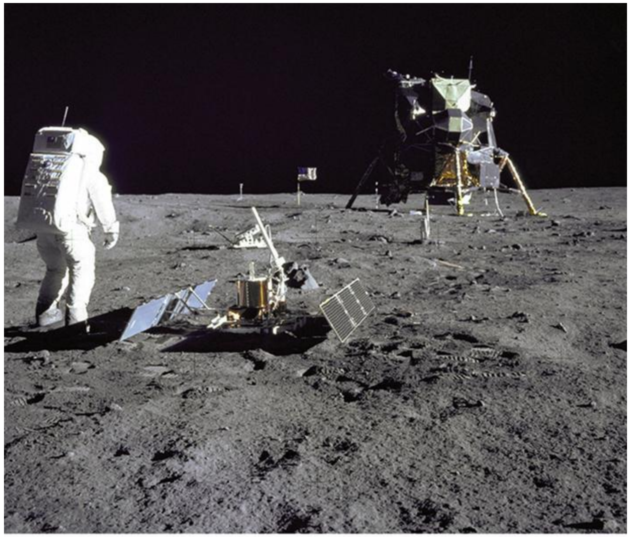
(b) An endoscope is used to probe the body, both transmitting light to the interior and returning an image such as the one shown. (credit: Med_Chaos, Wikimedia Commons)

# FIGURE 25.16

Fibers in bundles are clad by a material that has a lower index of refraction than the core to ensure total internal reflection, even when fibers are in contact with one another. This shows a single fiber with its cladding.



# FIGURE 25.17



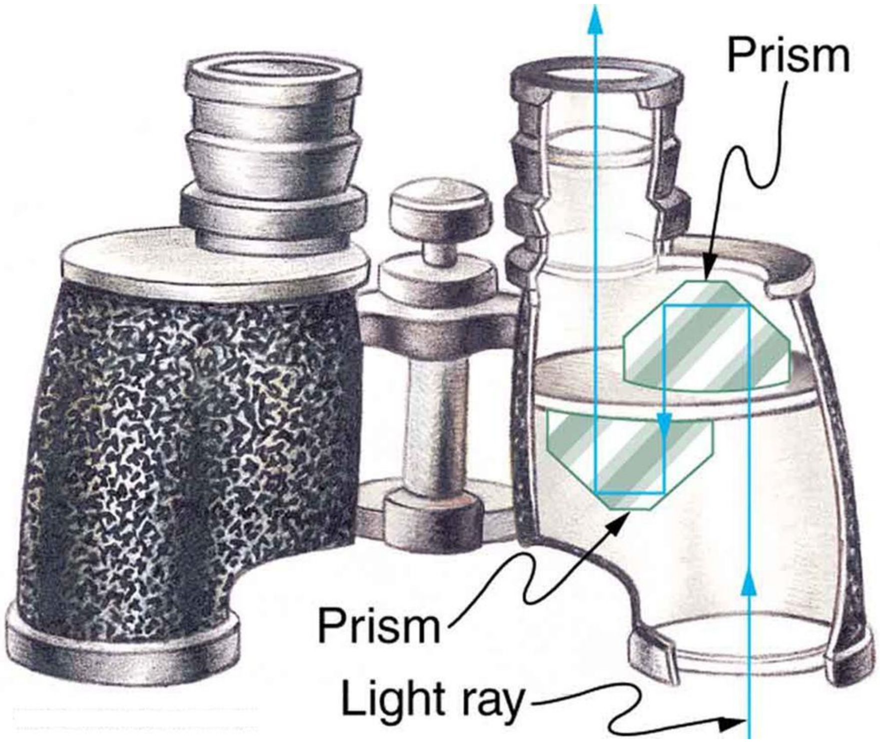
(a)

(b)

(a) Astronauts placed a corner reflector on the moon to measure its gradually increasing orbital distance. (credit: NASA)

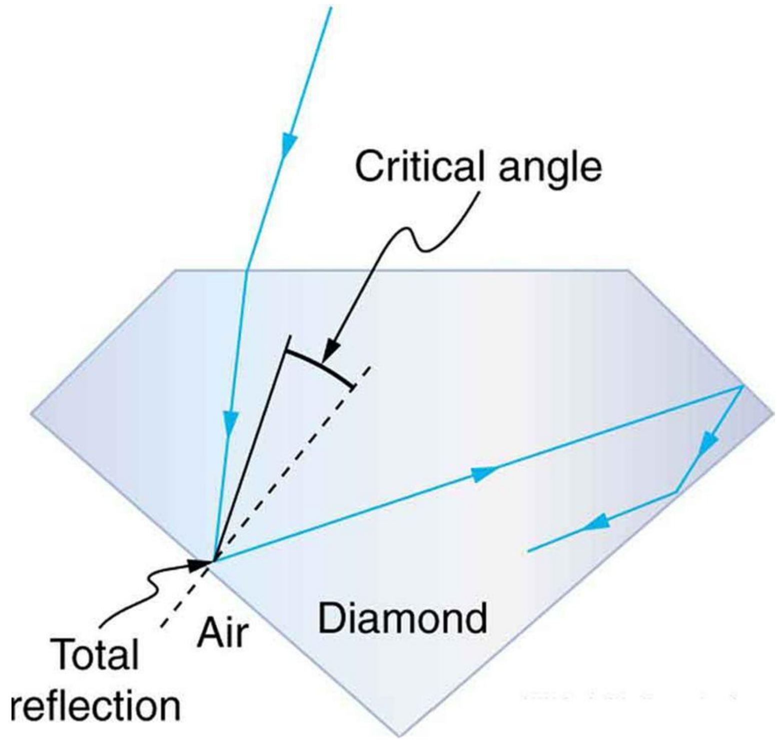
(b) The bright spots on these bicycle safety reflectors are reflections of the flash of the camera that took this picture on a dark night. (credit: Julo, Wikimedia Commons)

# FIGURE 25.18




These binoculars employ corner reflectors with total internal reflection to get light to the observer's eyes.

# FIGURE 25.19




Light cannot easily escape a diamond, because its critical angle with air is so small. Most reflections are total, and the facets are placed so that light can exit only in particular ways—thus concentrating the light and making the diamond sparkle.

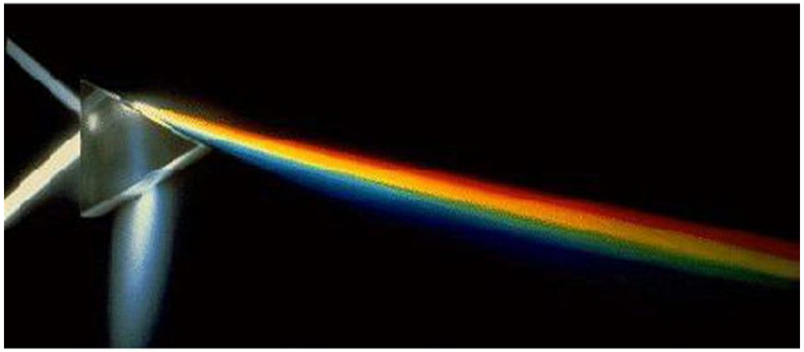
# FIGURE 25.21

The colors of the rainbow

(a) and those produced by a prism

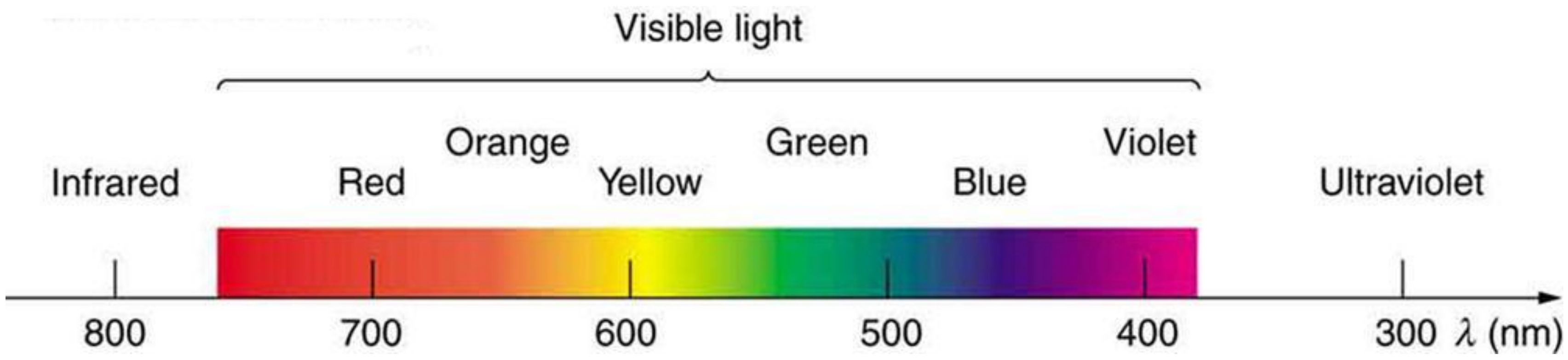
(b) are identical. (credit: Alfredo55, Wikimedia Commons; NASA)

(a)



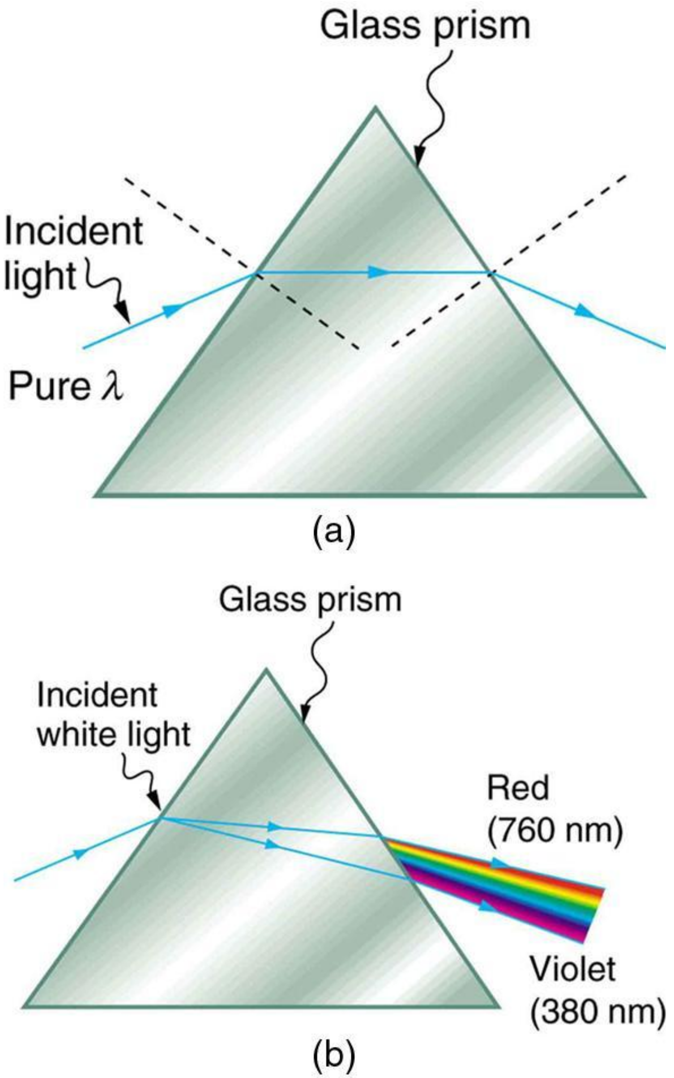
(b)

# FIGURE 25.22




Even though rainbows are associated with seven colors, the rainbow is a continuous distribution of colors according to wavelengths.

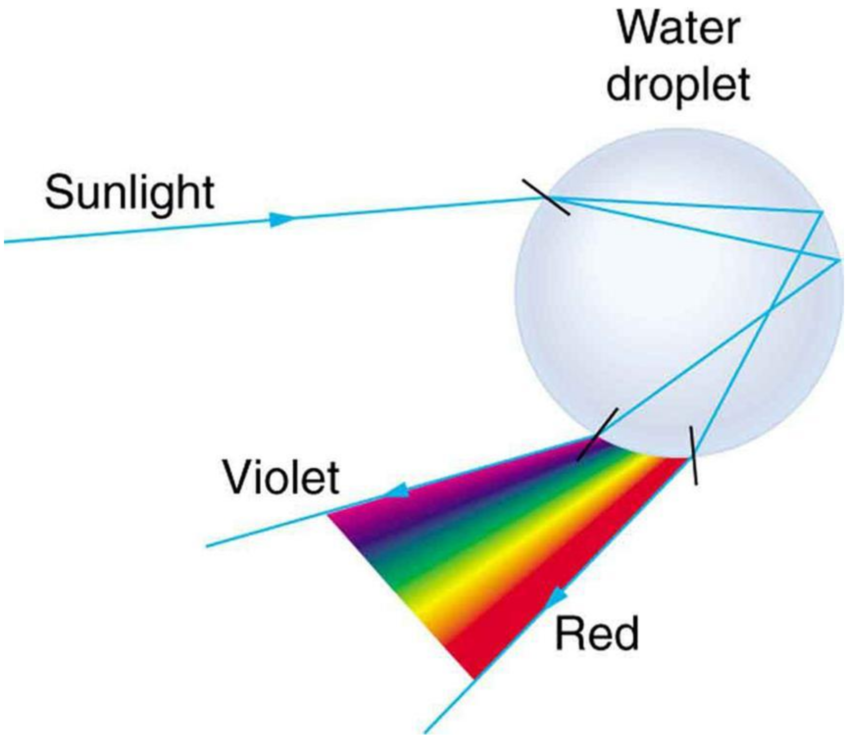
# FIGURE 25.23




(a) A pure wavelength of light falls onto a prism and is refracted at both surfaces.

(b) White light is dispersed by the prism (shown exaggerated). Since the index of refraction varies with wavelength, the angles of refraction vary with wavelength. A sequence of red to violet is produced, because the index of refraction increases steadily with decreasing wavelength.

# FIGURE 25.24



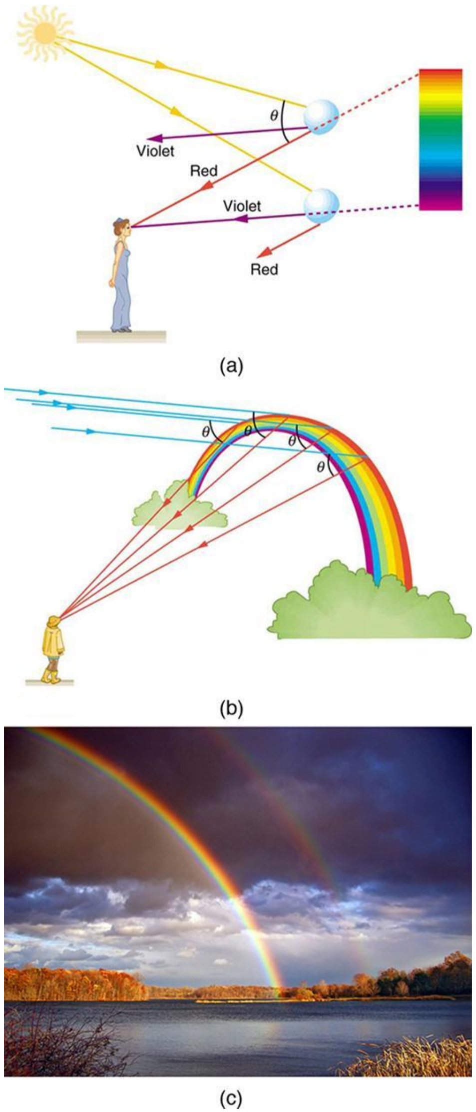

Part of the light falling on this water drop enters and is reflected from the back of the drop. This light is refracted and dispersed both as it enters and as it leaves the drop.

# FIGURE 25.25

(a) Different colors emerge in different directions, and so you must look at different locations to see the various colors of a rainbow.

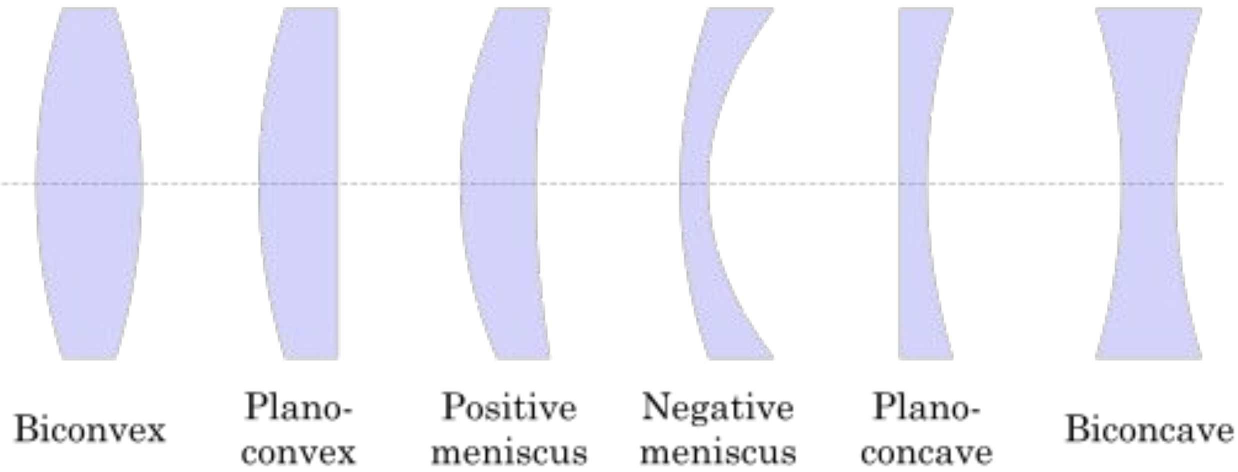
(b) The arc of a rainbow results from the fact that a line between the observer and any point on the arc must make the correct angle with the parallel rays of sunlight to receive the refracted rays.

(c) Double rainbow. (credit: Nicholas, Wikimedia Commons)

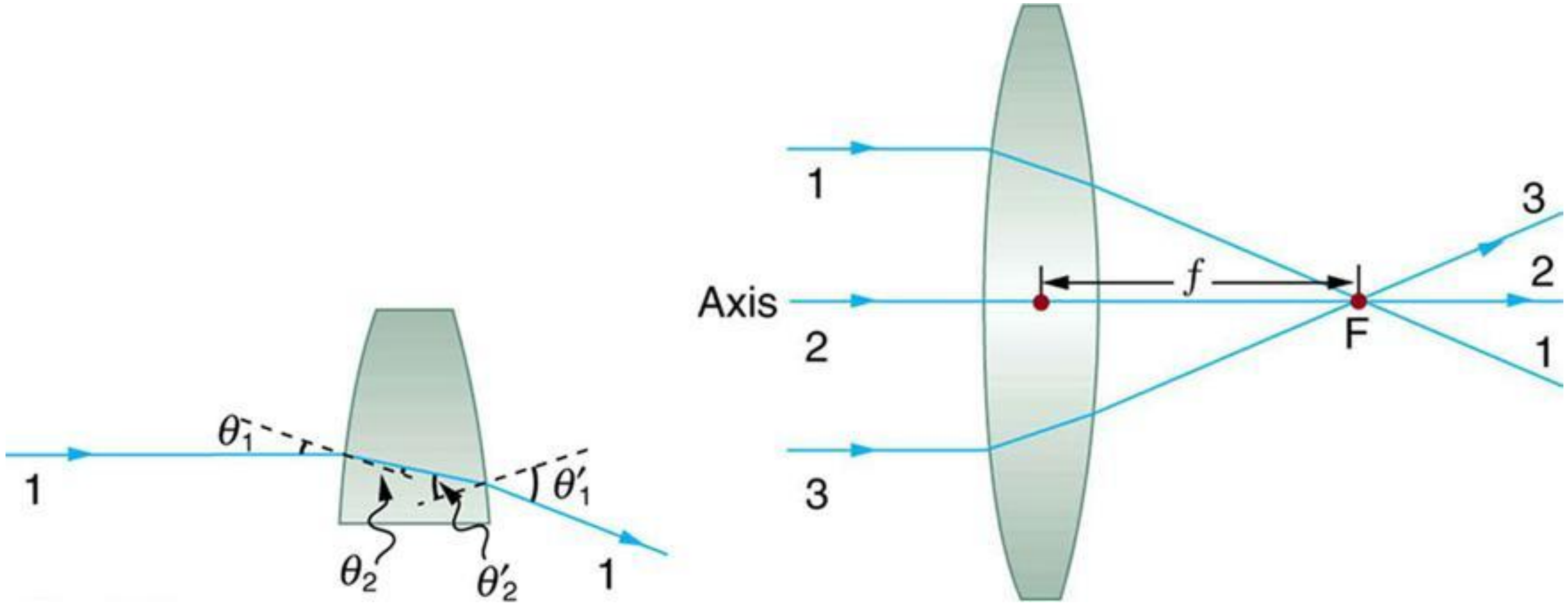


# Lenses

- Lenses are classified by the curvature of the two optical surfaces



# FIGURE 25.27



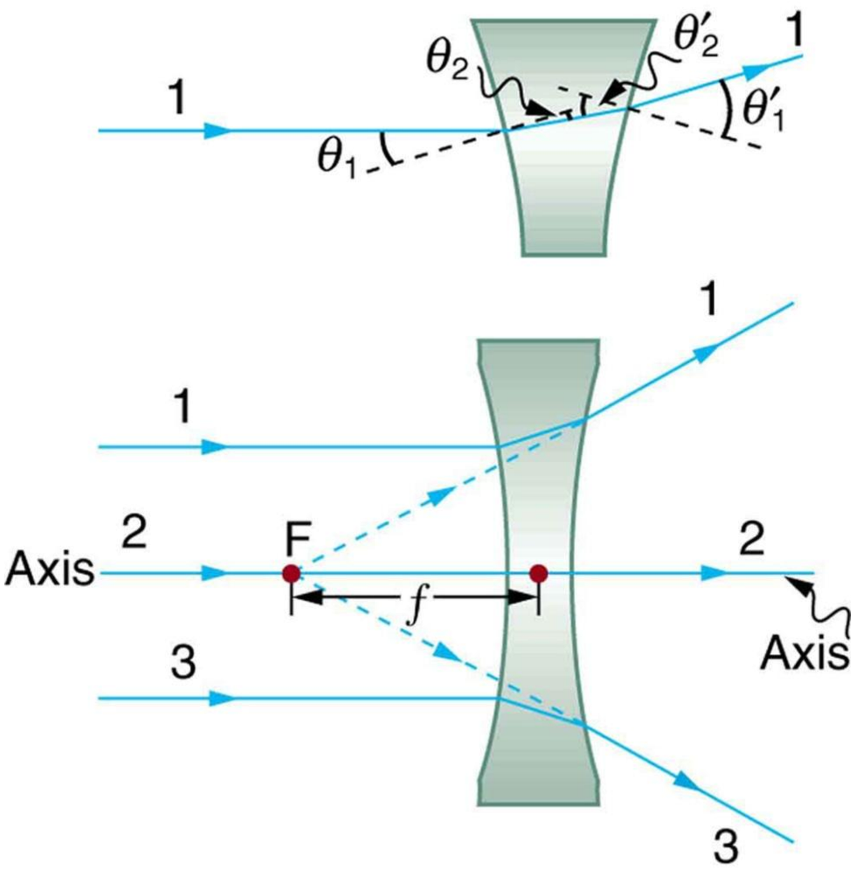

Rays of light entering a converging lens parallel to its axis converge at its focal point F. (Ray 2 lies on the axis of the lens.) The distance from the center of the lens to the focal point is the lens's focal length $f$ . An expanded view of the path taken by ray 1 shows the perpendiculars and the angles of incidence and refraction at both surfaces.

# FIGURE 25.28

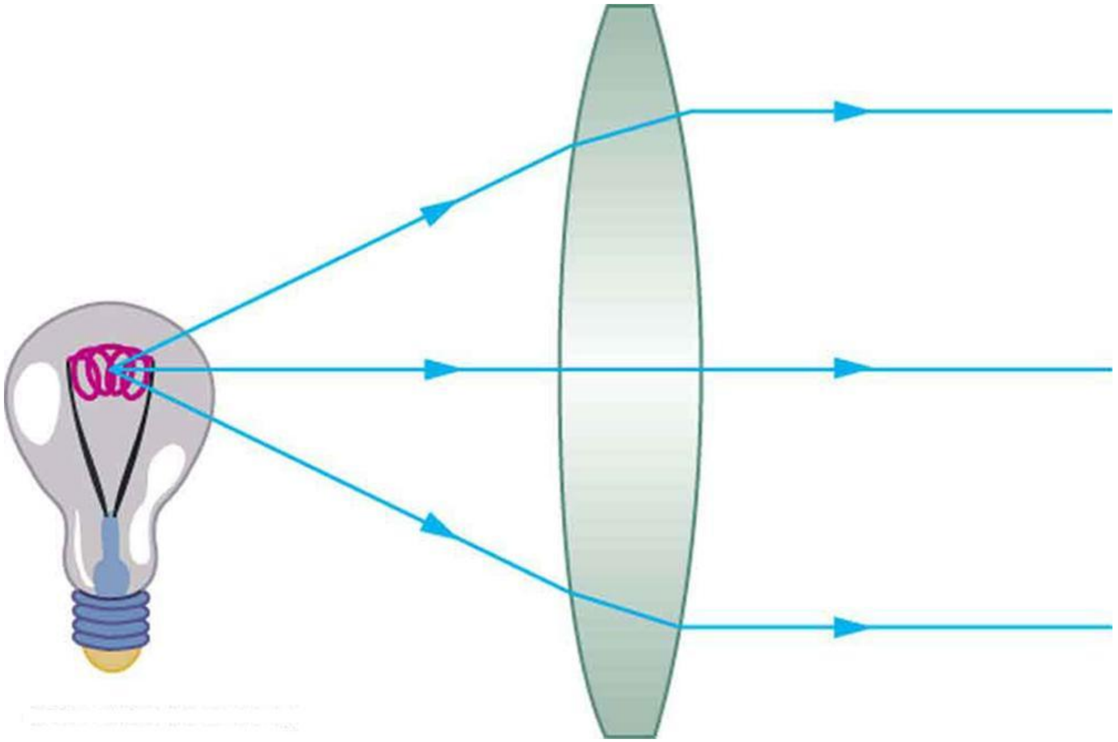
Sunlight focused by a converging magnifying glass can burn paper. Light rays from the sun are nearly parallel and cross at the focal point of the lens. The more powerful the lens, the closer to the lens the rays will cross.

# FIGURE 25.29

Rays of light entering a diverging lens parallel to its axis are diverged, and all appear to originate at its focal point F . The dashed lines are not rays—they indicate the directions from which the rays appear to come. The focal length $f$ of a diverging lens is negative.
An expanded view of the path taken by ray 1 shows the perpendiculars and the angles of incidence and refraction at both surfaces.



# FIGURE 25.30



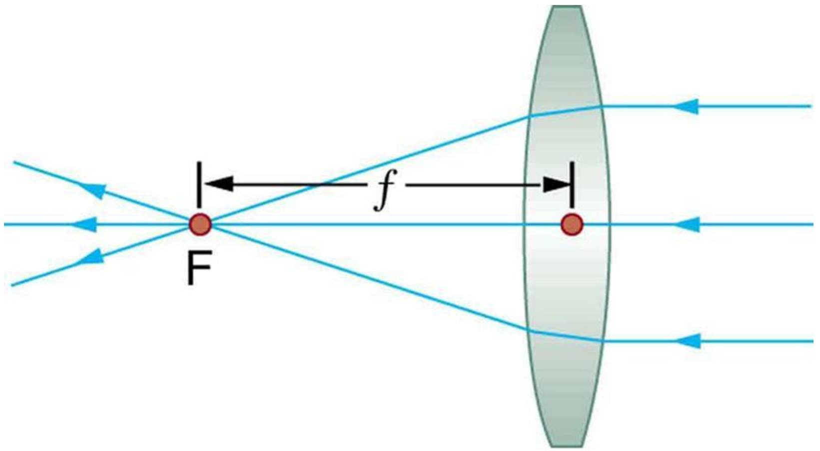
A small light source, like a light bulb filament, placed at the focal point of a convex lens, results in parallel rays of light emerging from the other side. The paths are exactly the reverse of those shown in **Figure 25.27**. This technique is used in lighthouses and sometimes in traffic lights to produce a directional beam of light from a source that emits light in all directions.

# FIGURE 25.31

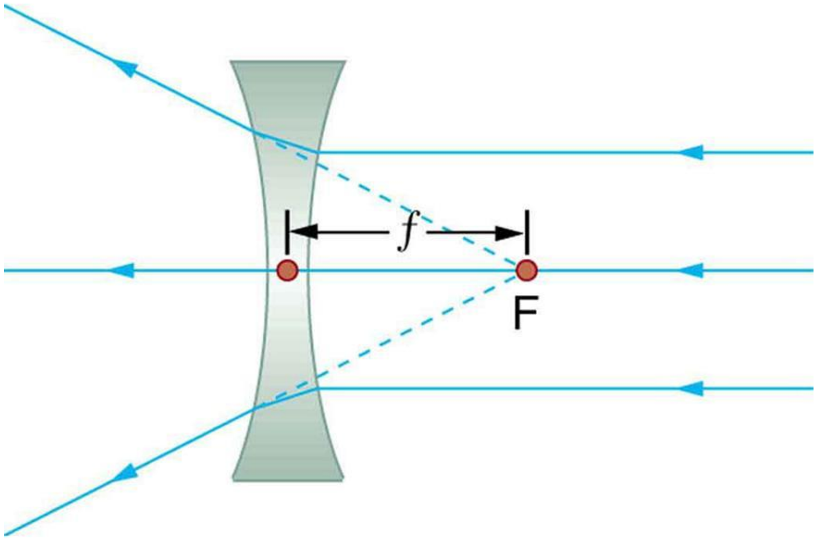
Thin lenses have the same focal length on either side.

(a) Parallel light rays entering a converging lens from the right cross at its focal point on the left.

(b) Parallel light rays entering a diverging lens from the right seem to come from the focal point on the right.

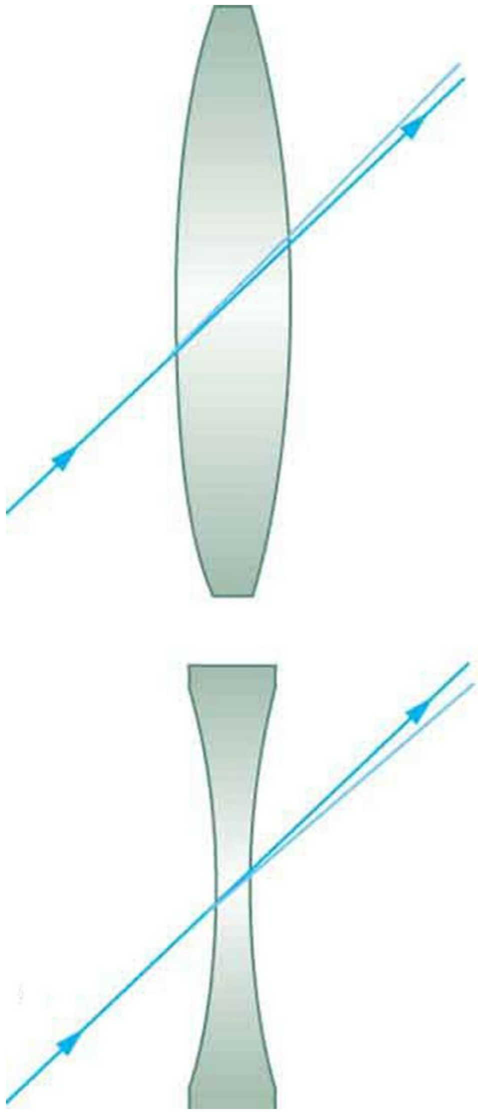



(a)



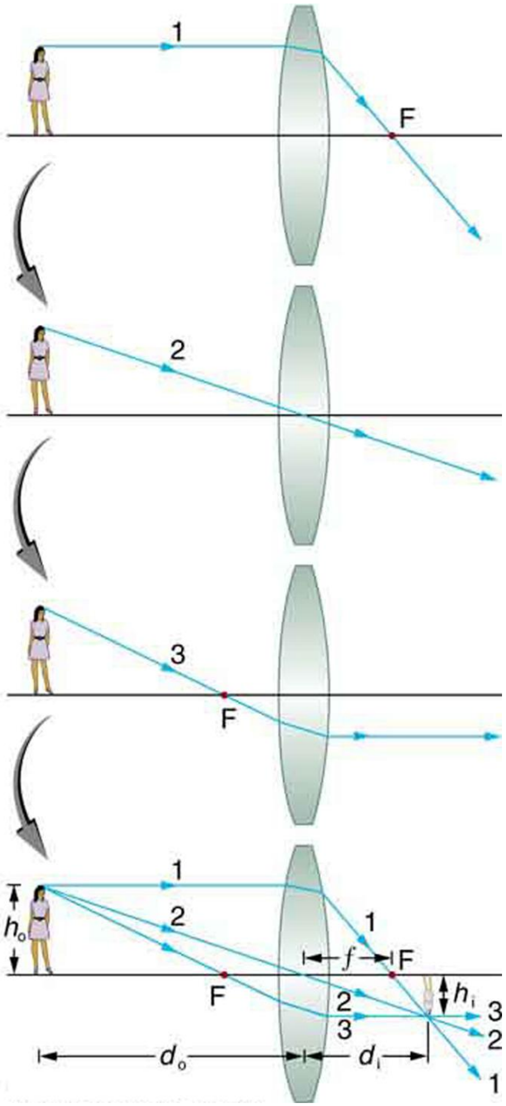

(b)

# FIGURE 25.32



The light ray through the center of a thin lens is deflected by a negligible amount and is assumed to emerge parallel to its original path (shown as a shaded line).

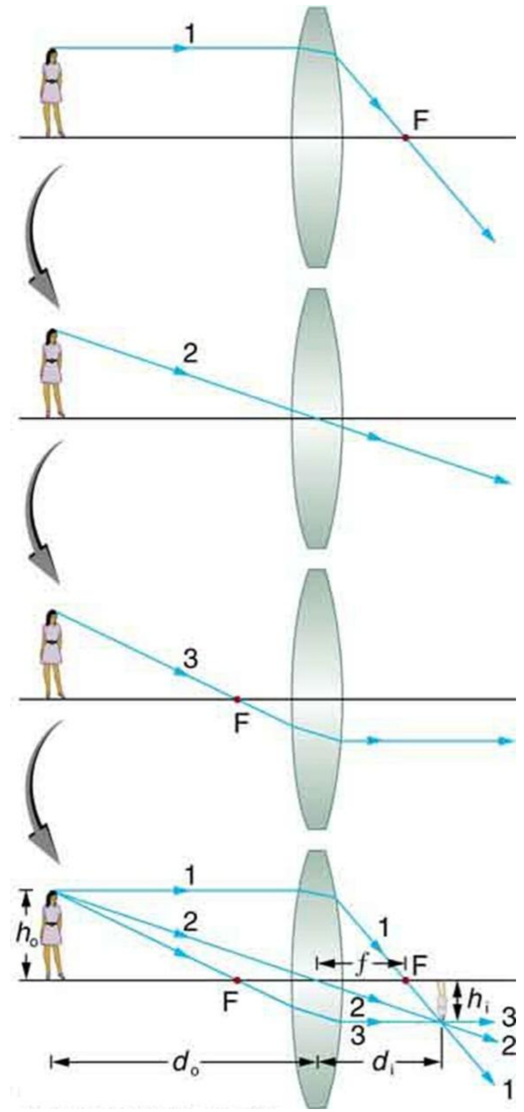
# Ray Tracing Rules



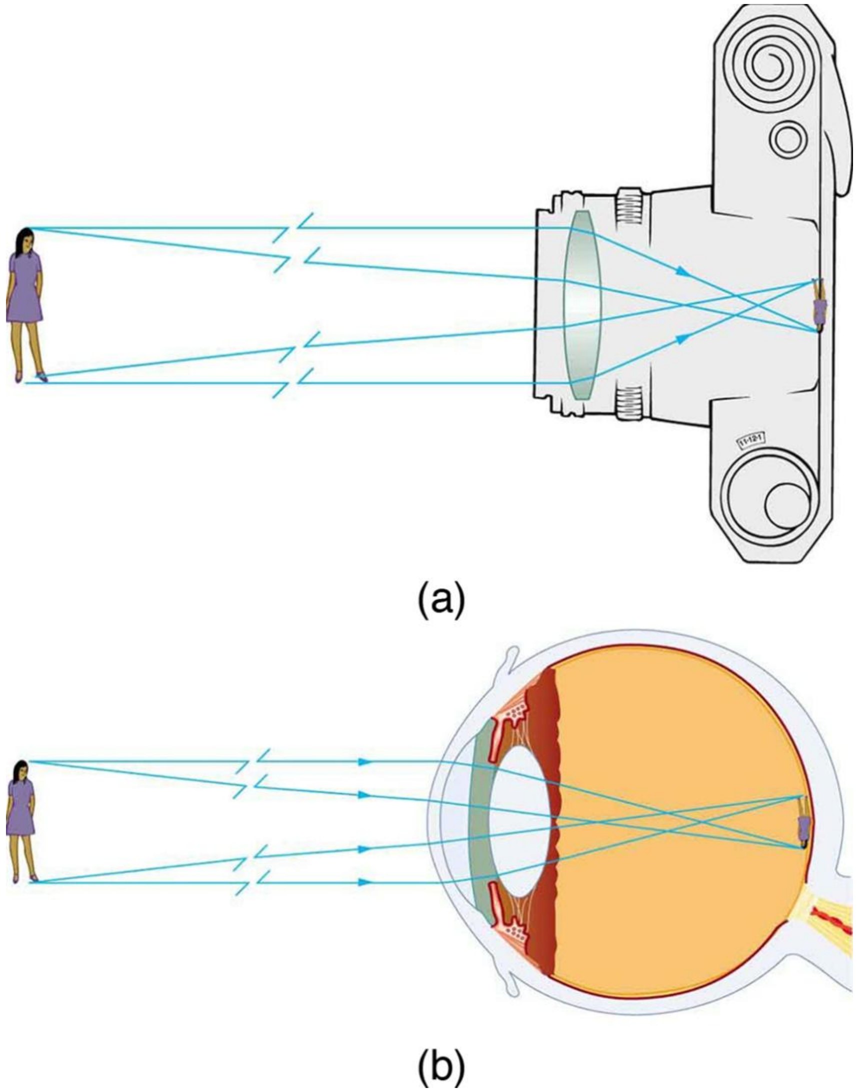

- A ray entering a converging lens parallel to its axis passes through the focal point F of the lens on the other side.
- A ray entering a diverging lens parallel to its axis seems to come from the focal point F.
- A ray passing through the center of either a converging or a diverging lens does not change direction.
- A ray entering a converging lens through its focal point exits parallel to its axis.
- A ray that enters a diverging lens by heading toward the focal point on the opposite side exits parallel to the axis.

# FIGURE 25.33

Ray tracing is used to locate the image formed by a lens. Rays originating from the same point on the object are traced—the three chosen rays each follow one of the rules for ray tracing, so that their paths are easy to determine. The image is located at the point where the rays cross. In this case, a real image—one that can be projected on a screen—is formed.



# FIGURE 25.34

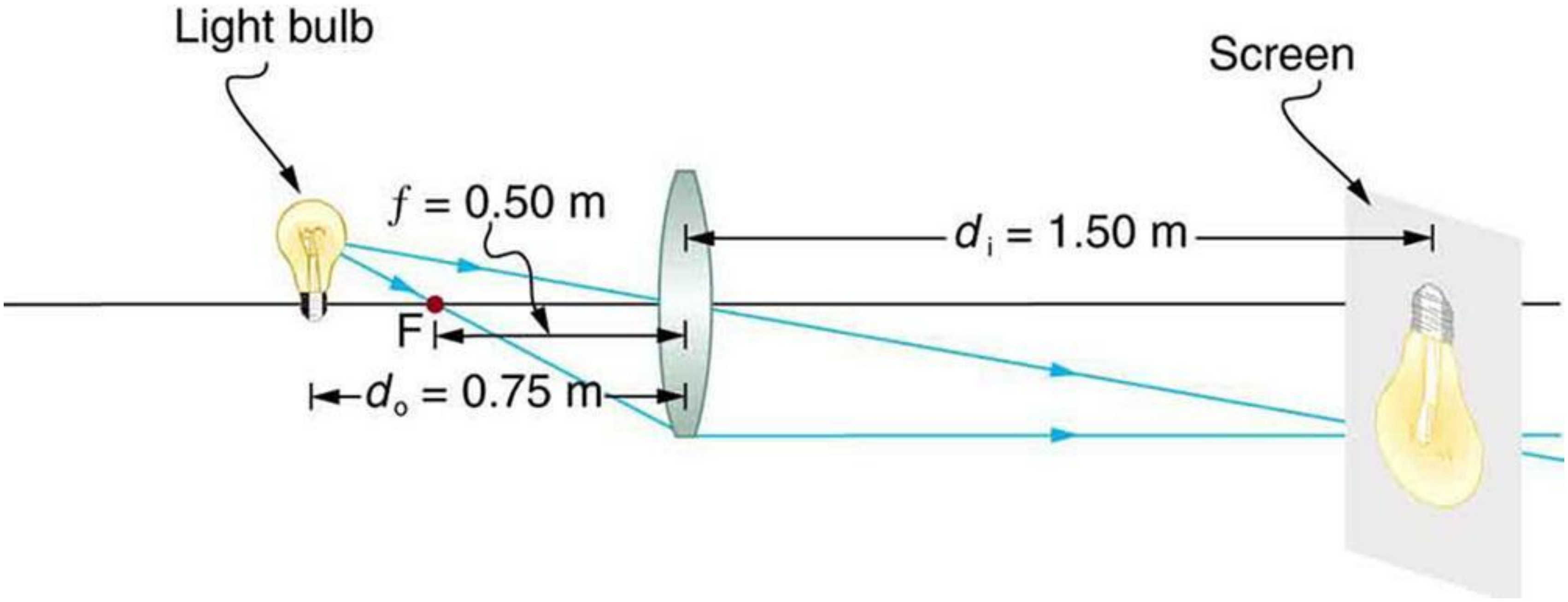



Real images can be projected.

(a) A real image of the person is projected onto film.

(b) The converging nature of the multiple surfaces that make up the eye result in the projection of a real image on the retina.

# FIGURE 25.35




A light bulb placed 0.750 m from a lens having a 0.500 m focal length produces a real image on a poster board as discussed in the example above. Ray tracing predicts the image location and size.

# FIGURE 25.36

(a)

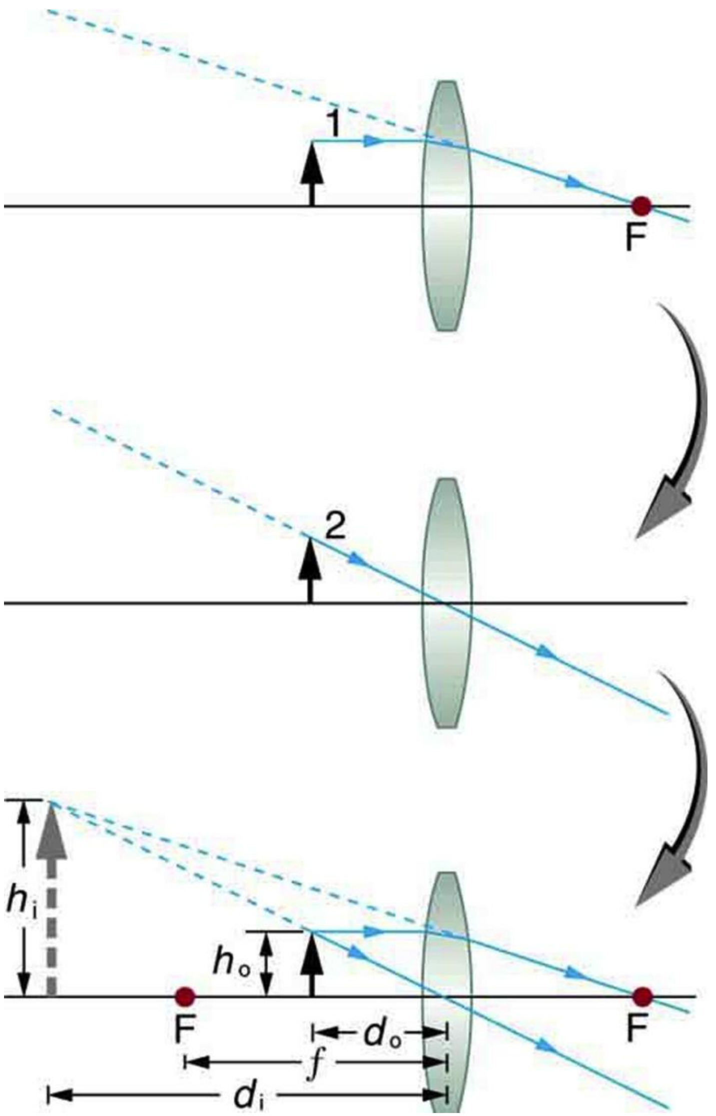
(b)

(a) When a converging lens is held farther away from the face than the lens's focal length, an inverted image is formed. This is a case 1 image. Note that the image is in focus but the face is not, because the image is much closer to the camera taking this photograph than the face. (credit: DaMongMan, Flickr)

(b) A magnified image of a face is produced by placing it closer to the converging lens than its focal length. This is a case 2 image. (credit: Casey Fleser, Flickr)

# FIGURE 25.37

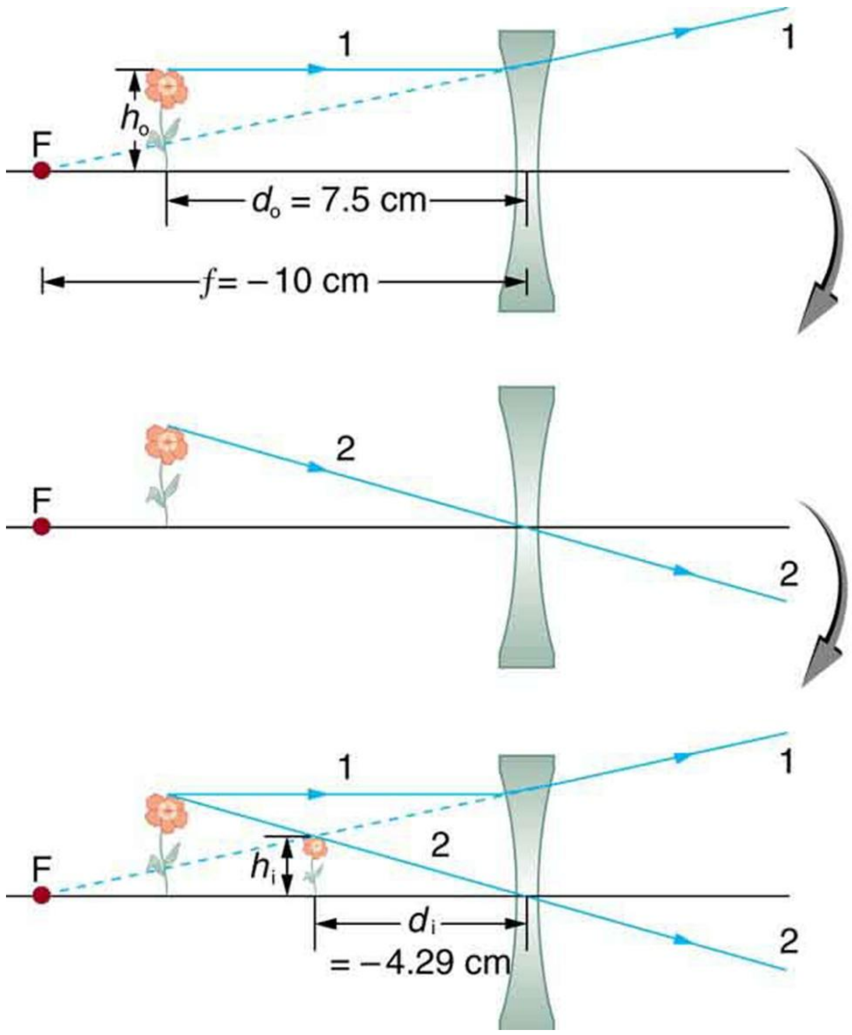
Ray tracing predicts the image location and size for an object held closer to a converging lens than its focal length. Ray 1 enters parallel to the axis and exits through the focal point on the opposite side, while ray 2 passes through the center of the lens without changing path. The two rays continue to diverge on the other side of the lens, but both appear to come from a common point, locating the upright, magnified, virtual image. This is a case 2 image.



# FIGURE 25.38

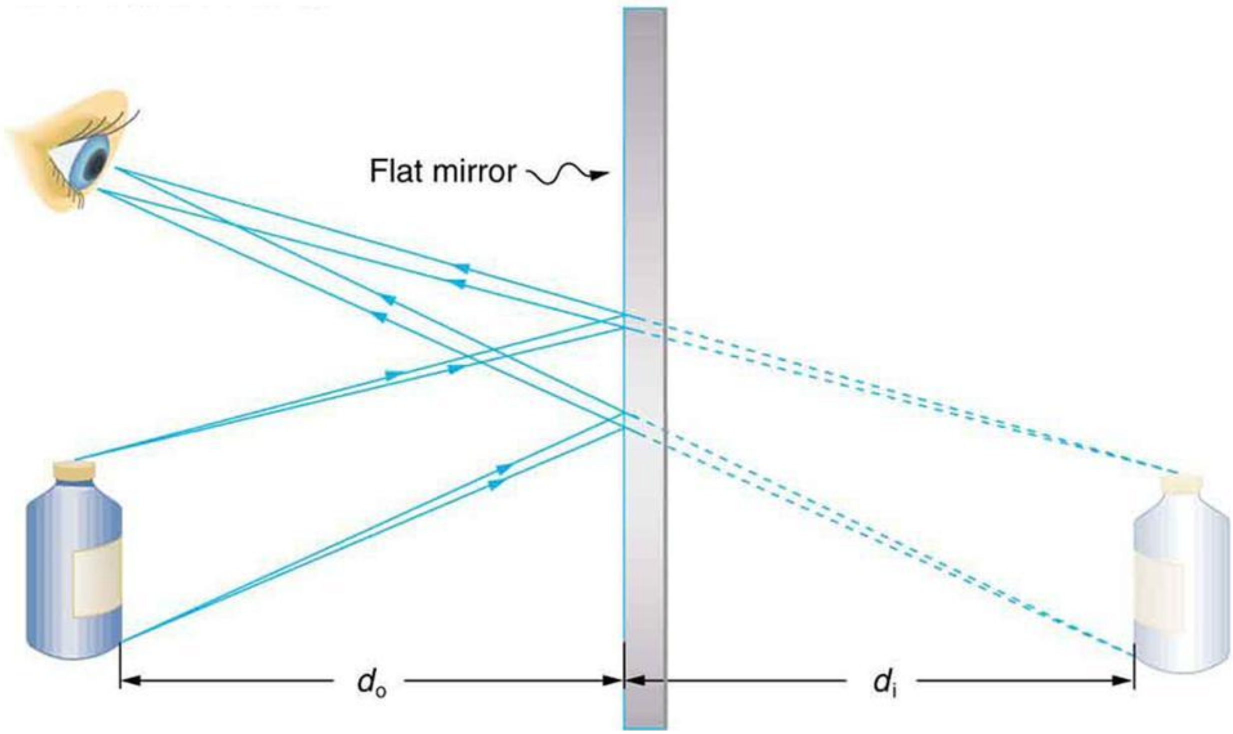
A car viewed through a concave or diverging lens looks upright. This is a case 3 image. (credit: Daniel Oines, Flickr)

# FIGURE 25.39



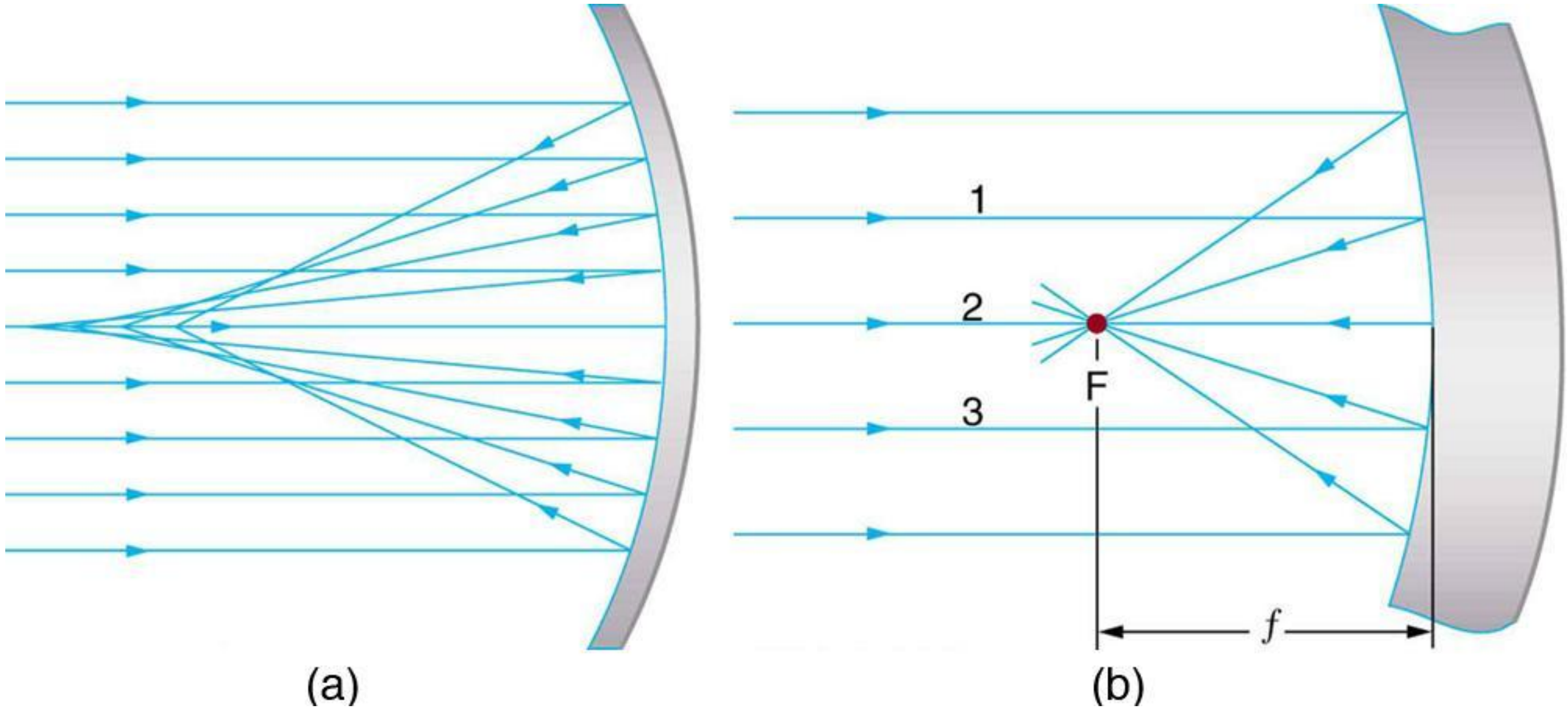

Ray tracing predicts the image location and size for a concave or diverging lens. Ray 1 enters parallel to the axis and is bent so that it appears to originate from the focal point. Ray 2 passes through the center of the lens without changing path. The two rays appear to come from a common point, locating the upright image. This is a case 3 image, which is closer to the lens than the object and smaller in height.

# FIGURE 25.40




Two sets of rays from common points on an object are reflected by a flat mirror into the eye of an observer. The reflected rays seem to originate from behind the mirror, locating the virtual image.

# FIGURE 25.41

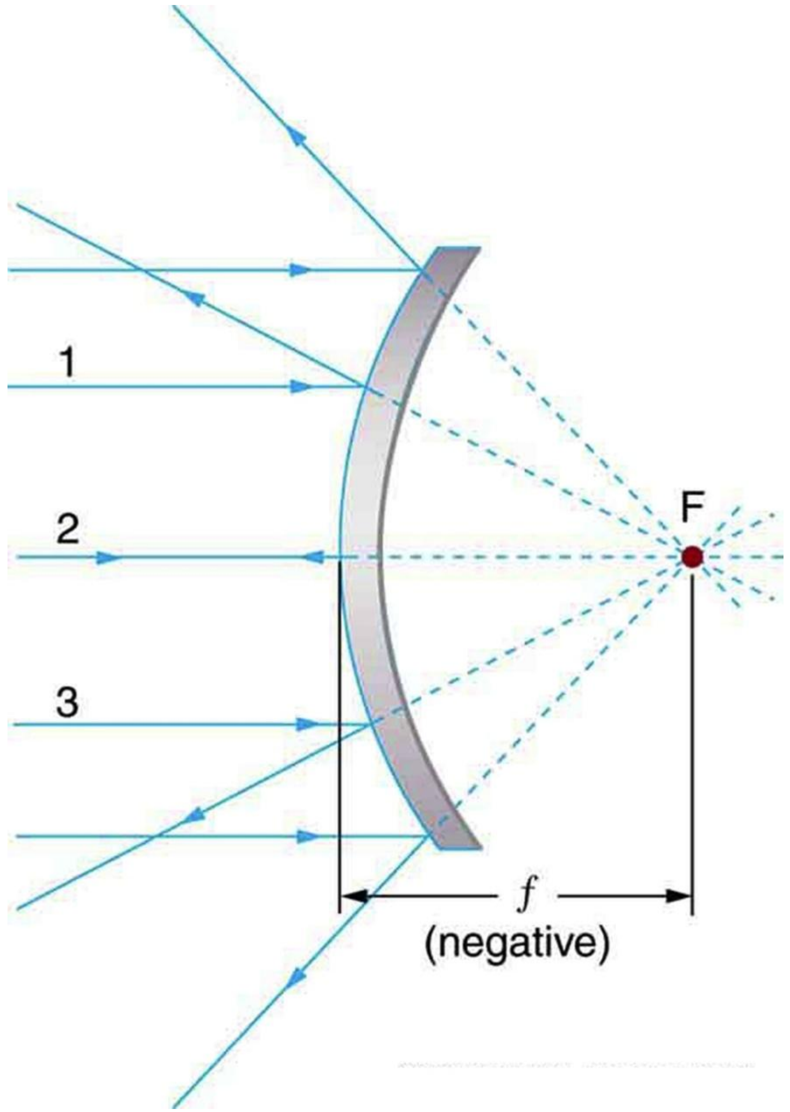



(a) Parallel rays reflected from a large spherical mirror do not all cross at a common point

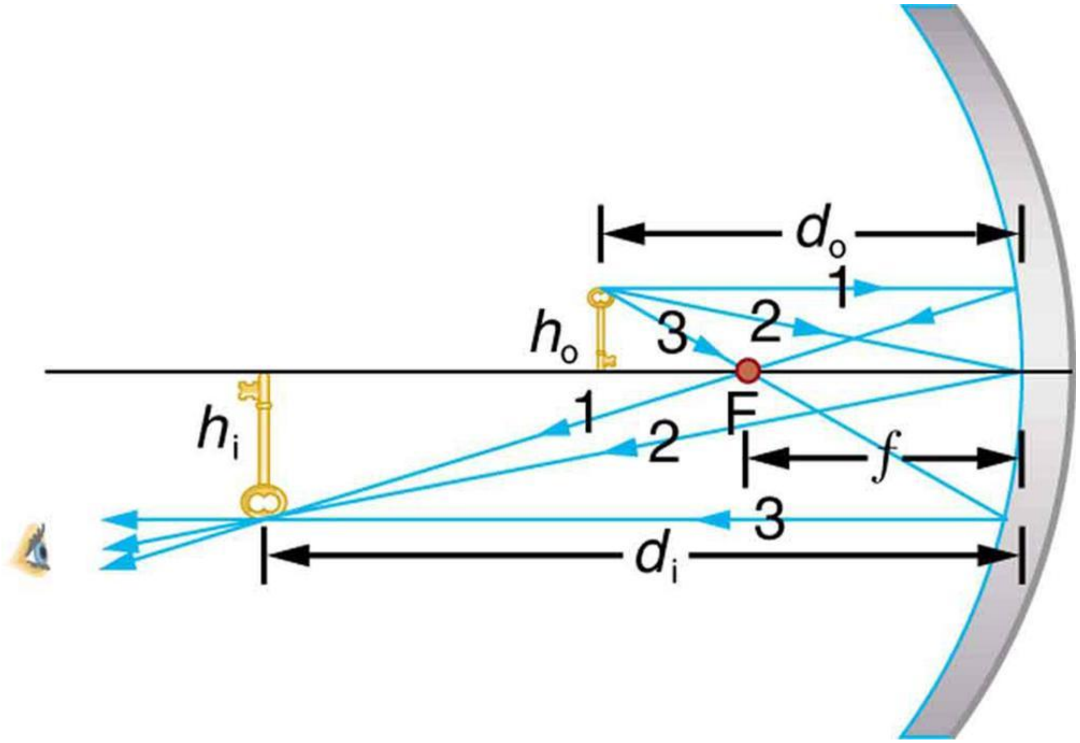
(b) If a spherical mirror is small compared with its radius of curvature, parallel rays are focused to a common point. The distance of the focal point from the center of the mirror is its focal length $f$ . Since this mirror is converging, it has a positive focal length.

# FIGURE 25.42

Parallel rays of light reflected from a convex spherical mirror (small in size compared with its radius of curvature) seem to originate from a well-defined focal point at the focal distance $f$ behind the mirror. Convex mirrors diverge light rays and, thus, have a negative focal length.



# FIGURE 25.43

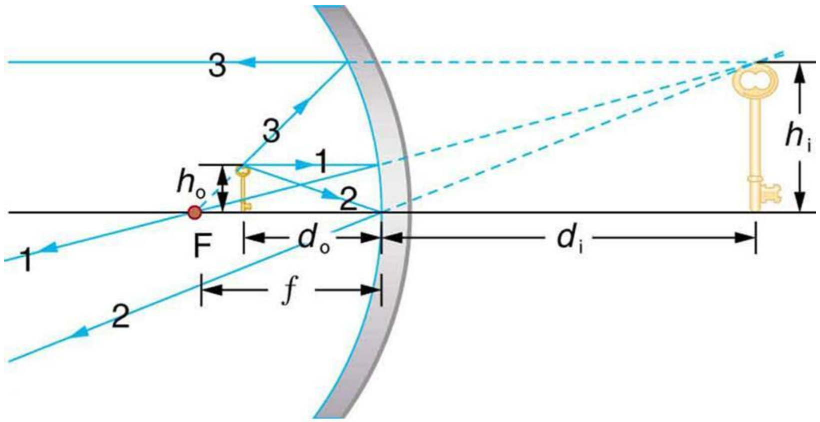



A case 1 image for a mirror. An object is farther from the converging mirror than its focal length. Rays from a common point on the object are traced using the rules in the text. Ray 1 approaches parallel to the axis, ray 2 strikes the center of the mirror, and ray 3 goes through the focal point on the way toward the mirror. All three rays cross at the same point after being reflected, locating the inverted real image. Although three rays are shown, only two of the three are needed to locate the image and determine its height.

# FIGURE 25.44

Parabolic trough collectors are used to generate electricity in southern California. (credit: kjkolb, Wikimedia Commons)

# FIGURE 25.45




(a)

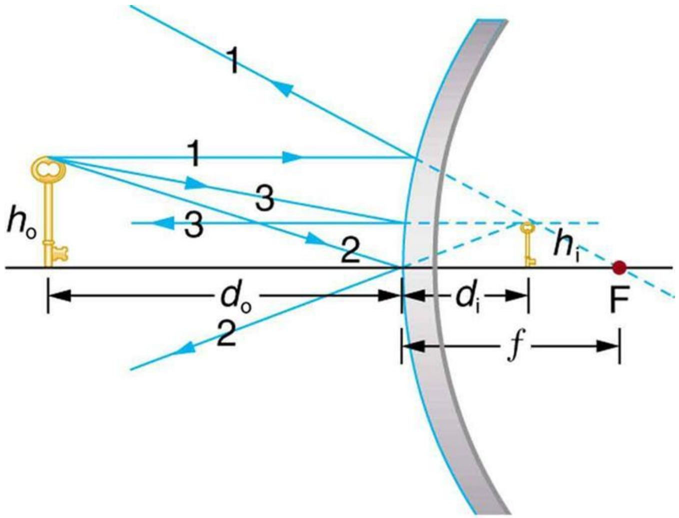

(b)

(a) Case 2 images for mirrors are formed when a converging mirror has an object closer to it than its focal length. Ray 1 approaches parallel to the axis, ray 2 strikes the center of the mirror, and ray 3 approaches the mirror as if it came from the focal point.

(b) A magnifying mirror showing the reflection. (credit: Mike Melrose, Flickr) openstax™

# FIGURE 25.46

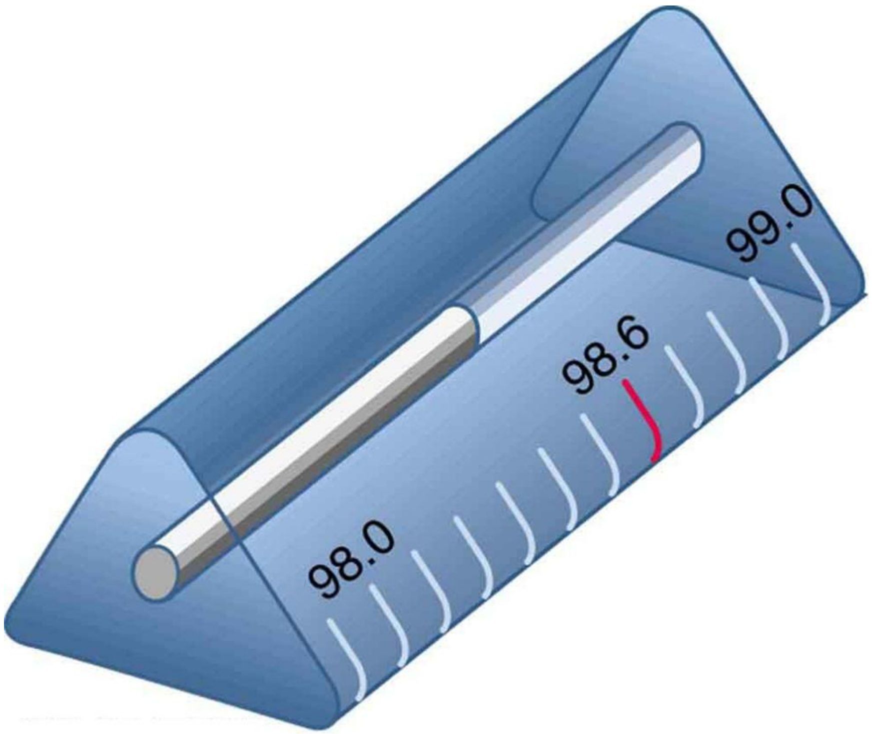
Case 3 images for mirrors are formed by any convex mirror. Ray 1 approaches parallel to the axis, ray 2 strikes the center of the mirror, and ray 3 approaches toward the focal point. All three rays appear to originate from the same point after being reflected, locating the upright virtual image behind the mirror and showing it to be smaller than the object. (b) Security mirrors are convex, producing a smaller, upright image. Because the image is smaller, a larger area is imaged compared to what would be observed for a flat mirror (and hence security is improved). (credit: Laura D’Alessandro, Flickr)




(a)

(b)

# FIGURE 25.47

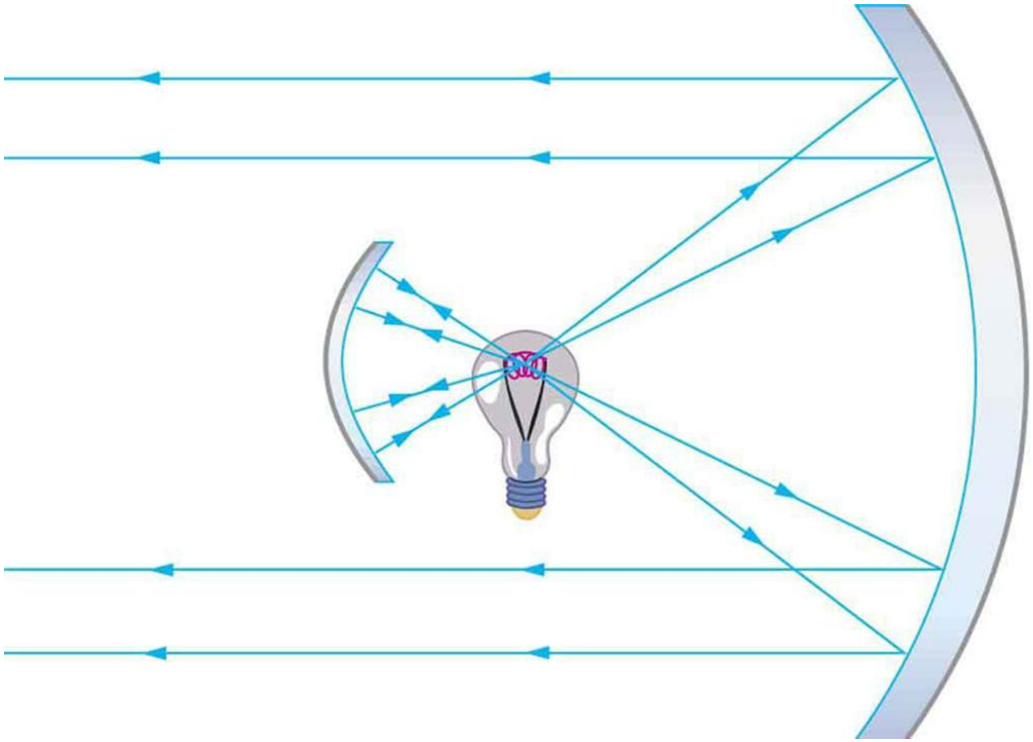



The curved surface of the thermometer serves a purpose.

# FIGURE 25.48

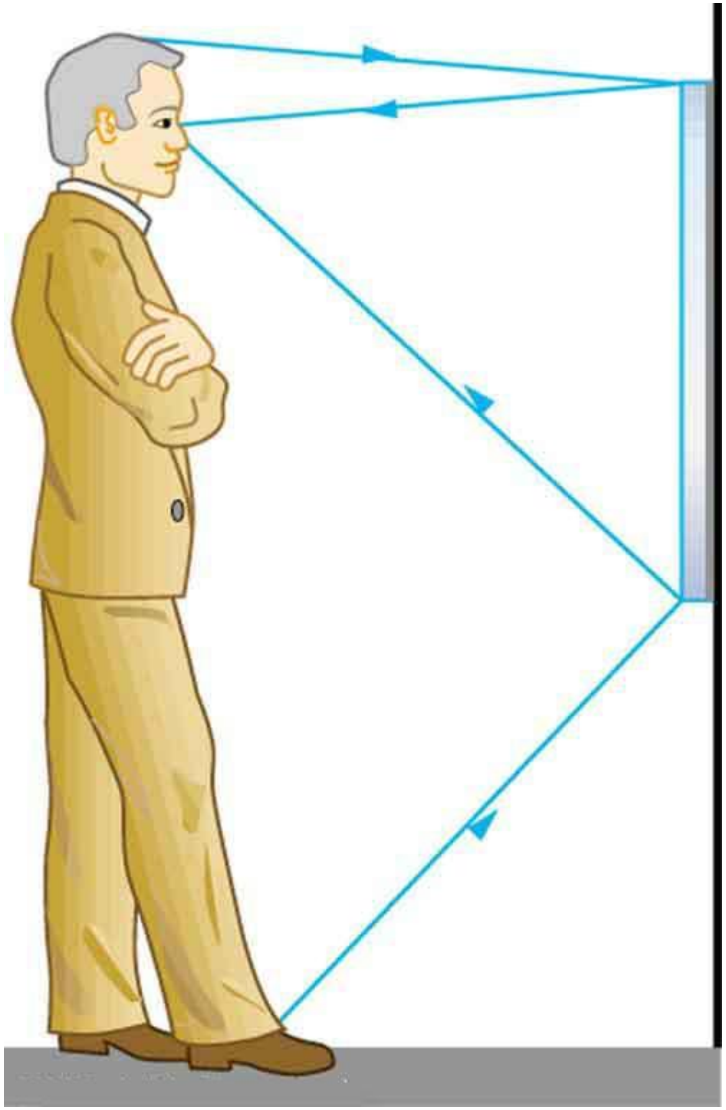
Double rainbows are not a very common observance. (credit: InvictusOU812, Flickr)

# FIGURE 25.49



The two mirrors trap most of the bulb’s light and form a directional beam as in a headlight.

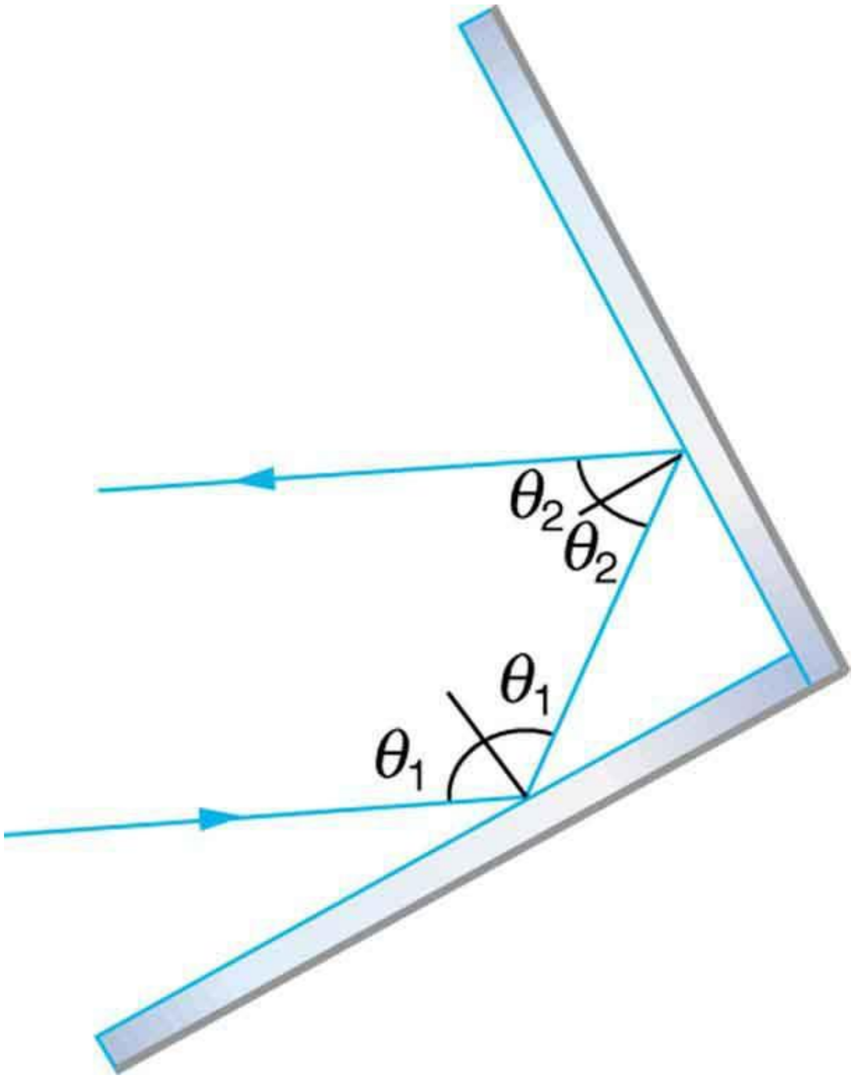
# FIGURE 25.50



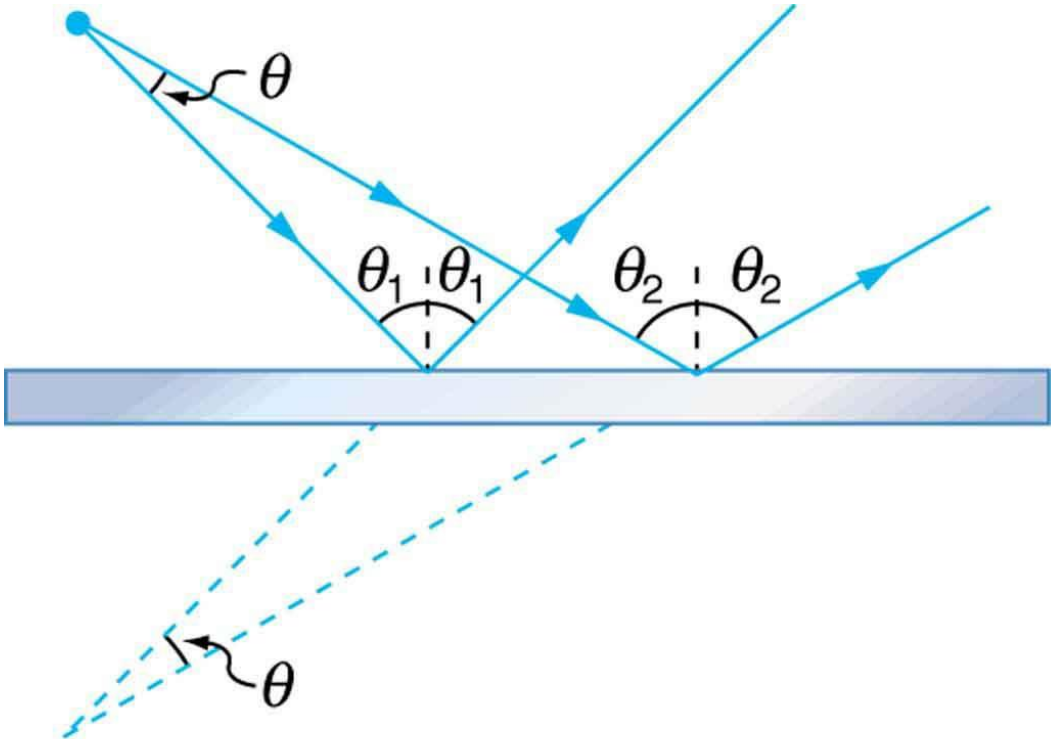
A full-length mirror is one in which you can see all of yourself. It need not be as big as you, and its size is independent of your distance from it.

# FIGURE 25.51

A corner reflector sends the reflected ray back in a direction parallel to the incident ray, independent of incoming direction.

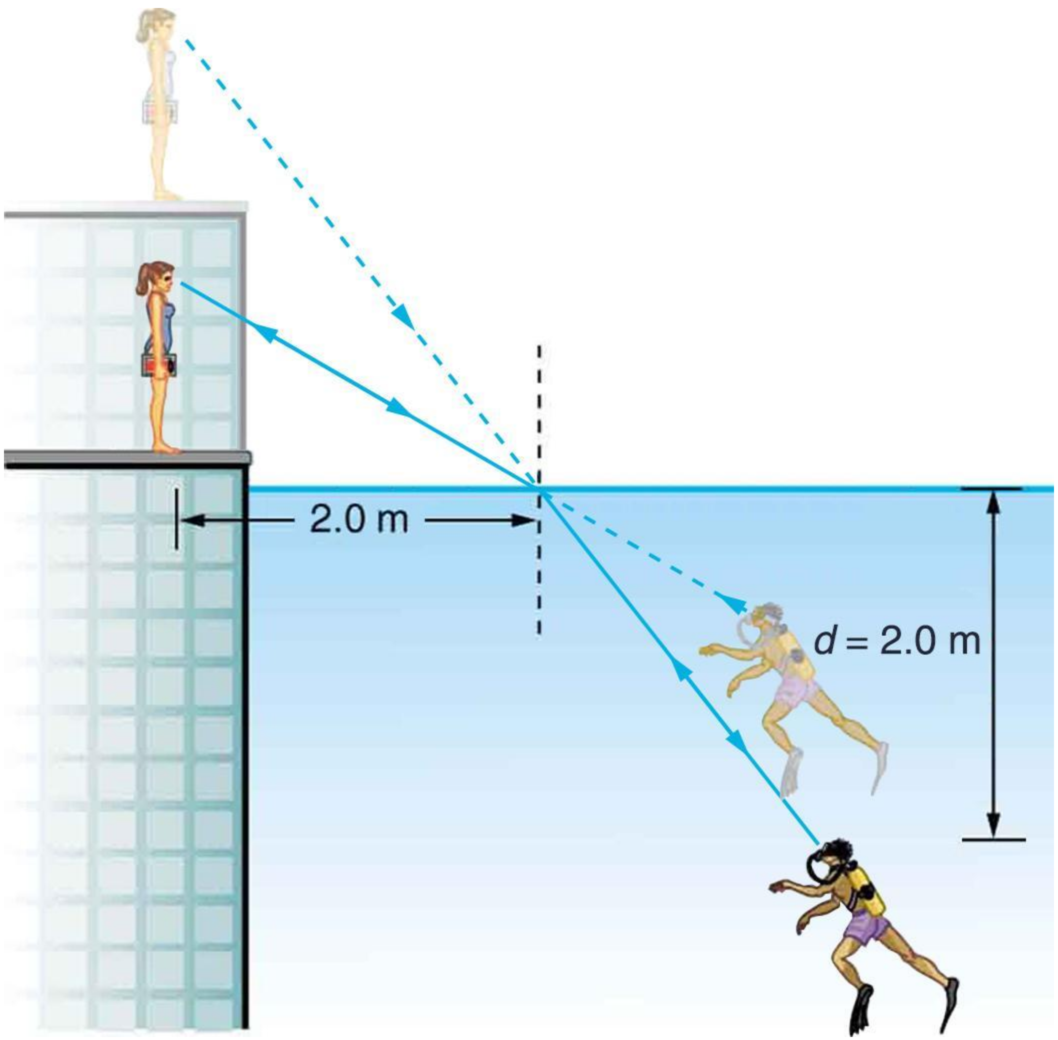


# FIGURE 25.52




A flat mirror neither converges nor diverges light rays. Two rays continue to diverge at the same angle after reflection.

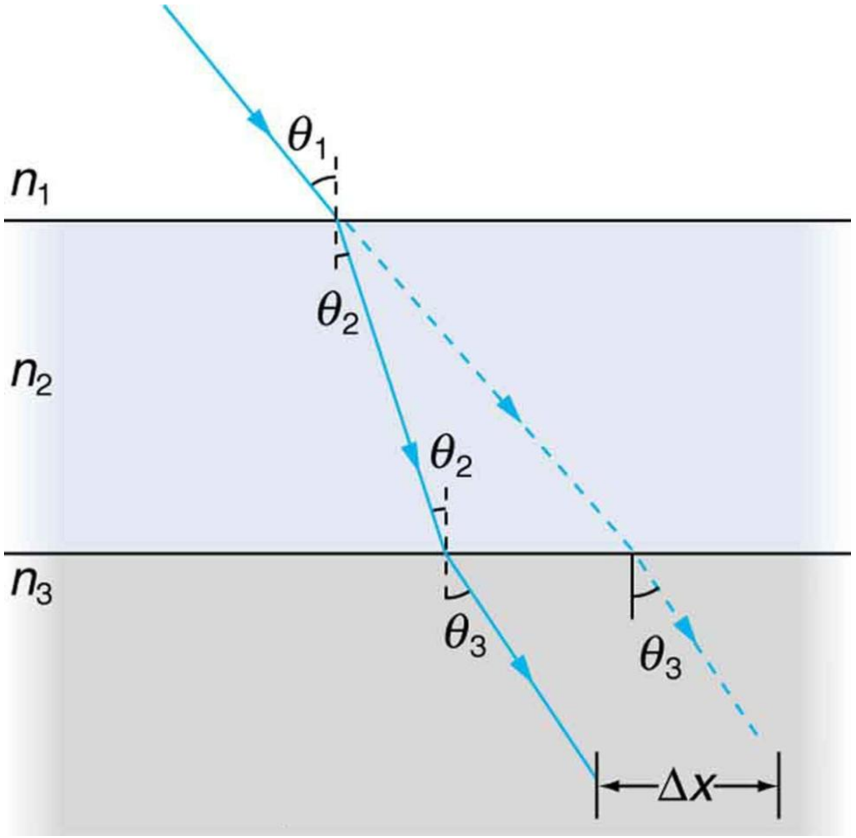
# FIGURE 25.53



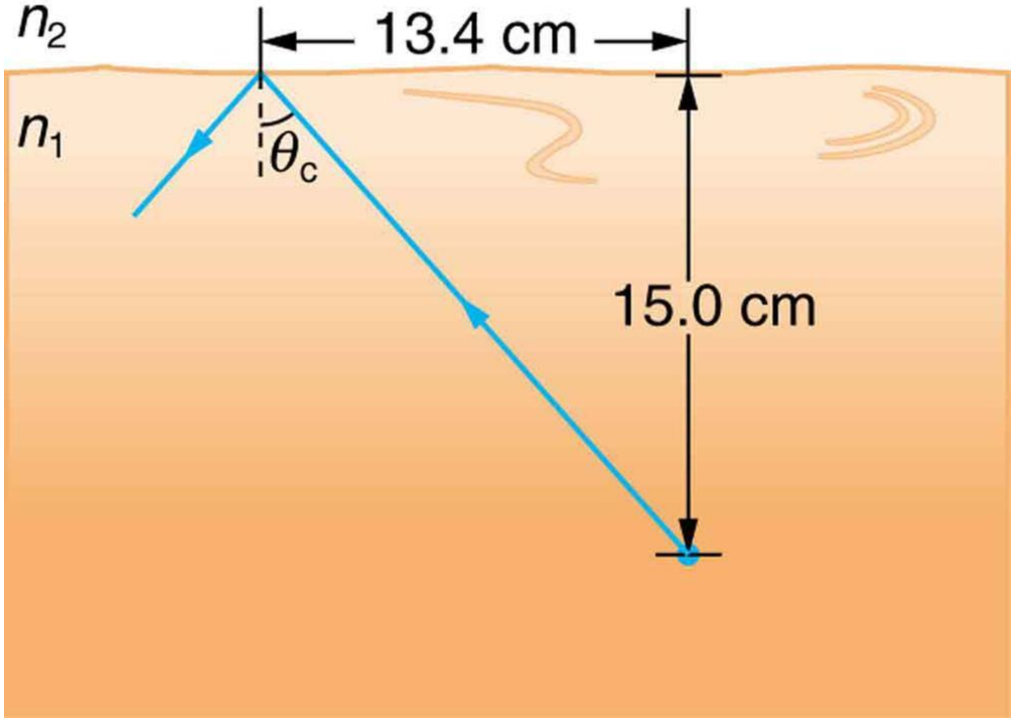

A scuba diver in a pool and his trainer look at each other.

# FIGURE 25.54

A ray of light passes from one medium to a third by traveling through a second. The final direction is the same as if the second medium were not present, but the ray is displaced by *Δx* (shown exaggerated).

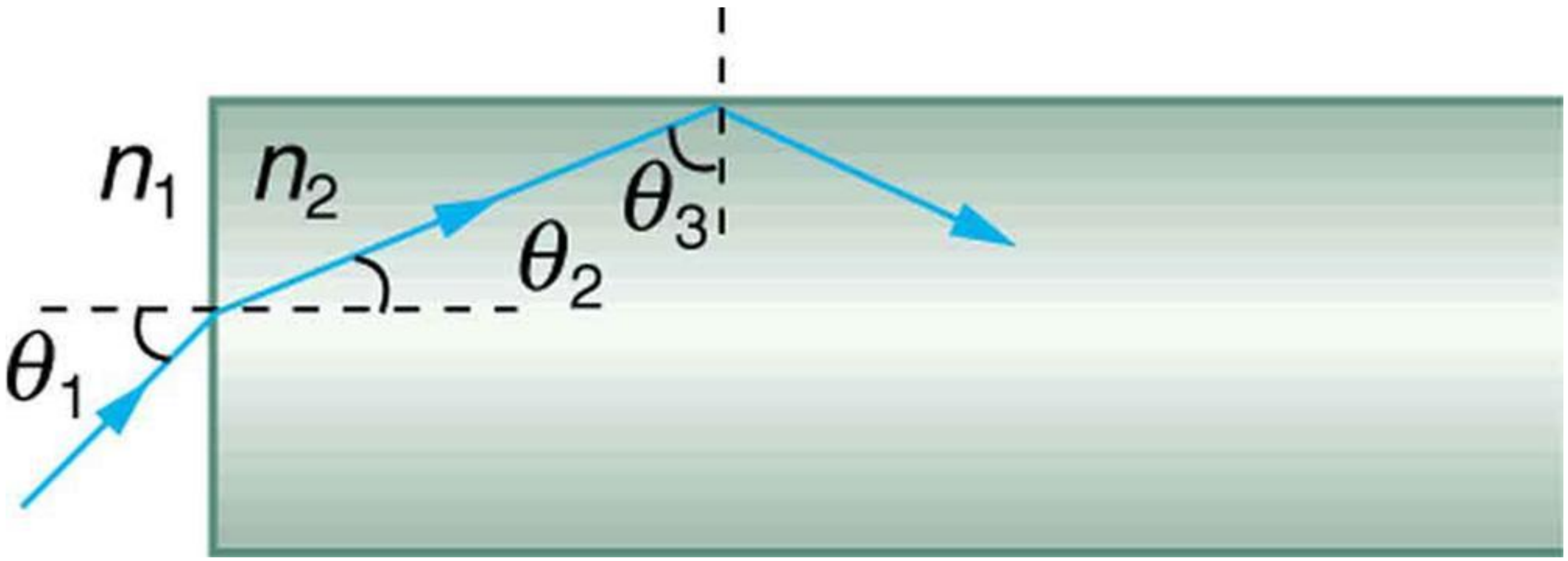


# FIGURE 25.55



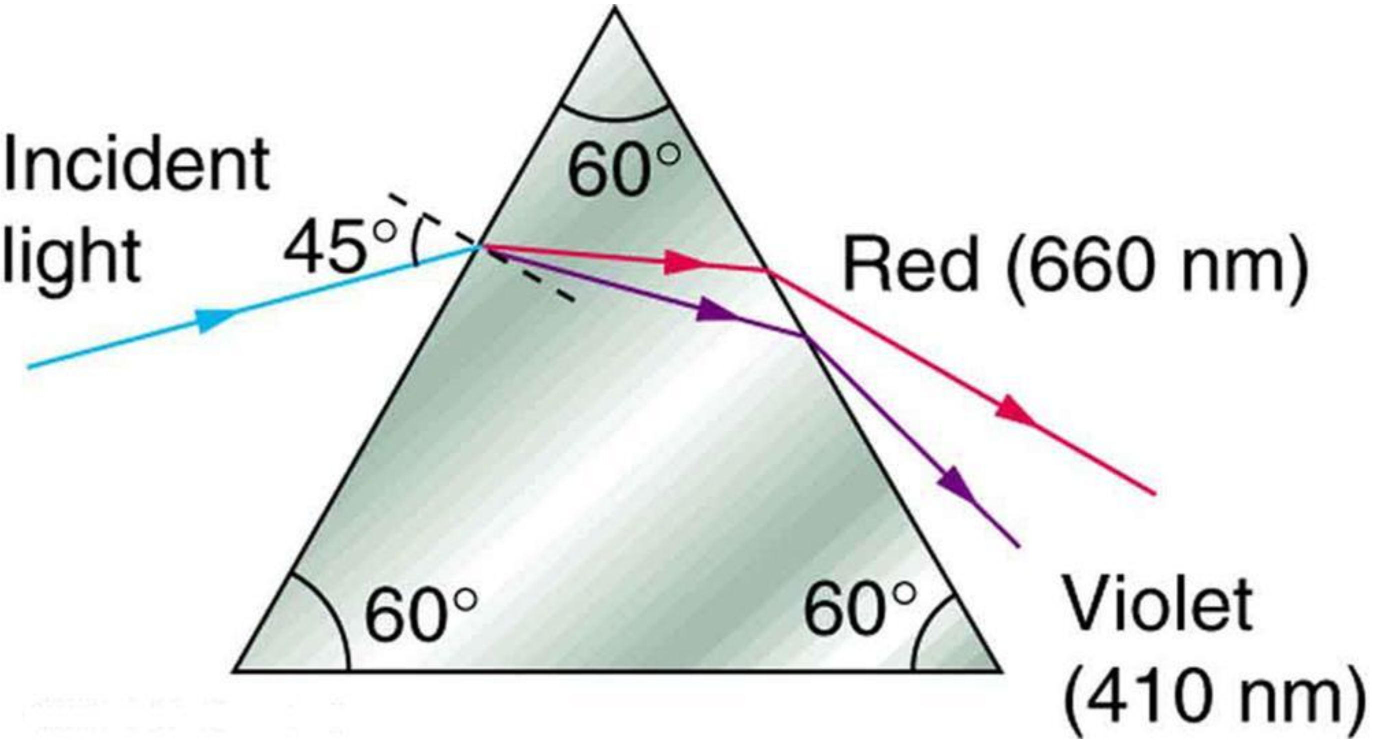

A light ray inside a liquid strikes the surface at the critical angle and undergoes total internal reflection.

# FIGURE 25.56




A light ray enters the end of a fiber, the surface of which is perpendicular to its sides. Examine the conditions under which it may be totally internally reflected.

# FIGURE 25.57




This prism will disperse the white light into a rainbow of colors. The incident angle is 45.0**º** , and the angles at which the red and violet light emerge are $\theta_R$ and $\theta_V$ .