The Big Picture

The Mystery of Light


Jerry Irwin/Photo Researchers, Inc.

Rainbow over a farm in Pennsylvania.

Throughout history our knowledge, attitudes, and values have been reflected in our sciences and in our arts. The most obvious example of this parallelism is light. Light and one of its characteristics, color, have followed parallel trends in science and art. In the Middle Ages, for example, light was sacred and mysterious; artists placed it in some heavenly plane. When St. John the Evangelist said, "God is light," his words reflected the belief that the presence of light in a place of worship was a sign of the presence of the Holy Spirit. Beautiful, brightly colored leaded-glass windows became the norm in the great churches being built at the time.

Light, as seen in these early works, had a surrealistic behavior. It wasn't until the Renaissance that artists studied the effects of light on objects, how it illuminates some sides of an object but not others. During the late 1600s, when light was shown to take a finite time to travel through space, paintings were just beginning to show objects casting shadows on the ground.

Still the scientific questions remained: What is light? Does light behave as a wave or as a stream of particles? It was known that light travels from the Sun to Earth and that space is a very good vacuum. If light is a wave, how can it travel through a vacuum where there is nothing to wave? The history of this debate about the wave or particle nature of light goes back at least to Newton's time. Newton, perhaps influenced by his successful work on apples and moons, believed that light was a stream of very tiny particles. His contemporary, Dutch scientist Christiaan Huygens, believed that light was a wave. The controversy was not resolved until 100 years later. (However, the question of the nature of light reemerged during the 20th century with the development of quantum mechanics.)

And what is the origin of the colors? Prior to Newton's work with clear glass prisms, color was thought to be something emanating from objects. A ruby's redness was only due to the characteristics of the ruby. As we will see, this is partially correct; the character of the light shining on the ruby also plays a role.

The next time you look at a star, think about the starlight that reaches your eyes. It probably began its journey hundreds or thousands of years ago, in many cases long before civilization began on Earth. When it arrives at your eye, its journey is over. The light is absorbed in your retina, producing an electrical signal that travels to your brain. However, this light is carrying a much more complex message than simply the location of the star in the heavens. With the exception of a few artificial satellites within the solar system and a variety of cosmic particles striking Earth, our entire knowledge of the cosmos comes from the information carried by light.

We continue to build our physics world view by studying this mysterious phenomenon in the next three chapters; then we will use our newly gained knowledge of light to probe the structure of matter at the atomic level . . . and beyond.

A prism spreads light out into its component colors.

Bill Kamin/Visuals Unlimited

17

Light

▶When a magician thrusts a sword through the lovely assistant or spooks sit next to you as you traverse the haunted mansion's dark innards, the explanation is, "It's done with mirrors." But how does light produce these illusions that are so convincing?

(See page 370 for the answer to this question.)

John C. Muegge/Visuals Unlimited

The reflection of light at the surface of the water acts like a mirror to produce a virtual image.

ALTHOUGH the phenomenon of light is so common to our everyday experience and has played such a central role in the histories of religion, art, and science, it is actually quite elusive. Even the act of seeing has confused people. We talk of looking *at* things—of looking *into* a microscope, of sweeping our glance *around* the room—as if seeing were an active process, much like beaming something in the direction of interest. This notion goes back to some early ideas about light in which rays were supposedly emitted by the eyes and found the objects seen. The idea is still common, perhaps perpetuated in part by the Superman stories. In these stories Superman supposedly has the ability to emit powerful X rays from his eyes, enabling him to see through brick walls or, in the modern movie version, through clothes.

Seeing is actually a rather passive activity. What you see depends on the light that enters your eyes and not on some mysterious rays that leave them. The light is emitted whether or not your eyes are there to receive it. You simply point your eyes toward the object and intercept some of the light. In fact, light passing through clean air is invisible. If a flashlight is shined across a room, you don't see the light passing through the air. You only see the light that strikes the wall and bounces back into your eyes. (Sometimes you can see the beam's path because part of the light scatters from dust, fog, or smoke particles in the air and is sent toward your eyes.)

Shadows

One of the earliest studies of light was how it moved through space. By observing shadows and the positions of the light sources and the objects causing the shadows, it is easy to deduce that light travels in straight lines. In drawings illustrating the paths of light, it is convenient to use the idea of **light rays.** Because there are an infinite number of paths, we draw only enough to illustrate the general behavior.

An opaque object illuminated by a point source of light blocks some of the rays from reaching a screen behind it, producing a shadow like the one shown in Figure 17-1. The shadow has the same shape as the cross section of the object but is larger.

Most sources of light are not points but extend over some space. However, we can think of each small portion of the source as a point source casting its own sharp shadow. All these point-source shadows are superimposed on the screen behind the object. The darkest region is where all of the shadows overlap. This is known as the **umbra** (Figure 17-2). Surrounding the umbra is the **penumbra,** where only some of the individual shadows overlap.

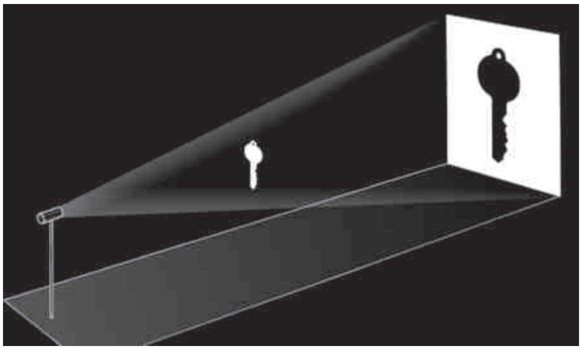


Figure 17-1 The shadow produced by a point source of light is very sharp.

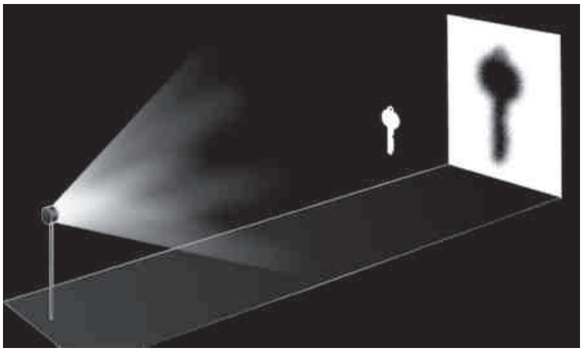


Figure 17-2 The shadow produced by an extended source of light has a dark central umbra surrounded by a lighter penumbra.

Everyday Physics | *Eclipses*

The most spectacular shadows are eclipses, especially total solar eclipses. During a solar eclipse, the Moon's shadow sweeps a path across a portion of Earth, as shown in Figure A. If you are in the path of the umbra, the Sun is totally obscured (Figure B). Observers to the side of the umbra's path but in the path of the penumbra see a partial eclipse.

One of Aristotle's arguments that Earth is a sphere involved the shadow during lunar eclipses (Figure C). Here, Earth's shadow falls onto the face of the Moon. Because (1) the shape of the shadow is always circular and (2) the only solid that always casts a circular shadow is a sphere, Aristotle correctly concluded that Earth must be a sphere.

Few people experience a solar eclipse, although the population on half of Earth can see a lunar eclipse. To see a solar eclipse, observers must be directly in the shadow of the Moon. This only covers a small portion of Earth's surface. During a lunar eclipse, we observe Earth's shadow on the Moon (Figure D). Anyone who can see the Moon can therefore see this eclipse.

1. Explain the difference between the umbra and the penumbra. Use the idea that an extended light source (such as the Sun) can be thought of as a collection of many point sources of light.
2. Why is it more likely that you will observe a total lunar eclipse than a total solar eclipse in your lifetime?
3. Your friend thinks that the phases of the Moon are caused by Earth's shadow on the Moon. What evidence could you present to convince your friend that she is mistaken?

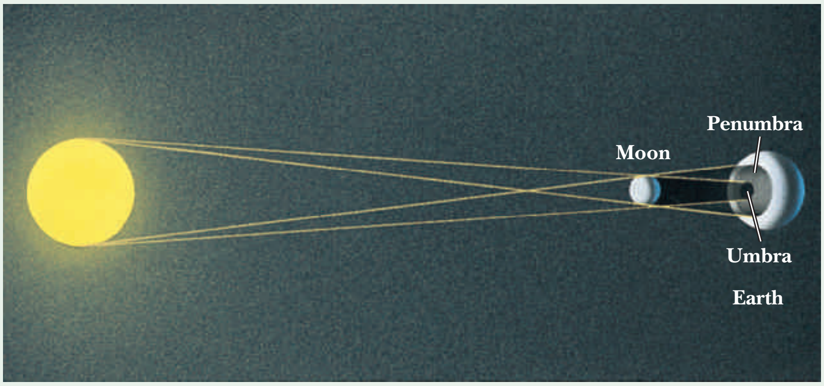


Figure A A total solar eclipse occurs when the umbra of the Moon's shadow falls on Earth.

Jim Anderson, Montana State University, Physics Department

Figure B A total eclipse of the Sun.

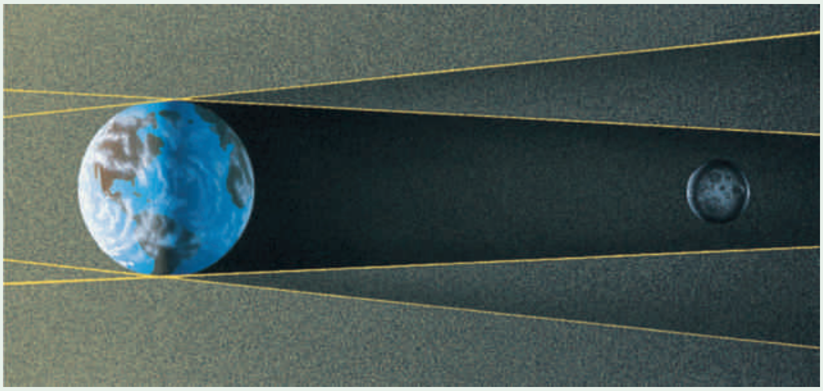


Figure C During a lunar eclipse, the Moon is in Earth's shadow.

Courtesy of Mike Murray

Figure D During a lunar eclipse, we can see part of Earth's circular shadow.

Rather than looking at the shadow, imagine standing in the shadow looking back toward the source. If your eye is located in the umbra, you will not see any portion of the source of light; the object between you and the source blocks out all of the light. If your eye is in the penumbra, you will see part of the light source.

Shadows that we observe on Earth are not totally black and devoid of light. We can, for example, see things in shadows. This is due to the light that scatters into the shadow from the atmosphere or from other objects. On the Moon, however, the shadows are much darker because there is no lunar atmosphere. Astronauts exploring the Moon's surface have to be careful. Stepping into their own shadows can be dangerous because the extreme blackness of the shadow would hide everything within it—sharp rocks, uneven terrain, even a deep hole.

Pinhole Cameras

Extended presentation available in the *Problem Solving* supplement

Light that strikes most objects leaves in a great many directions. (This must be true because we can see the object from many different viewing directions.) If we place a piece of photographic film in front of a vase of flowers, as in Figure 17-3(a), the film will be completely exposed, leaving no record of the scene. Light from one part of the vase hits the film at the same place as light from many other parts of the vase and flowers. Every spot on the film receives light from virtually every spot that faces the film.

We can get an image by controlling which light rays hit the film. A screen with a small hole in it is placed between the vase and the film, as shown in Figure 17-3(b). Now only the light from a small portion of the vase reaches a given region of the film. Making the hole smaller, as in Figure 17-3(c), further reduces the portion of the vase exposed to a given spot on the film. If the hole is made small enough, a recognizable image of the vase is formed on the film. This technique can be used to make a pinhole camera by enclosing the film in a light-tight box with a hole that can be opened and shut. The photograph in Figure 17-4 was taken with a pinhole camera made from a shoebox.

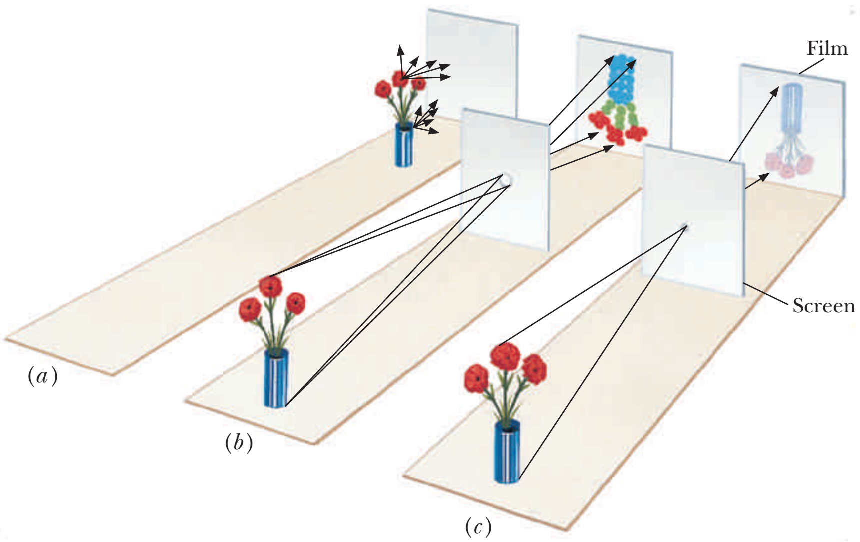


Figure 17-3 (a) Each part of the film receives light from many parts of the vase and flowers, and no image is recorded. (b) The screen restricts the light so that each part of the film receives light from a small portion of the scene. (c) Reducing the size of the hole produces a sharper but dimmer image.

Figure 17-4 A photograph made with a pinhole camera. The exposure time was 2 seconds.

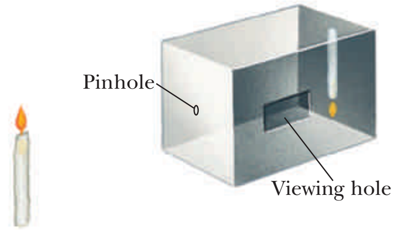


Figure 17-5 A pinhole in one end of the box produces an inverted image on the opposite end.

The problem with pinhole cameras is the very small amount of light that reaches the film. Exposure times generally must be long, requiring that the scene be relatively static. We will see in Chapter 18 that this problem was eventually overcome by using a lens.

Pinhole cameras were used before the invention of film. If you add another hole to the box, as illustrated in Figure 17-5, you can see the image on the back wall. During solar eclipses, some observers use this process to watch the partial phases of the eclipse safely. On a grander scale, an entire room can be converted into a pinhole camera known as a *camera obscura*. Renaissance artists used smaller versions to help them draw landscapes and portraits; they traced the images formed on the back wall.

Reflections

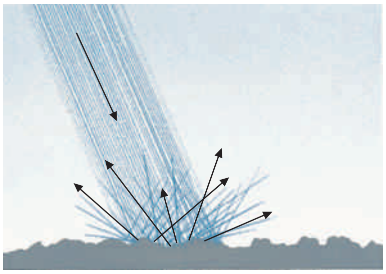


Figure 17-6 A beam of light striking a rough surface is scattered in many directions.

Some things emit their own light—a candle, a lightbulb, and the Sun, to mention a few. But we see most objects because they reflect some of the light that hits them. The incident light, or the light striking the object, is scattered in many directions by the relatively rough surface of the object, a process known as **diffuse reflection.** If the surface of the object is very smooth, a light beam reflects off it much as a ball rebounds from a wall. Presumably then, when light hits rougher surfaces, the same thing happens. But with rough surfaces, different portions of the incident light reflect in many directions, as shown in Figure 17-6.

By looking at the reflection of a thin beam of light (a good approximation to a "ray" of light) on a smooth surface, we can discover a rule of nature. Figure 17-7(a) shows the reflections of light beams hitting a mirror at three different angles. Clearly, the angle between the incident and the reflected ray is different in each situation. However, if we examine only one case at a time, we notice that the angles that the incident and reflected rays make with the surface of the mirror are equal. If we measure the angles of the incident ray and the reflected ray for many such situations, we discover that the two angles are always equal.

In our illustration of this phenomenon, we used the angles made with the reflecting surface. It is more convenient to consider the angles between the rays and the **normal,** an invisible line perpendicular to the surface that touches the surface where the rays hit [Figure 17-7(b)]. The reflected ray lies in the same plane as the normal and the incident ray. Using these angles we state the **law of reflection:**

law of reflection ▶

The angle of reflection is equal to the angle of incidence.

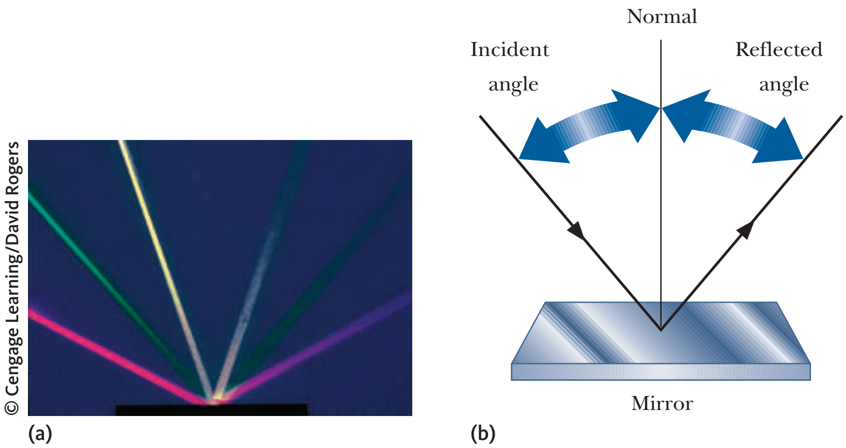


Figure 17-7 (a) Reflections of three thin beams of light hitting a mirror at different angles from the left. (b) For each one the angle of reflection is equal to the angle of incidence.

Q: Assume that you are stranded on an island. Where would you aim a mirror to signal a searching aircraft with sunlight?

A: The normal to the mirror would have to be directed at the point midway between the Sun and the aircraft. Luckily, this is easier to do than it may seem.

Flat Mirrors

When we look at smooth reflecting surfaces, we don't see light rays; we see images. We can see how images are produced by looking at the paths taken by light rays. In Figure 17-8 we locate the image Q of a single point P in front of a flat mirror. Light leaves the point P in all directions; some of the light strikes the mirror at point A, then reflects and travels in the direction of B. An eye at B would receive the light coming along the direction AB.

Remember that seeing is a passive activity. Our eye–brain system records only the direction from which the light arrives. We do not know from how far away the light originated, but we do know that it came from someplace along the line from B to C. However, we can say the same thing about the light that arrives from another direction, say, at E. The eye perceives this light as coming from someplace along the line EF. Because the only place that lies on both lines is Q, our brain says that the light originated at point Q. This is the location of the image. We see an image of P located behind the mirror at point Q. After the light reflects from the mirror, it has all of the properties it would have had if the object had actually been at Q.

The image has a definite location in space. Figure 17-8 shows that the point Q is located the same distance behind the mirror as the point P is in front of the mirror. A straight line drawn between P and Q is normal to the mirror. These observations allow us to locate the image quickly. For example, in Figure 17-9 we can locate the image of the pencil by first locating the image of its tip and then the image of its eraser. The size of the image is the same as that of the object (although it is farther away from you and looks smaller). Note that the pencil doesn't have to be directly in front of the mirror. However, the mirror must be between the entire image and the observer's eyes, as illustrated in Figure 17-10.

A magician's trick illustrates the realism of an image by presenting the audience with a live, talking head on a table, as in Figure 17-11(a). Like many other illusions, the trick lives up to the cliché that "it's all smoke and mirrors." But where is the person's body? Your eye–brain system is tricked by the images. You think that the table is an ordinary one with legs and a wall behind it. You "know" this because you can see the wall between the table's legs. Figure

Figure 17-9 The image of a pencil formed by a flat mirror is located behind the mirror.

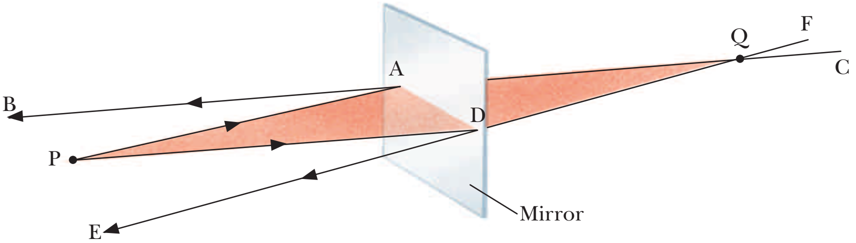


Figure 17-8 A ray diagram showing that the location of the image Q is determined by the crossing of the two lines of sight. The image Q is as far behind the mirror as the object P is in front.

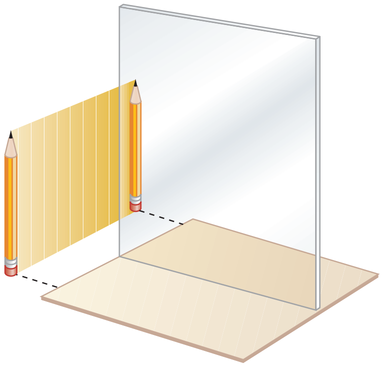
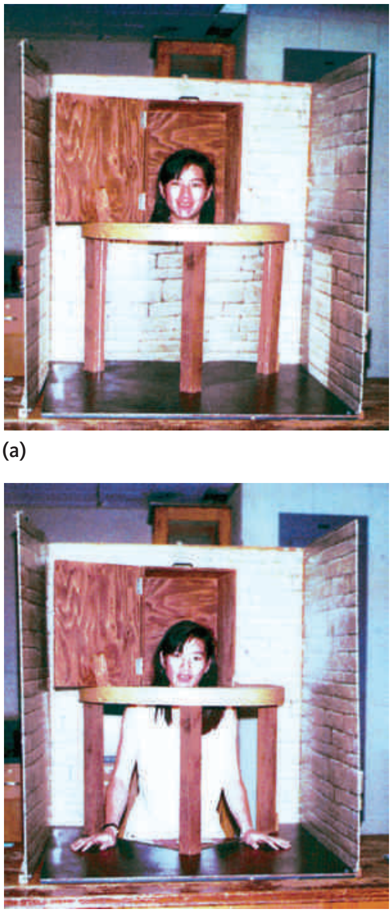


Figure 17-10 A flat mirror forms an image of an object even if the object is not located directly in front of the mirror.



Gerald F. Wheeler (both)

Figure 17-11 (a) The woman's head appears to sit on the table. How is this done? (b) The same scene with both mirrors removed.

FLAWED REASONING

Cassandra complains to her mother: "Physics is hard. I am supposed to light a match in front of a mirror and find the location of the flame's image. When I move my head to the left, the image of the flame is located on the left-hand side of the mirror. When I move my head to the right, it is located on the right-hand side of the mirror. How can I find the location of something that keeps moving?"

Help Cassandra's mother convince her that physics is easy.

ANSWER Suppose Cassandra looks at a tree through her kitchen window. By moving her head back and forth, she can align the tree with the left-hand side or the right-hand side of the window. The tree, however, is not moving. The mirror is like the kitchen window, and the flame is like the tree. The light that reflects from the mirror behaves as if it came directly from the image. The image is not on the mirror's surface; it is located behind the mirror and does not move. Cassandra should think of the mirror as a window through which she can view this "image world."

17-11(b) shows the set-up with the mirrors removed. The table has mirrors between its legs so that the walls you see under the table are really images of the side walls.

Multiple Reflections

When a light beam reflects from two or more mirrors, we get interesting new optical effects from the multiple reflections. If the two mirrors are directly opposite each other, such as in some barbershops and hair salons, we get an infinite number of images, with successive images being farther and farther away from the object. To see how this works, remember that the light appearing to come from an image has the same properties as if it actually came from an object *at the location of the image*. Each mirror forms images of everything in front of it, *including* the images formed by the other mirror. Each of the mirrors forms an image of the object. The light from these images forms an additional set of images behind the opposing mirrors, and on and on, as illustrated in Figure 17-12.

Are You On the Bus?

Q: Would the opposing mirrors in Figure 17-12 allow you to see the back of your head?

A: Yes, provided the mirrors are tilted a bit so that your head doesn't get in the way of your view. The second image in the mirror in front of you will be of the back of your head.

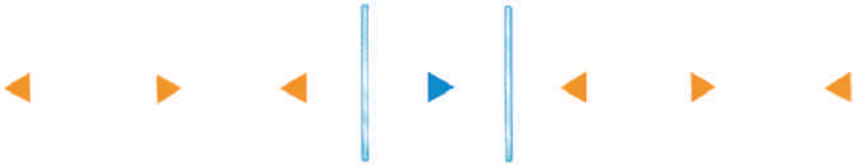


Figure 17-12 Two opposing parallel mirrors form an infinite number of images. Notice the reversals in the orientations of the triangles.

WORKING IT OUT *Full-Length Mirror*

Jonathan needs to buy a "full-length" mirror to mount on his wall. He is extremely thrifty (cheap) and wants to buy the shortest mirror that will allow him to see a reflection of his entire body. If Jonathan is 6 feet tall, how short can the mirror be and how high should it be mounted on the wall? Does your answer depend on how far from the mirror Jonathan will be standing?

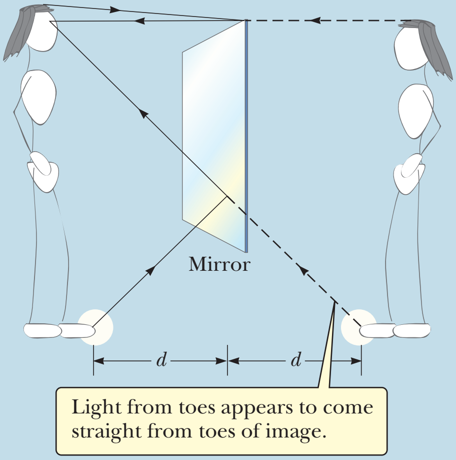
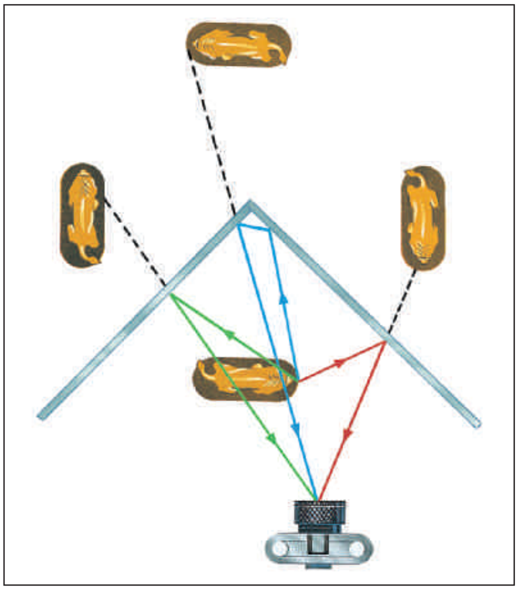


Figure 17-13 A "full-length" mirror need only be half the height of the person using it.

If Jonathan stands some distance d in front of the mirror, then an image of Jonathan, exactly the same size, will be formed a distance d behind the mirror, as shown in Figure 17-12. Jonathan can see his toes "in the mirror" because light travels from his toes, bounces off the mirror, and enters his eyes. This light appears to travel in a straight line path from the toes of the image of Jonathan behind the mirror. The mirror is mounted on the wall, halfway between Jonathan and his image, so the light coming from his toes will bounce off the mirror at a height halfway between the floor and his eyes. A similar argument can be used to claim that the light from the top of his head bounces off the mirror at a height halfway between his eyes and the top of his head. The shortest "full-length" mirror that would do the job would be 3 feet tall, and should be mounted on the wall with the top of the mirror at the same height as Jonathan's forehead (halfway between his eyes and the top of his head). Our reasoning is independent of the distance d, so it does not matter how far from the mirror Jonathan will be standing.

(a)



(b)

Figure 17-14 (a) Two mirrors at right angles to each other produce three images of the lion. (b) The red, green, and blue lines show sample paths taken by rays that enter the camera lens.

In Figure 17-14(a) we have placed a figurine of a lion in front of two mirrors that form a right angle. Figure 17-14(b) shows the paths taken by the rays that entered the camera. Notice that there are three images; each mirror forms

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Figure 17-15 When the mirrors form an angle of 60 degrees, five images of the lion are produced.

one image, and then each mirror forms an image of these images. (Remember that a mirror does not have to actually extend between the image and the object. However, it is often useful to imagine that each mirror is extended.) If the angle between the mirrors is precisely 90 degrees, these latter two images overlap to form a single image beyond the corner.

If the angle between the mirrors is made smaller, the overlapping images beyond the corner separate. When the angle between the mirrors reaches 60 degrees, we once again get overlapping images beyond the corner and a total of five images, as shown in Figure 17-15.

Curved Mirrors

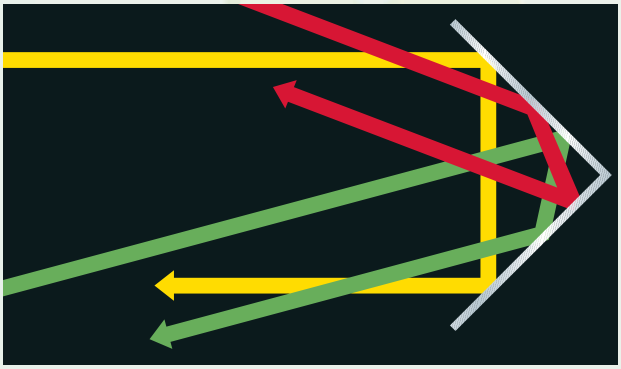
Fun-house mirrors are interesting because of the distortions they produce. The distortions are not caused by a failure of the law of reflection but result from the curvature of the mirrors. Some distortions are desirable. If the distortion is a magnification of the object, we can see more detail by looking at the image.

Cosmetics mirrors and some rearview mirrors on cars are simple curved mirrors that don't produce bizarre distortions but do change the image size. A cosmetics mirror uses the concave side—the reflecting surface is on the inside of the sphere—to generate a magnified image of your face. The con-

Everyday Physics | *Retroreflectors*

An interesting consequence of having two mirrors at right angles is that an incoming ray (in a plane perpendicular to both mirrors) is reflected back parallel to itself, as shown by the three rays in the figure. This works for all rays if we add a third mirror to form a "corner" reflector, such as by putting mirrors on the ceiling and the two walls in the corner of a room. These *retroreflectors* are used in the construction of bicycle reflectors so that the light from a car's headlights is reflected back to the car driver and not off to the side as it would be with a single mirror. Examination of many reflectors reveals a surface covered with holes in the shape of the corners of cubes. Reflectors used on clothing and the surfaces of stop signs are often covered with a layer of reflective beads. The surfaces in the regions between the beads work like corner reflectors.

An outer-space application of retroreflectors involves an experiment to accurately measure the distance to the Moon. The Apollo astronauts placed panels of retroreflectors on the Moon to allow scientists on Earth to bounce a laser beam off the Moon and receive the reflected signal back on Earth. Ordinary mirrors would not have worked because the astronauts could not have aimed them well enough to send the beam back to Earth. Additionally, the Moon's wobbly rotation would send the reflected beam in many directions. Because retroreflectors work for all incident angles, they could be simply laid on the Moon's surface. We now know that the Earth–Moon distance increases by 3 to 4 centimeters per year.



Each of the three rays is reflected back parallel to itself.

1. Explain in detail the process used to measure the distance between Earth and the Moon.
2. Is the orbital speed of the Moon increasing, decreasing, or staying the same? Explain your answer using the concept of conservation of angular momentum, discussed in Chapter 8.

Q: Sometimes mirrors are installed in stores to inhibit shoplifting. Are these concave or convex mirrors?

A: The mirrors must be convex to provide a wide view of the store.

vex reflecting surface—the outside of the sphere—always produces a smaller image but has a bigger field of view. Convex mirrors are quite often used on cars and trucks and on "blind" street corners because they provide a wide-angle view.

Figure 17-16 shows the essential geometry for a concave spherical mirror; the reflecting surface is the inside of a portion of a sphere. The line passing through the center of the sphere C and the center of the mirror M is known as the **optic axis.** Light rays parallel to the optic axis are reflected back through a common point F called the **focal point.** The focal point is located halfway between the mirror and the center of the sphere. The distance from the mirror to the focal point is known as the **focal length** and is equal to one-half the radius R of the sphere.

Concave mirrors can be used to focus light. Some solar collectors use them to concentrate sunlight from a large area onto a smaller heating element. Because the Sun is very far away, its rays are essentially parallel, and a concave spherical mirror can focus the sunlight at the focal point. A cylindrical mirror focuses sunlight to a line instead of a point. A pipe containing a fluid can be placed along this line to carry away the thermal energy. If the heat energy is used to generate electricity, the higher temperature makes the process more efficient.

Light rays are reversible. The law of reflection is still valid when the incident and reflected rays are reversed. So the shape that focuses parallel rays to a point will take rays from that point and send them out as parallel rays. This idea is used in automobile headlights. The bulb is placed near the focal point of the mirror, producing a nearly parallel beam.

The optic axis of a convex mirror also passes through the center of the sphere C, the focal point F, and the center of the mirror M, but in this case, the focal point and the center of the sphere are on the back side of the mirror. (Again, the focal point is halfway between the center of the sphere and the center of the mirror.) Rays parallel to the optic axis are now reflected *as if they came from* the focal point behind the mirror, as shown in Figure 17-17.

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The curved surfaces of fun-house mirrors produce interesting images.

Ross Anania/Stone/Getty Images

Convex mirrors allow clerks to watch for potential shoplifters.

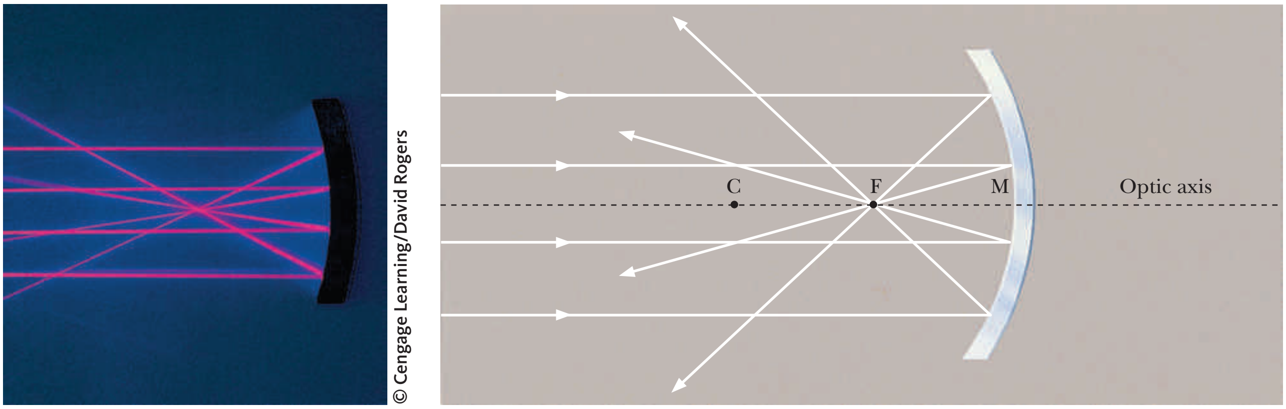

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Figure 17-16 The focal point F of a spherical concave mirror lies along the optic axis midway between the center of the sphere C and the center of the mirror M. Rays parallel to the optic axis are focused at the focal point F.

Cylindrical mirrors are used to concentrate sunlight at this solar farm.

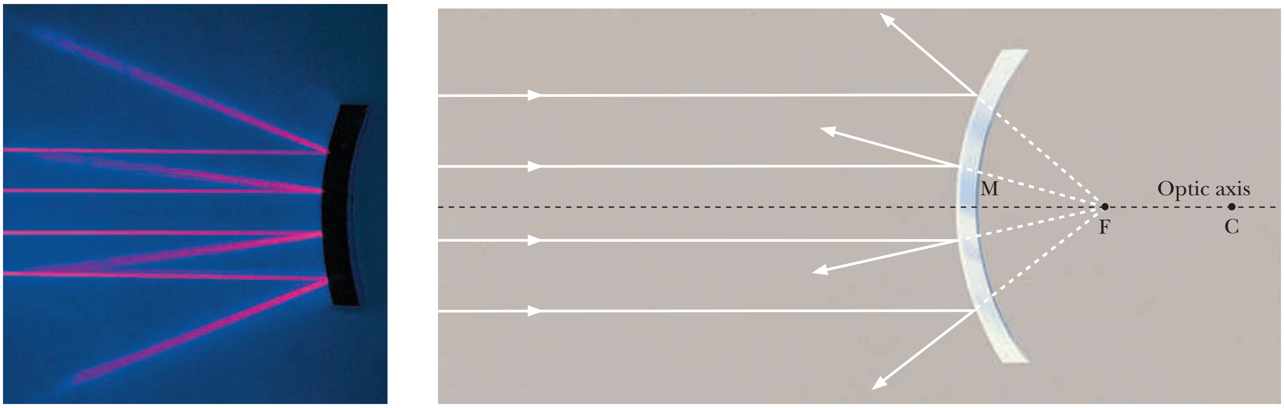


Figure 17-17 The focal point F of a spherical convex mirror lies along the optic axis midway between the center of the sphere C and the center of the mirror M. Rays parallel to the optic axis are reflected as if they come from the focal point F.

Figure 17-18 An inverted image is formed when the head is located outside the focal point of a concave mirror. Note that both the face and the floor tiles are inverted.

Images Produced by Mirrors

A concave mirror can form two different types of image, depending on how close the object is to the mirror. Imagine walking toward a large concave mirror. At a large distance from the mirror, you will see an image of your face that is inverted and reduced in size (Figure 17-18). This image is formed by light from your face reflecting from the mirror and converging to form an image in front of the mirror. This image is known as a **real image,** because the rays reflect from the mirror and converge to form the image. The rays then diverge, behaving as if your face were actually at the image location.

As you walk toward the mirror, the image of your face moves toward you and gets bigger. As you pass the center point of the mirror, the image moves behind you. When your face is closer to the mirror than the focal point, the image is similar to that in a flat mirror except that it is magnified (Figure 17-19). As with the flat mirror, the rays diverge after reflecting, and the image is located behind the mirror's surface. In this case there can be no light at the location of the image because it is formed behind the mirror. The light only appears to come from the location of the image. This second type of image is called a **virtual image.** As you continue approaching the mirror, the image moves closer and gets smaller.

The essential difference between a real and a virtual image is whether the light actually comes from the image location or only appears to come from there. If the rays diverge upon reflecting, they never come together to form a real image. They will, however, appear to originate from a common location behind the mirror. Reflected rays that converge to form a real image can be seen on a piece of paper placed at the image location because the light actually converges at that location. However, if you put a piece of paper at the location of a virtual image, you get nothing because there is no light there.

Figure 17-19 A magnified, erect image is formed when the head is located inside the focal point of a concave mirror.

Locating the Images

A simple way of locating an image without measuring any angles is by looking at a few special rays. Light leaves each point on the object in all directions; rays that strike the mirror form an image. Although any of these rays can be used to locate the image of a point, three are easy to draw and are therefore useful in locating the image. Because all rays from a given point on the object are focused at the same place for a real image (or appear to come from the same point for a virtual image), we need only find the intersection of any two of them. The third one can be drawn as a check. (In actual drawings these three rays do not always meet at a point. However, they give a pretty good location for the image if the object is small enough that the special rays strike the mirror near the optic axis.)

The three rays that are useful in these ray diagrams are shown in Figure 17-20. The easiest ray to draw is the red one lying along a radius of the sphere. It strikes the mirror normal to the surface and reflects back on itself. Another easy ray is the blue one that approaches the mirror parallel to the optic axis. It is reflected back toward the focal point. The third ray (shown in green) is a reverse version of the second one; a ray passing through the focal point reflects back parallel to the optic axis. (This ray does not actually need to pass through the focal point. If the object is closer than the focal point, the ray still lies along the line from the focal point to the mirror.)

If the mirror is small, some of these special rays may not strike the actual surface of the mirror. For the purposes of the ray diagram, we extend the mirror because a larger mirror with the same focal length would produce the same image. In fact, the mirror could be so small that none of the three easily drawn rays hits the mirror.

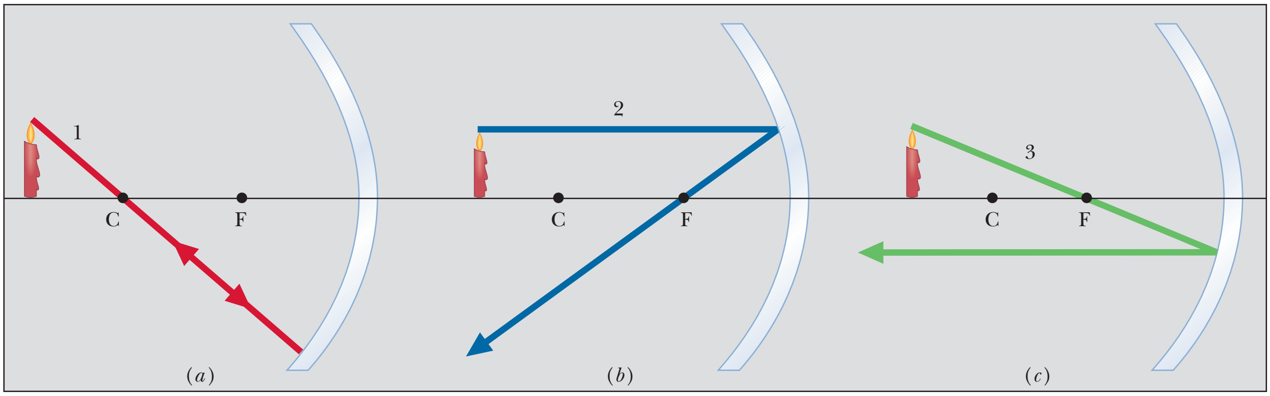


Figure 17-20 The three light rays used in drawing ray diagrams for concave mirrors.

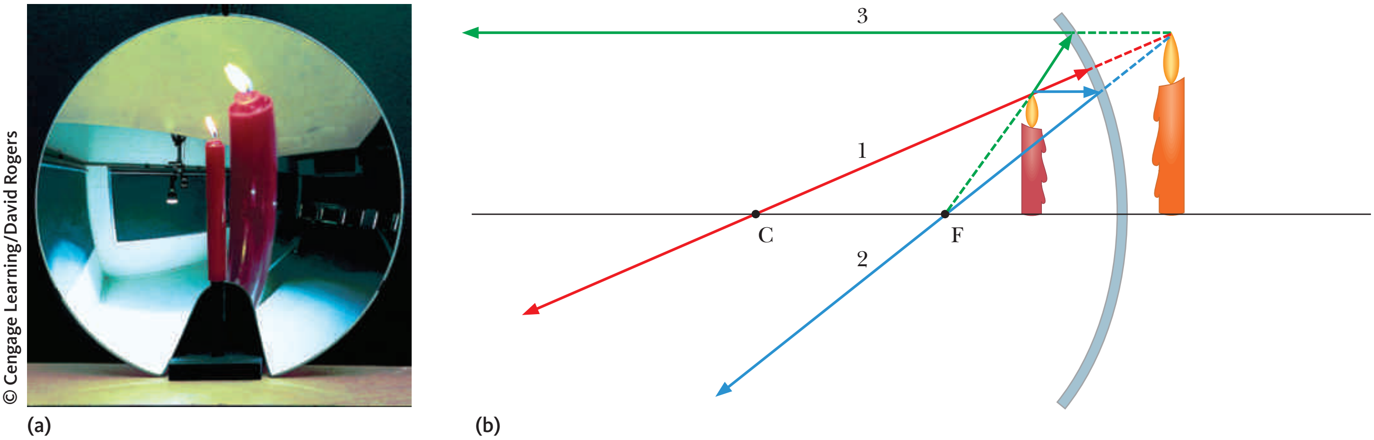


Figure 17-21 The image of a candle inside the focal point of a concave spherical mirror is virtual, erect, and magnified.

The descriptions of these rays can be abbreviated as follows:

rays for curved mirrors ▶

1. Along radius—back on itself
2. Parallel to optic axis—through focal point
3. Through focal point—parallel to optic axis

To illustrate the use of these ray diagrams, consider an object located inside the focal point of a concave mirror [Figure 17-21(a)]. Figure 17-21(b) shows the three special rays that we use to locate the image of the tip of the candle. The rays are color-coded to correspond to the descriptions given earlier. Because the base of the candle is on the optic axis, we know that the image of the base is also on the optic axis. So finding the location of the tip of the candle gives the image location, orientation, and magnification. For the case illustrated in Figure 17-21, we can see that the rays intersect behind the mirror, forming a virtual image that is erect and magnified.

As the candle is moved away from the mirror, the image size and the distance of the image behind the mirror increase. As the candle approaches the focal point, the image becomes infinitely large and infinitely far away. You can verify this by drawing a ray diagram.

When the candle is beyond the focal point, a real image is formed [Figure 17-22(a)]. The ray diagram in Figure 17-22(b) shows that the reflected rays do not diverge as in the previous case but come together, or converge. These rays actually cross at some point in front of the mirror to form a real image.

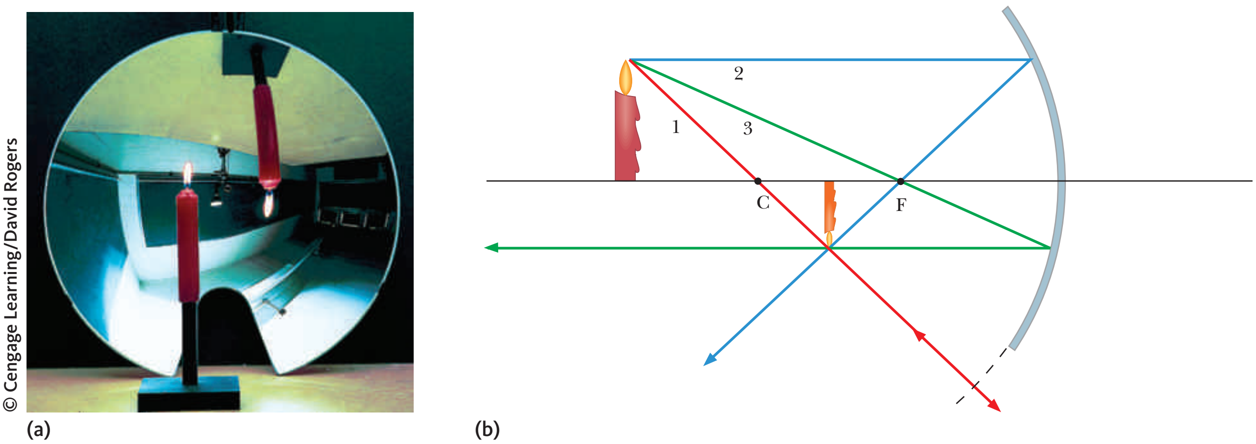
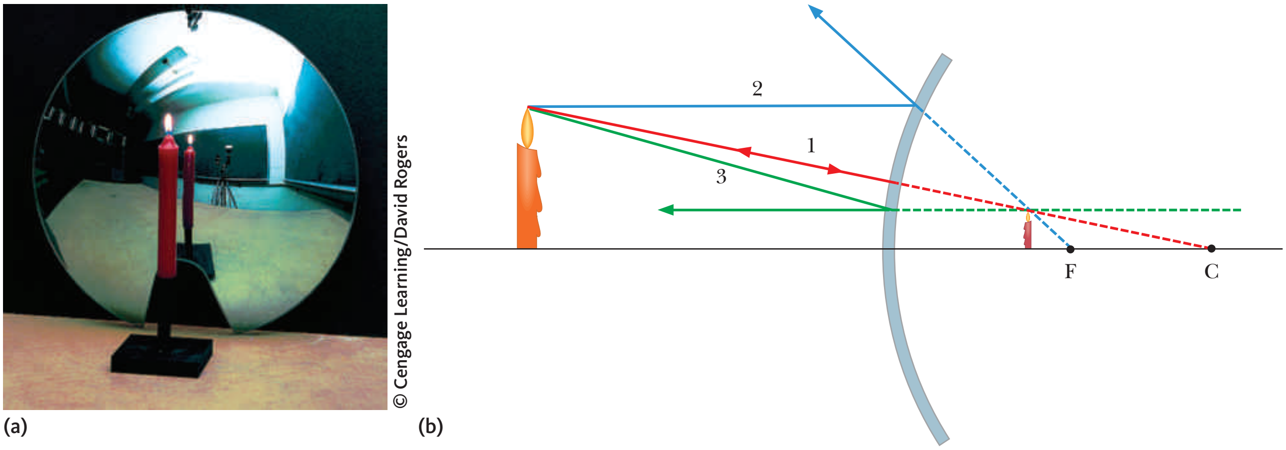


Figure 17-22 The image of a candle outside the focal point of a concave spherical mirror is real and inverted and may be larger or smaller than the object.

Q: Where would you place an object to get an image at the same location?

A: At the center of the sphere. This can be checked with a ray diagram.



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(a) (b)

Figure 17-23 The image of a candle in front of a convex spherical mirror is always virtual, erect, and reduced in size. Ray 2 reflects as if it came from the focal point, and ray 3 starts toward the focal point.

Fortunately, locating images formed by convex mirrors is the same process used for images formed by concave ones. A ray diagram showing how to locate the image is given in Figure 17-23(b). The same three rays are used. You must only remember that the focal point is now behind the mirror. With ray diagrams you can verify that images formed by convex mirrors are always erect, virtual, and reduced in size.

Speed of Light

Besides traveling in a straight line in a vacuum, light moves at a very high speed. In fact, people originally thought that the speed of light was infinite—that it took no time to travel from one place to another. It was clear to these observers that light travels much faster than sound; lightning striking a distant mountain is seen long before the thunder is heard.

Because of light's great speed, early attempts to measure the speed of light failed. Galileo made one interesting attempt when he tried to measure the speed of light by sending a light signal to an assistant on a nearby mountain. The assistant was instructed to uncover a lantern upon receiving Galileo's signal. Galileo measured the time that elapsed between sending his signal and receiving that of his assistant. Knowing the distance to the mountain, he was able to calculate the speed of light. Upon repeating the experiment with a more distant mountain, however, he found the same elapsed time! Had the speed of light increased? No. Galileo correctly concluded that the elapsed time was due to his assistant's reaction time. Therefore, the time it took light to travel the distance was either zero or much smaller than he was able to measure.

About 40 years later, in 1675, Danish astronomer Ole Roemer made observations of the moons of Jupiter that showed that light had a finite speed. Roemer found that the period of revolution of a moon around Jupiter was shorter during the part of the year when Earth approached Jupiter and longer when Earth receded from Jupiter. He expected the period to be constant like

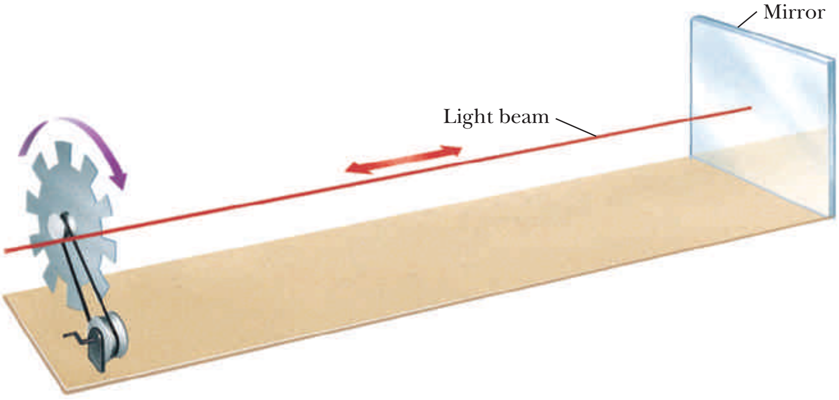


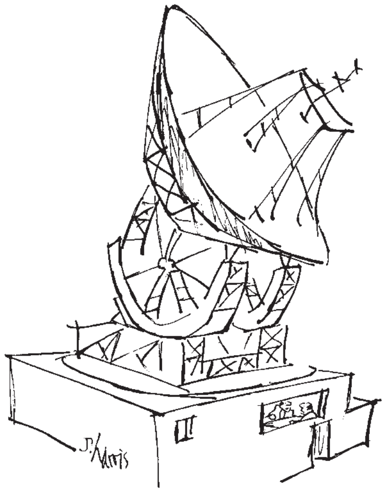
Figure 17-24 A schematic drawing of Fizeau's apparatus for measuring the speed of light.

that of our Moon about Earth. He correctly concluded that the period of the Jovian moon was constant and that the variations observed on Earth were due to the varying distance between Earth and Jupiter. When Earth approaches Jupiter, the light emitted at the beginning of the period must travel farther than that emitted at the end of the period. Therefore, the light emitted at the end of the period arrives sooner than it would if Earth and Jupiter remained the same distance apart. This difference in distance makes the period appear shorter. Once the radius of Earth's orbit was determined, the speed of light could be calculated.

speed of light ▶

French physicist Hippolyte Fizeau performed the first nonastronomical measurement of the speed of light in 1849. He sent light through the gaps in the teeth of a rotating gear to a distant mirror. The mirror was oriented to send the light directly back (Figure 17-24). At moderate speeds of rotation, the returning light would strike a tooth. But at a certain rotational speed, the light would pass through the next gap. Knowing the speed of the gear and the distance to the mirror, Fizeau was able to calculate the speed of light to a reasonable accuracy.

The speed of light has been measured many times. As the methods improved, the uncertainty in its value became less than 1 meter per second. In 1983 an international commission set the speed of light in a vacuum to exactly 299,792,458 meters per second and used it with atomic clocks to define the length of the meter. The speed of light is usually rounded off to 3×10^8 meters per second (186,000 miles per second). If light traveled in circles, it could go around Earth's equator 7.5 times in 1 second. It's no wonder that early thinkers thought light traveled at an infinite speed. Although the speed of light is finite, it can be considered infinite for many everyday experiences.



"As I understand it, they want an immediate answer. Only trouble is, the message was sent out 3 million years ago."

Q: Given that radio waves travel at the speed of light, would you expect there to be longer than normal pauses in a conversation between two people talking via radio from the two U.S. coasts? How about in a conversation with astronauts on the Moon?

A: Because light can travel around the world 7.5 times in 1 second, we would expect it to travel across the United States and back in a small part (about $\frac{1}{30}$) of a second. Therefore, the pauses would seem normal. The round-trip time for the signal to the Moon is a little less than 3 seconds; this would produce noticeable pauses.

Color

Color is all around us and adds beauty to our lives. Color and the way we perceive it is an area of research involving many disciplines, including physics, chemistry, physiology, and psychology. One example of our body's role in detecting color is the fact that there is no such thing as white light. What we perceive as white is really the summation of many different colors reaching our eyes. The color of an object is determined by the color, or colors, of the light that enters our eyes and the way that this is interpreted by our brains.

Besides the additive effect within our brain, there is also the issue of what reaches our eyes. If you have ever tried to match the color of two pieces of clothing under different kinds of lighting, you know it can be difficult. They may match very well in the store but be quite different in sunlight. The colors we perceive are determined by two factors: the color present in the illuminating light and the colors reflected by the object. A red sweater is red because the pigments in the dye absorb all colors except red. When viewed under white light, the sweater looks red. If the illuminating light does not contain red, the sweater will appear black because all the light is absorbed. A brightly colored box and dice look different under different illuminating lights (Figure 17-25).

Although most lights give off all colors, the colors do not have the same relative intensities found in sunlight. Fluorescent lights are often brighter in the blue region and therefore highlight blues. At the risk of taking some of the romance out of candlelit dinners, we note that your date's warm glow is due to the yellow-red light from the candles and may have nothing to do with your date's feelings toward you.

Often an object that appears to be a single color reflects several different colors. Although different colors may enter our eyes, we do not see each of these colors. Our eye–brain systems process the information, and we perceive a single color sensation at each location. The color perceived may appear to have nothing in common with the component colors. For instance, if an object reflects red and green, it will appear yellow. This behavior is in sharp contrast with the sense of hearing. Our ear–brain combination can hear and distinguish many different sounds coming from the same place at the same time.

Placing colored filters in front of spotlights or slide projectors and allowing the colored beams from each one to overlap demonstrates the additive effects of color. One combination of light beams that produces most of the colors that we perceive is red, green, and blue. Figure 17-26 illustrates the colors that are seen on the screen. For instance, red and green yield yellow, blue and green yield cyan (a bluish green), and red and blue yield magenta (a reddish purple). All three colors together produce white!

Two colors that produce white light when added together are called **complementary colors.** This process is illustrated by positive and negative color

(a) (b)

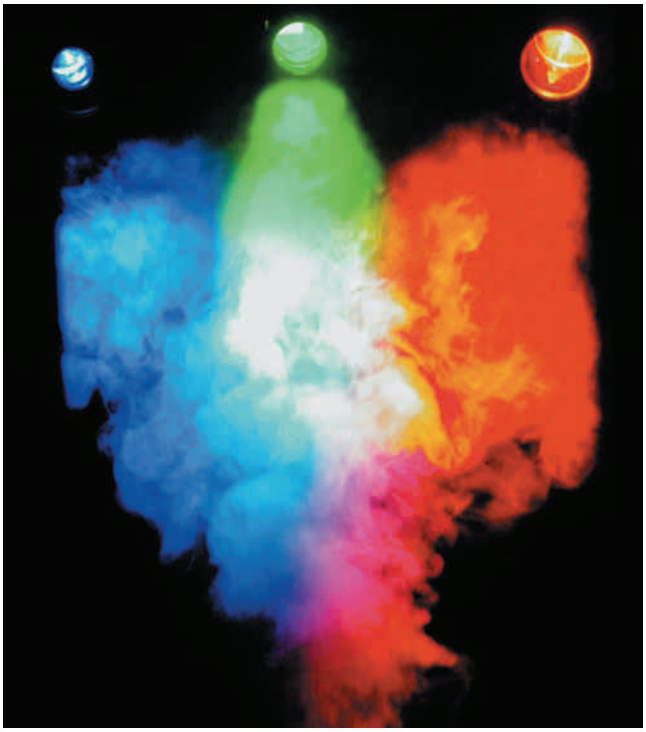
Figure 17-25 (a) A brightly colored box and dice illuminated with yellow light. (b) The same box and dice illuminated with white light.

Are You On the Bus?

Q: What color would you expect to see if you remove some of the blue light from white light?

A: This leaves red and green behind, creating a yellow color.

Figure 17-26 The overlap of colored lights produces new colors.



Courtesy of American Association of Physics Teachers. Photo by Caitlin C. Morgan.

Figure 17-27 The colors in the positive image on the film are the complements of those in the negative image.

film of the same scene; the colors on one are the complements of those on the other, as illustrated in Figure 17-27.

By using dimmer switches to vary the brightness of each beam, we can generate a wide range of colors. This process is the basis of color television. Exam-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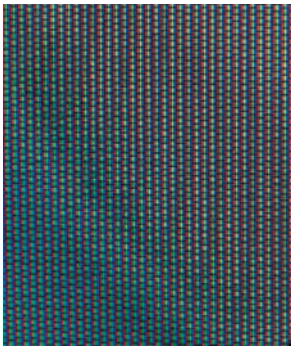
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Figure 17-28 The array of colors on your television comes from the addition of three basic colors—red, green, and blue.

ine a color TV screen with a magnifying glass and you will see that it is covered with arrays of red, green, and blue dots or lines like those in Figure 17-28.

It may seem strange to find that mixing certain colors yields white; from childhood we have learned that mixing many different-colored paints together does not yield white, but rather a dark brownish color. Mixing paints is different from mixing colored lights. Mixing paints is a *subtractive* process, whereas with light beams you are *adding* colors. When white light strikes a red object, the pigment in the object subtracts all colors except red and reflects the red back to the viewer. Likewise, a red filter subtracts all colors except the red that passes through it. Each additional color pigment or filter subtracts out more colors from the incident light. This suggests that the primary colors of light—red, green, and blue—are not the best colors to use as primary colors of paint. Red paint absorbs both green and blue. Magenta paint, on the other hand, reflects both blue and red, absorbing only one primary color of light, green. Likewise, cyan paint absorbs only red and reflects both blue and green, and yellow paint absorbs only blue light and reflects both red and green. Indeed, most color printing is done with four colors of ink—cyan, magenta, yellow, and black. (Although black could be created by combining the other three colors, using a separate black improves image quality.)

FLAWED REASONING

What is wrong with the following statement? "If I take a green banana into a dark room and shine red light on it, it should appear yellow—that is, ripe."

ANSWER It is true that overlapping green and red lights produce yellow. However, green bananas are not a source of green light. Green bananas absorb all colors of light except green, so they appear green under white light. However, if we shine only red light on the bananas, they will absorb this red light and appear black (overripe).

This brief coverage of color perception allows us to answer the questions, Why is the sky blue? and, Why is the Sun yellow? The Sun radiates light that is essentially white. Because it appears yellow, we can assume that some of the complementary color has somehow been removed. The complement of yellow is blue—the color of the sky. The molecules in the atmosphere are more effective in scattering blue light than red light. As the sunlight passes through the atmosphere, more and more of the blue end of the spectrum is removed, leaving the transmitted light with a yellowish color (Figure 17-29). When we look away from the Sun, the sky has a bluish cast because more of the blue light is scattered into our eyes. This effect is enhanced when the rays have a

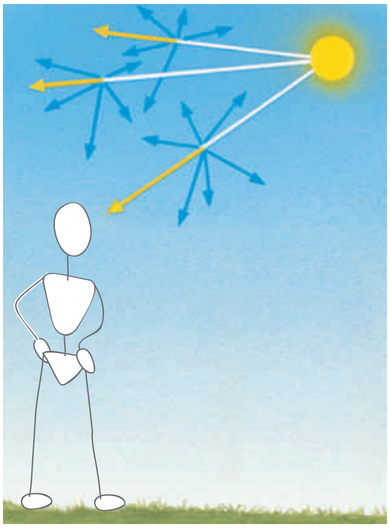


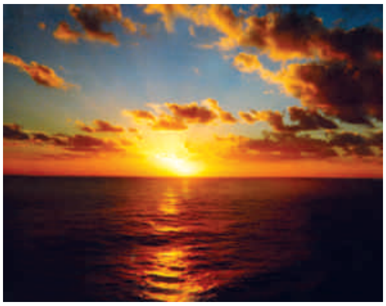
Figure 17-29 The sky is blue and the Sun yellow because air scatters more blue light than red light.

longer path through the atmosphere: the Sun turns redder near sunrise and sunset. The redness also increases with increased numbers of particles in the air (such as dust). The additional dust in the air during harvest time produces the spectacular harvest moons. Although much less romantic, the same effect results from the air pollution near urban industrial sites.

These ideas also account for the color of water. Because water absorbs red light more than the other colors, the water takes on the color that is complementary to red—that is, cyan. Consequently, underwater photographs taken without artificial lighting look bluish green.

Q: If red light were scattered more than blue light, what color would the Sun and sky appear?

A: The sky would appear red because of the scattered light, and the Sun would appear cyan because of the removal of more of the red end of the spectrum.



Courtesy of American Association of Physics Teachers. Photo by Rhian E. Vanderburg.

The sun appears redder as it sets because the sunlight passes through more of the atmosphere.

Summary

Light is seen only when it enters our eyes. Because we know that light travels in straight lines, we can use rays to understand the formation of shadows and images.

When light reflects from smooth surfaces, it obeys the law of reflection, which states that the angles the incident and reflected rays make with the normal to the surface are equal. The reflected ray lies in the same plane as the normal and the incident ray.

Mirrors produce real and virtual images. Light converges to form real images that can be projected, whereas light only appears to come from virtual images. The virtual image formed by a flat mirror is located on the normal to the mirror that passes through the object. The image is located the same distance behind the mirror as the object is in front of the mirror. The sizes of the image and the object are the same.

Images formed by spherical mirrors can be located by drawing three special rays: (1) along the radius—back on itself; (2) parallel to the optic axis—through the focal point; and (3) through the focal point—parallel to the optic axis. The focal point is located halfway between the surface and the center of the sphere.

Light travels through a vacuum at 299,792,458 meters per second.

The additive effects of color mean that adding red and green lights yields yellow, blue and green lights yield cyan, and red and blue lights yield magenta. All three colors produce white. Mixing paints is a subtractive process, whereas mixing light beams is an additive process. The sky is blue and the Sun is yellow because the molecules in the atmosphere preferentially scatter blue light, leaving its complement.

CHAPTER 17 *Revisited*

When light reflects from a smooth mirror or clean piece of glass, its direction is changed, giving the viewer false information about the location of the source of the light. For instance, reflections of the walls of a box make the box appear to be empty when, in fact, a rabbit is hiding behind the mirrors. This is the basis of many visual illusions.

Key Terms

complementary color For lights, two colors that combine to form white.

diffuse reflection The reflection of rays from a rough surface. The reflected rays do not leave at fixed angles.

focal length The distance from a mirror to its focal point.

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

law of reflection The angle of reflection (measured relative to the normal to the surface) is equal to the angle of incidence. The incident ray, the reflected ray, and the normal all lie in the same plane.

light ray A line that represents the path of light in a given direction.

normal A line perpendicular to a surface or curve.

optic axis A line passing through the center of a curved mirror and the center of the sphere from which the mirror is made.

penumbra The transition region between the darkest shadow and full brightness. Only part of the light from the source reaches this region.

real image An image formed by the convergence of light.

umbra The darkest part of a shadow where no light from the source reaches.

virtual image The image formed when light only appears to come from the location of the image.

Questions and exercises are paired so that most odd-numbered are followed by a similar even-numbered.

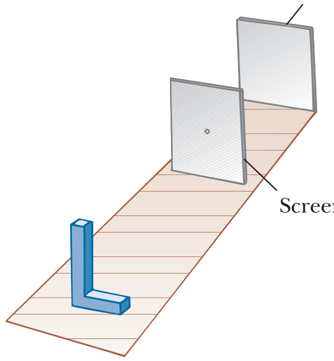
Blue-numbered questions and exercises are answered in Appendix B.

indicates more challenging questions and exercises.

WebAssign **Many Conceptual Questions and Exercises for this chapter may be assigned online at WebAssign.**

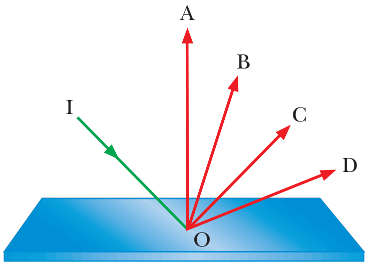
Conceptual Questions

1. A professor shines a light beam across the front of a lecture hall. Why can you see the light on the wall but not in the air?
2. If you shine a laser pointer across the room, you see only a red spot on the far wall. However, you can see the path of the beam if you create a dust cloud with a pair of chalk erasers. Explain how the cloud allows you to see the beam.
3. You place a plane mirror flat on the floor ahead of you and shine a laser beam toward its center. Why do you not see a red dot on the face of the mirror?
4. If you spread a fine layer of dust on the mirror in Question 3, you suddenly see a red dot on the face of the mirror. Why does this happen?
5. Which of the following will cast a shadow that has an umbra but no penumbra: the Sun, a lightbulb, a campfire, or a point source of light? Explain.
6. You hold your hand 3 feet above the ground and look at the shadow cast by the Sun. You repeat this inside using the light from a 2-foot by 4-foot fluorescent light box in the ceiling. In which case will the penumbra be more pronounced? Which of these two sources is acting more like a point source? Explain.
7. You are in a dark room with a single incandescent 60-watt bulb in the center of the ceiling. You hold a book directly beneath the bulb and begin lowering it toward the floor. As the book is lowered, what happens to the size of the umbra?
8. Repeat Question 7 using a 2-foot by 4-foot fluorescent light box in place of the incandescent bulb.
9. Under what conditions will the shadow of a ball on a screen not have an umbra? What does this have to do with the observation that some solar eclipses are not total for any observer on Earth?
10. During some solar eclipses, the angular size of the Moon is smaller than that of the Sun. What would observers on Earth see if they stood directly in line with the Sun and Moon?
11. What effect does enlarging the hole in a pinhole camera have on the image?
12. What happens to the image produced by a pinhole camera when you move the back wall of the camera closer to the pinhole?
13. You form the letter L using two fluorescent light tubes in front of the opening of a pinhole camera as shown in the following figure. Sketch the image formed on the film.

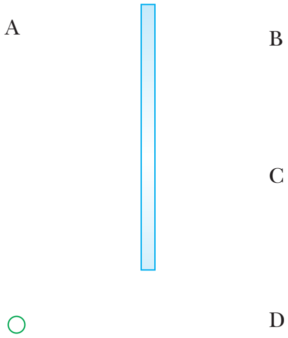


14. You are sitting under a large maple tree on a sunny day. You notice that the light filtering through the leaves does not have the sharp lines you would expect from maple leaves. Instead, the pattern consists of many small round circles of light. Use the concept of a pinhole camera to explain this.

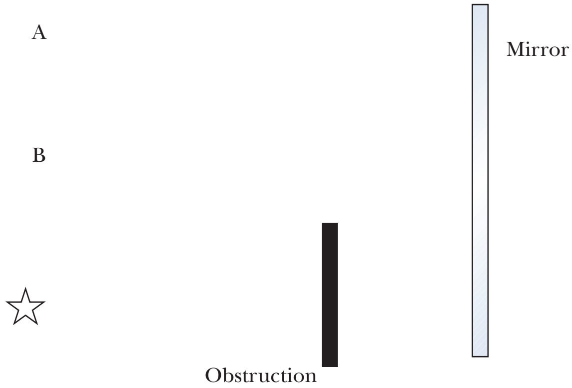
15. When the incident ray IO reflects from the mirror in the following figure, the reflected ray lies along the line O_______.



16. Which letter corresponds to the location of the image of the object O in the following figure?



17. In the following figure, observers at locations A and B are attempting to see the image of the star in the plane mirror. An obstruction is placed in front of the mirror as shown. Which observers, if either, can see the star's image?

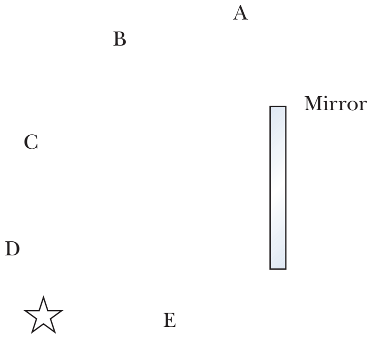


18. In talking about Question 17, Miguel claims, "The star still has an image directly behind the mirror because the light doesn't have to travel from the object to the image." Antonio counters, "The obstruction prevents light from going directly to the mirror, so no image can be formed." Jocelyn argues, "There has to be an image, it just can't be directly behind the obstruction." Which student(s), if any, do you agree with?

19. If a 0.7-meter-tall child stands 0.6 meter in front of a vertical plane mirror, how tall will the image of the child be?

20. How do the size and location of your image change as you walk away from a flat mirror?

21. At which of the lettered locations in the following figure would an observer be able to see the image of the star in the mirror?



22. Where is the image of the arrow shown in the following figure located? Shade in the region where an observer could see the entire image.

23. What is the magnification of a flat mirror? What is its focal length?

24. If you walk toward a flat mirror at a speed of 1.2 meters per second, at what speed do you see your image moving toward you?

25. How does the height of the shortest mirror in which a woman can see her entire body compare with her height? Does your answer depend on how far she stands from the mirror?

26. The word *AMBULANCE* is often written backward on the front of the vehicle so that it can be read correctly in a rearview mirror. Why do we have to switch the left and right but not the up and down?

27. You are standing in a room that has large plane mirrors on opposite walls. Why do the images produced appear to get progressively smaller? Are these images real or virtual?

28. How many images would be formed by two mirrors that form an angle of 45 degrees?

29. Why are the back surfaces of automobile headlights curved?

30. If rays of light parallel to the optic axis converge to a point after leaving the mirror, what kind of mirror is it?

31. Most of us find that we really have to strain our eyes to focus on objects located close to our noses. You hold two mirrors 1 foot in front of your face. One is a plane mirror, and the other is a concave mirror with a 3-inch focal length. In which case are you more likely to have to strain your eyes to see the image of your nose?

32. Can the image produced by a convex mirror ever be larger than the object? Explain.

33. What type of mirror would you use to produce a magnified image of your face?

34. The image produced by a convex mirror is always closer to the mirror than the object. Then why do the convex mirrors used on cars and trucks often have the warning "Caution: Objects Are Closer Than They Appear" printed on them?

35. What are the size and location of the image of your face when your face is very close to a concave mirror? How do the size and location change as you move away from the mirror?

36. If you hold your face very close to a convex mirror, what are the size and location of the image of your face? How do the size and location change as you move away from the mirror?

37. What is the fundamental difference between a real image and a virtual one?

38. Can both real and virtual images be photographed? Explain.

39. You hold a small lightbulb directly in front of a convex mirror. Is it possible for two rays leaving the lightbulb to intersect after reflecting from the mirror? Is the bulb's image real or virtual? Explain.

40. You hold a small lightbulb directly in front of a concave mirror beyond the mirror's focal point. Is it possible for two rays leaving the lightbulb to intersect after reflecting from the mirror? Is the bulb's image real or virtual? Explain.

41. A searchlight uses a concave mirror to produce a parallel beam. Where is the bulb located?

42. What happens to the location of the real image produced by a concave mirror if you move the object to the original location of this image?

43. Why does the arrival of the sound from a bass drum in a distant band not correspond to the blow of the drummer?

44. Astronomers claim that looking at distant objects is the same as looking back in time. In what sense is this true?

45. The Sojourner rover that explored the surface of Mars as part of NASA's Pathfinder mission had to make decisions on its own rather than be driven by remote control from Earth. Why?

NASA

46. Without asking, how could you tell whether you were talking to astronauts on the Moon or on Mars?

47. What color is produced by the overlap of a blue spotlight and a red spotlight?

48. A substance is known to reflect red and blue light. What color would it have when it is illuminated by white light? By red light?

49. A surface appears yellow under white light. How will it appear under red light? Under green light? Under blue light?

50. An actress wears a blue dress. How could you use spotlights to make the dress appear to be black?

51. A Crest toothpaste tube viewed under white light has a red C on a white background. What would you see if you used red light?

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52. When you place a blue filter in the light from a projector, it produces a blue spot on the wall. If you use a red filter, you get a red spot. What would you see on the wall if you passed the light through both filters at once?

53. When you mix red and green light from separate projectors, you get a yellow spot on the wall. However, if you mix red and green paint, you get a muddy brown color. How do you account for this difference?

54. What color do you expect to get if you mix magenta and cyan paints?

55. What is the complementary color to green?

56. What is the complementary color to cyan?

57. If you removed all of the red light from white light, what color would you see?

58. A lens for a spotlight is coated so that it does not transmit yellow light. If the light source is white, what color is the spot?

59. If the atmosphere primarily scattered green light instead of blue light, what color would the sky and Sun appear?

60. How would the color of sunlight change if the atmosphere were much more dense?

Exercises

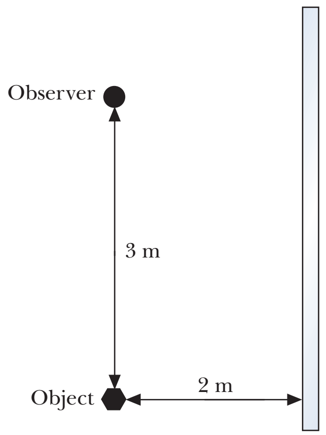
61. A 4-cm-diameter ball is located 40 cm from a point source and 80 cm from a wall. What is the size of the shadow on the wall?

62. A 4-cm-diameter ball is located 50 cm in front of a pinhole camera. If the film is located 10 cm from the pinhole, what is the size of the image on the film?

63. Use a ruler and a protractor to verify that the image produced by a flat mirror is as far behind the mirror as the object is in front.

64. George's eyes are 60 in. from the floor. His belt buckle is 36 in. from the floor. Determine the maximum distance from the floor that the bottom of a plane mirror can be placed such that George can see the belt buckle's image in the mirror. (*Hint:* You can verify that it does not matter how far George stands from the mirror.)

65. An object and an observer are located 2 m in front of a plane mirror, as shown in the following figure. If the observer is 3 m from the object, find the distance between the observer and the location of the object's image.



66. In Exercise 65 find the distance that the light travels from the object to the observer.

67. In the figure associated with Exercise 65, light leaves the object, reflects from the mirror, and reaches the observer. Use a protractor to find the angle of reflection.

68. Use a compass and a protractor to verify that the three rules for drawing ray diagrams for spherical mirrors satisfy the law of reflection.

69. What is the radius of the spherical surface that would produce a mirror with a focal length of 5 m?

70. A telescope mirror is part of a sphere with a radius of 3 m. What is the focal length of the mirror?

71. An object is located three times the focal length from a concave spherical mirror. Draw a ray diagram to locate its image. Is the image real or virtual, erect or inverted, magnified or reduced in size? Explain.

72. An object is located midway between the focal point and the center of a concave spherical mirror. Draw a ray diagram to locate its image. Is the image real or virtual, erect or inverted, magnified or reduced in size? Explain.

73. A 6-cm-tall object is placed 60 cm from a concave mirror with a focal length of 20 cm. Draw a ray diagram to find the location and size of the image.

74. How would your answer to Exercise 73 change if the same object were 120 cm from a concave mirror with a focal length of 40 cm?

75. Draw a ray diagram to locate the image of a 10-cm-tall object located 90 cm from a convex mirror with a focal length of 45 cm.

76. How would your answer to Exercise 75 change if the same object were 30 cm from a concave mirror with a focal length of 15 cm?

77. A convex mirror has a focal length of 60 cm. Draw a ray diagram to find the location and magnification of the image of an object located 30 cm from the mirror.

78. Repeat Exercise 77 for a concave mirror.

79. If you place an object 40 cm in front of a concave spherical mirror with a focal length of 20 cm, where will the image be located?

80. You have a concave spherical mirror with a focal length of 30 cm. Where could you place a candle to make it appear to burn at both ends?

81. If Galileo and his assistant were 15 km apart, how long would it take light to make the round-trip? How does this time compare with reaction times of about 0.2 s?

82. Suppose Galileo, in the experiment described in Exercise 81, had assumed that the entire 0.2-s delay was due to the travel time of light rather than to his assistant's reaction time. What value would he have calculated for the speed of light?

83. Approximately how long would it take a telegraph signal to cross the United States from the East Coast to the West Coast? (Telegraph signals travel at about the speed of light.)

84. Mars and Earth orbit the Sun at radii of 228 million km and 150 million km, respectively. When, in the future, your friend from Mars calls you on the phone and you answer, "Hello," what are the minimum and maximum times you will have to wait for your friend to reply?

85. How far does light travel in 1 year? This distance is known as a light-year and is a commonly used length in astronomy.

86. How far does light travel in 1 nanosecond—that is, in one-billionth of a second?