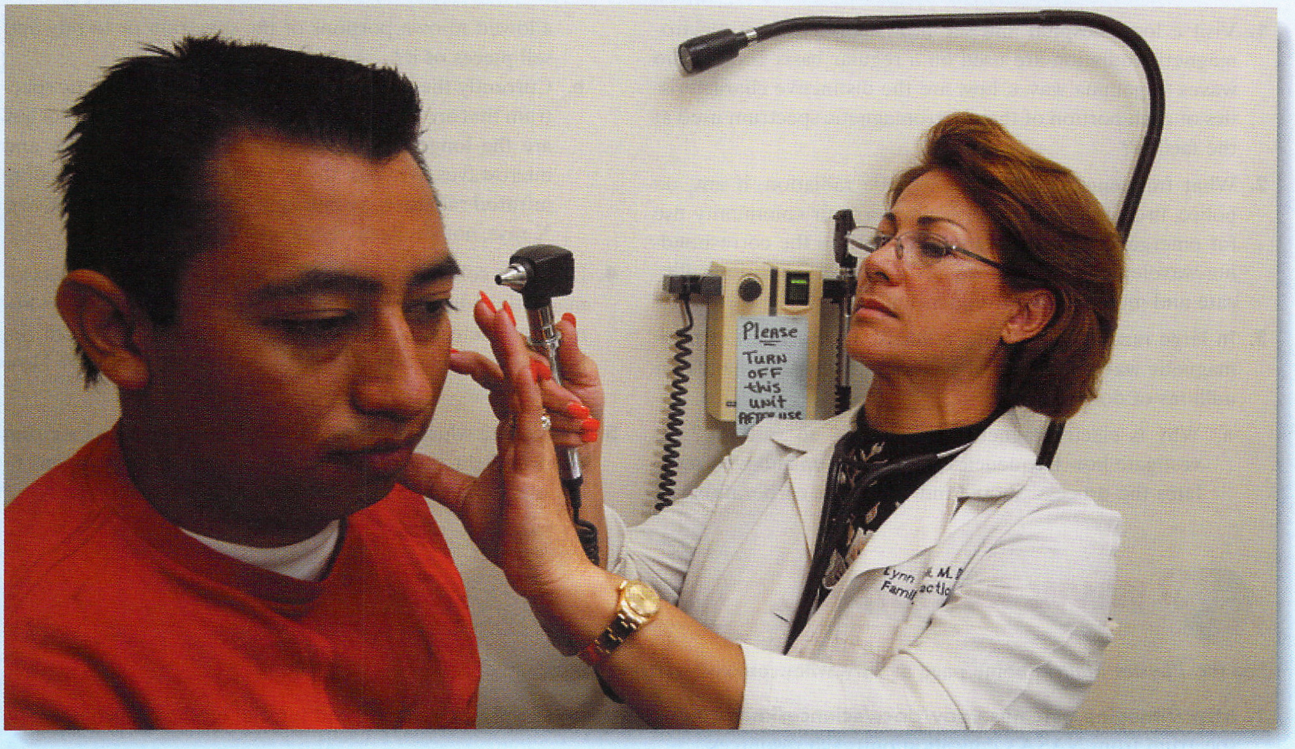
20 Classical and Modern Optics

KEY IDEA

Mirrors, lenses, and other optical devices alter the paths of electromagnetic waves by scattering, transmission, and absorption.



Physics Around Us . . . A Day in the Life

You pass your physical checkup easily this year. The X rays of the knee ligaments you tore last year show they have healed well. You won't need arthroscopic surgery after all. Examination of your blood under a microscope indicates you have a normal range of red and white cells. Your doctor puts on his reading glasses to sign your form, saying you're in excellent health. As you put on your clothes, you smile at yourself in the mirror; no health problems for you this year.

That night you celebrate the good news by heating up a pizza in the microwave and watching a movie on TV. The new satellite dish is working fine and reception is great. In the middle of the movie you get a call from a friend spending a semester abroad in Europe. Her voice is carried to you on cables laid across the floor of the Atlantic Ocean.

Many of the devices you've seen or used today—the X-ray machine, the arthroscopic surgery instrument, the microscope, the doctor's glasses, the mirror, the microwave, the satellite dish, the telephone cables, even your eyes themselves—involve applications of the principles of optics, both classical and modern.

ELECTROMAGNETIC WAVES AND MATTER

Interactions between electromagnetic waves and matter encompass some of the most important phenomena in physics and daily life. We rely on the entire electromagnetic spectrum, from radio waves to gamma rays, in countless ways—in cooking, communications, space exploration, medical diagnosis, surgery, and the full range of scientific and artistic pursuits (see Physics and Daily Life—Optics, page 420). Interactions between light and matter provide the foundation for what we know about the natural world. This chapter examines some of these interactions.

Recall some of the distinctive properties of electromagnetic waves. In a vacuum or in a uniform medium (and in the absence of a large mass), electromagnetic waves travel in straight lines. In a vacuum, all of these waves travel with the same speed, the *speed of light,* designated by *c*. As we have seen in Chapter 19, there is a reason for these sorts of similarities. All electromagnetic waves have basically the same structure (crossed electric and magnetic fields) and they differ from one another only in wavelength and frequency. This similarity means that although visible light is the most familiar electromagnetic wave, every device that we use to control the light we see (the lenses in eyeglasses, for example, or the mirror in your bathroom) has an analogous device to control other parts of the spectrum.

The challenge facing researchers is to devise means to produce, detect, and change the direction of electromagnetic waves in every part of the spectrum. Devices such as lenses and mirrors that are used to alter and control electromagnetic radiation are collectively called *optical devices* or **optics.** (We should note that the term *optics* is used to refer both to the field of physics devoted to the behavior of electromagnetic radiation and to the apparatus used to study and control that behavior.) Originally, the term *optics* was applied only to devices that work on visible light. That's hardly surprising since, for most of the history of science, light was the only electromagnetic wave known. Today, the term *optics* has been broadened to include the entire spectrum, so we can speak of "X-ray optics" or "microwave optics."

The interactions between electromagnetic waves and matter make it possible to build a wide variety of optical devices. Radiation interacts with matter in three principal ways:

1. The radiation can be scattered from the material's surface.
2. The radiation can be absorbed by the material.
3. The radiation can be transmitted through the material, often changing direction in the process.

All these processes are familiar from our everyday experience with light.

In describing the way that light and other kinds of electromagnetic radiation move through devices, it is often convenient to visualize the direction in which the wave is moving rather than the wave itself. For example, if, as shown in Figure 20-1, a series of crests and troughs are moving to the right, then we can represent the motion of the wave by following the path of a particular point on a wave crest, as shown. In this way, a single line replaces the entire crest and trough structure of the wave. The line that traces the motion of the wave is called a **ray.** In much of this chapter we are concerned with tracing rays of light and other kinds of electromagnetic radiation through various kinds of optical systems.

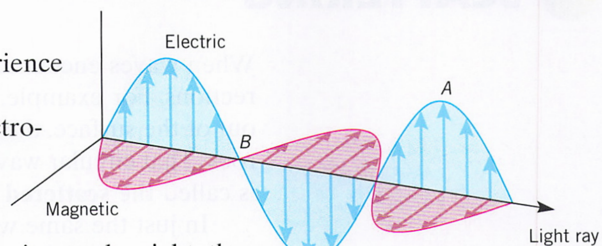
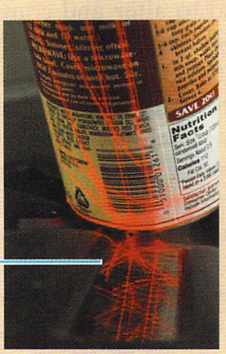


FIGURE 20-1. The motion of a light wave can be represented as a line that traces the motion of the wave, called a *ray*.

Physics and Daily Life–Optics

Our lives are surrounded by electromagnetic waves, from light to radio to infrared. The laws of **optics**—reflection, absorption, and refraction—are so common that we hardly notice them; they are part of the way things are. If you look around you, you can find them in operation everywhere.



SCATTERING

When waves encounter material bodies, they often scatter in many different directions. For example, when a water wave on a lake encounters a rock sticking out of the surface, the wave produces an outgoing circular wave centered on the rock. That circular wave, moving in a direction different from the incoming wave, is called the **scattered** wave.

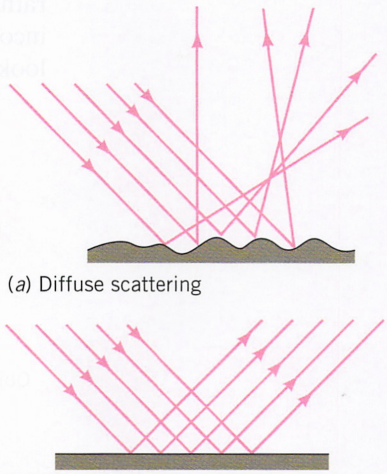
In just the same way, when electromagnetic waves encounter obstacles, they scatter as well. Most familiar surfaces scatter light in many different directions—a process called *diffuse scattering* (Figure 20-2*a*). White surfaces are particularly efficient at scattering visible light diffusely. In the same way, the interior of your microwave oven is specially designed to scatter microwaves efficiently so that they reach all parts of the food being heated.

Waves scattered by a rock produce circular waves.

Perhaps the most important optical device that scatters light is the **mirror,** which relies on a scattering process known as **reflection.** When a beam of parallel light rays encounters a smooth mirrored surface, the scattered light rays are also parallel (Figure 20-2*b*). As shown in Figure 20-3, we define the *angle of incidence* as the angle that the direction of the incoming radiation makes with a line drawn perpendicular to the surface. Similarly, the *angle of reflection* is the angle that the direction of the reflected radiation makes with that same perpendicular. A simple rule relates these two angles:

The angle of incidence equals the angle of reflection.

For a beam of light encountering a smooth mirrored surface, this rule explains how it is that we see a reflected image when we look at the mirror. Light rays from neighboring points on an illuminated object (such as your face) travel in all directions. However, consider two rays from neighboring points on your face that take parallel paths to the mirror. If these parallel light rays strike the mirror at a particular angle, then they are reflected in parallel light rays at the same angle. Because the light rays travel in parallel bundles, when they arrive at your eye they allow you to see an undistorted image of the object being reflected. An ordinary flat mirror works this way.



(*a*) Diffuse scattering

(*b*) Reflection

FIGURE 20-2. (*a*) Diffuse scattering of light rays off an irregular surface. (*b*) Reflection of light rays off a flat mirror surface.

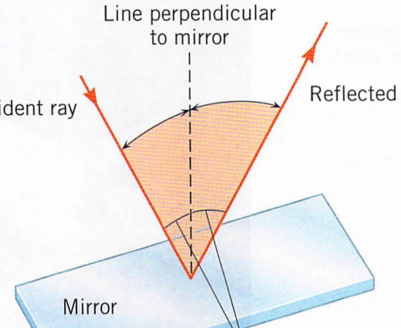


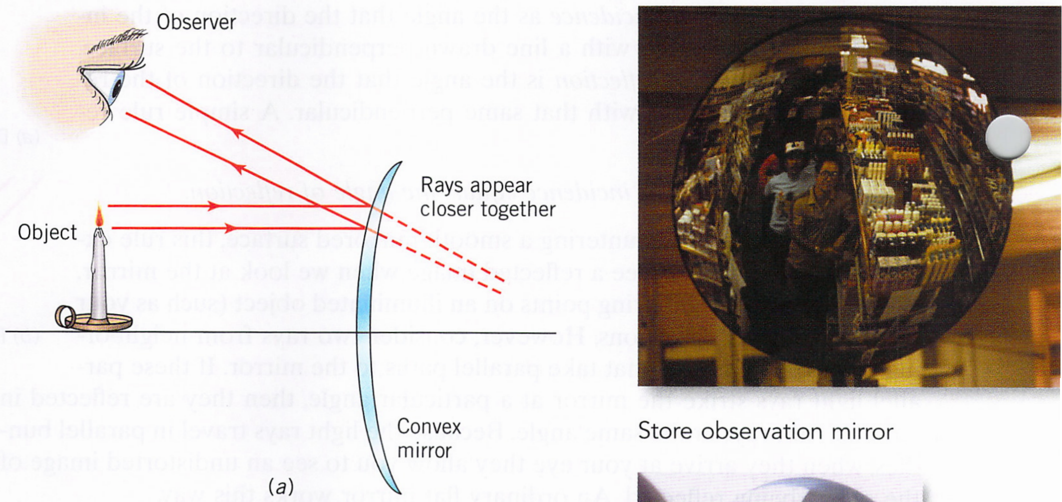
FIGURE 20-3. A light ray strikes a mirror at the angle of incidence, which is the angle that the direction of the incoming radiation makes with a line drawn perpendicular to the surface. Similarly, the angle of reflection is the angle that the direction of the reflected radiation makes with that same perpendicular. The angle of incidence equals the angle of reflection.

Develop Your Intuition: Mirror Image Reversal

Why is it that when you look at your face in the bathroom mirror, the image is reversed (that is, the right side of your face appears on the left side of the image, and vice versa)?

Because it is reflected, the light that comes to your eyes from the left side of your face appears to come from a point behind the right side of the mirror. The analogous situation occurs for light from the right side. Thus, the image appears reversed. Convince yourself of this by holding up your right hand in front of a mirror and seeing how its image appears.

We can learn several important lessons from the simple process of light's reflection from a mirror. When you look at a mirror image, there's nothing to tell your eye that it is not seeing light coming directly from the illuminated object, rather than being reflected from a mirror. Consequently, your brain interprets the incoming light signals as indicating the position of a real object. Thus, to you it looks as if the object is located behind the plane of the mirror. This tendency of



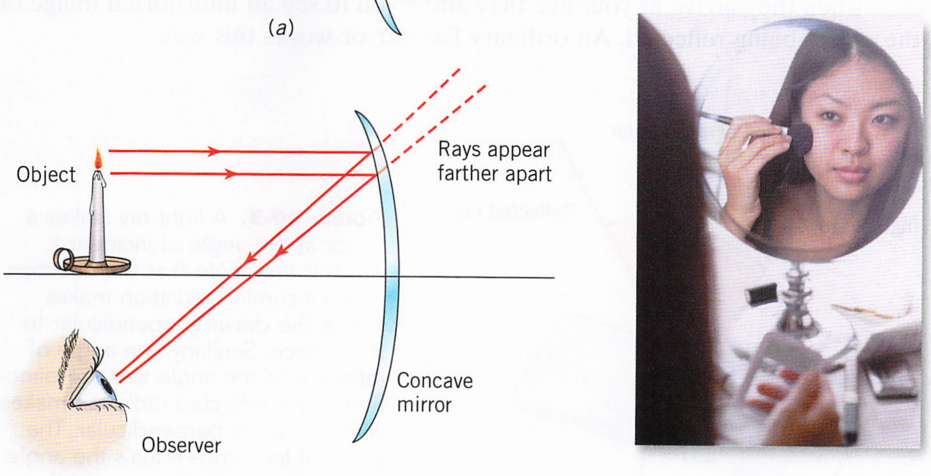


Figure 20-4. Curved mirror surfaces. (*a*) A *convex* mirror, which bows outward, makes an object appear smaller than it really is. This kind of mirror is often used in stores to survey large areas of the store from one place. (*b*) A *concave* mirror bows inward and makes an object appear larger than it really is. This kind of mirror is used for shaving mirrors and cosmetic mirrors.

the eye to see objects by tracing back along straight light rays plays an important role in understanding several optical illusions we discuss later in the chapter.

Some useful mirrors are not plane surfaces, but are curved in some way. For example, in Figure 20-4*a* we show a person in front of a *convex mirror*—one that bows outward. In this case, we can still consider rays from neighboring points on the object (the candle flame) that travel in parallel lines to the mirror, but they strike at points where the directions of the perpendiculars to the mirror surface are different, as shown. The angle of incidence, in other words, is different for the two rays and so are the angles of reflection. Once the rays have left the mirror, they no longer travel in parallel lines. When your eye receives these rays, it traces them back along the direction of travel and (mistakenly) assumes that the two neighboring points on the object are closer together than they really are. You see the object as being smaller than it really is. This kind of mirror is often used in stores to survey large areas of the store from one place.

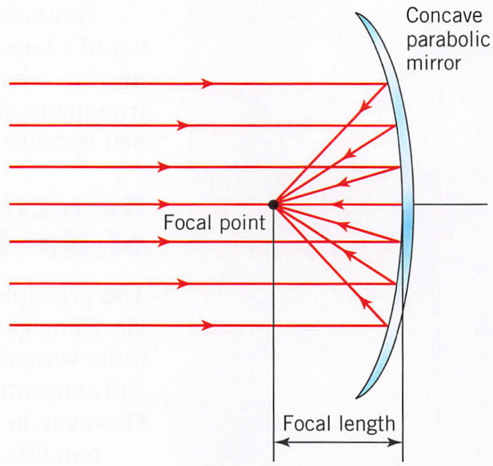
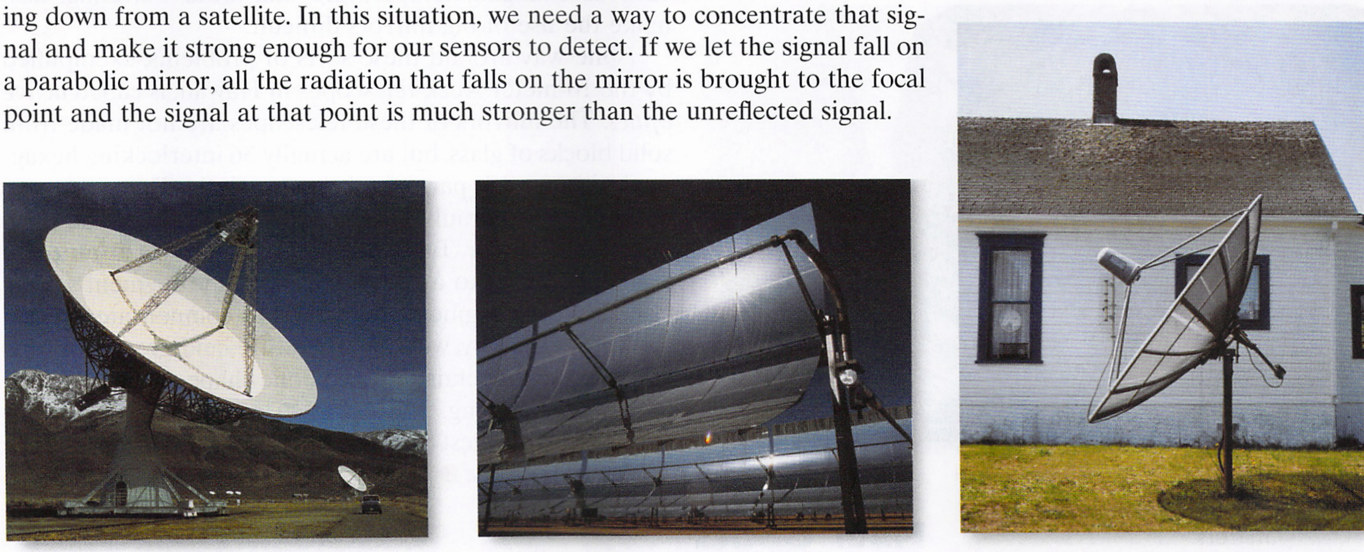


FIGURE 20-5. A concave parabolic mirror focuses incoming parallel rays to a focal point. The distance between the mirror and the focal point is the focal length.

A mirror curved the other way—a *concave mirror*—produces exactly the opposite effect. As shown in Figure 20-4*b,* someone standing close to the mirror sees adjacent points farther apart than they really are and hence sees an object as larger than it really is. This kind of mirror is used for shaving mirrors or cosmetic mirrors.

Some concave mirrors have another interesting property. If parallel rays of light fall on a concave mirror that is shaped like a parabola, all the reflected rays pass through a single point, as shown in Figure 20-5. The point at which all the rays are focused is called the *focal point* of the mirror, and the distance between the mirror and the focal point is called the *focal length.*

Parabolic mirrors are useful in many situations. It often happens that we have a weak signal—a faint light source, for example, or a weak microwave signal beaming down from a satellite. In this situation, we need a way to concentrate that signal and make it strong enough for our sensors to detect. If we let the signal fall on a parabolic mirror, all the radiation that falls on the mirror is brought to the focal point and the signal at that point is much stronger than the unreflected signal.



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

A variety of devices employ parabolic mirrors, including (*a*) radio telescopes, (*b*) solar energy collectors, and (*c*) satellite TV receivers.

Parabolic mirrors are the basis for many important devices. Most of the world's large astronomical telescopes, for example, are built around parabolic mirrors, which collect and focus the light of distant stars and galaxies. The astronomers' slang for these telescopes—"light buckets"—tells us that they are valued because they can collect large amounts of light and focus it.

Reflection in Other Parts of the Electromagnetic Spectrum

The principle of scattering for visible light can be applied to other parts of the electromagnetic spectrum as well. For example, radio telescopes (which monitor radio waves emitted by distant sources) also rely on parabolic dishes that reflect and concentrate radio waves at the focal point, where a receiver measures them. However, in this case the radio waves are reflected from a mirror made of metal.

Satellite dishes, which detect microwaves, operate on the same principle. Weak microwave signals sent from satellites are reflected by the parabolic surface of the dish and focused at one point. Next time you see one of these dishes, look for the receiver suspended above the dish, precisely at the focal point.

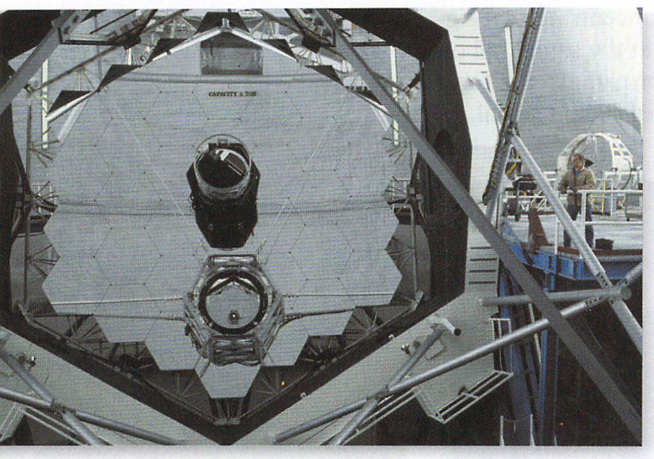
Infrared and ultraviolet radiation can also be reflected off mirrorlike surfaces. In fact, you may have noticed a curved metal reflector at the back of a space heater.

Connection
Active Optics

Large telescope mirrors capable of collecting large amounts of light pose special technical problems for engineers. For one thing, a mirror made from a single block of glass is very heavy. Not only does this weight make it difficult to move, but gravity causes the glass to sag, destroying the parabolic shape. Other effects, such as changing temperature and wind buffeting, also make the use of big mirrors difficult.

One way around these sorts of problems, exemplified by the 10-meter Keck telescopes in Hawaii, is called *active optics.* The mirrors of these telescopes are not made from solid blocks of glass, but are actually 36 interlocking hexagonal pieces, each part of a large parabola. The pieces are mounted on hydraulic supports that can change the position of the mirror. Twice each second, sensors around the segments report to a computer about the segment's position, and each segment is adjusted to compensate for distortions caused by wind, temperature, and gravity. In this way, the mirror retains its parabolic shape, even when the telescope is moving.

All of the largest modern land-based telescopes now use similar technology. ●



The Keck Telescopes in Hawaii employ multiple mirrors.

Fiber Optics

When light moves from a more dense to a less dense medium (from glass to air, for example), the ray bends away from a line perpendicular to the boundary surface. This is a process called *refraction.* If the light approaches the surface at a large enough angle, this bending can make light skim along a material's surface,

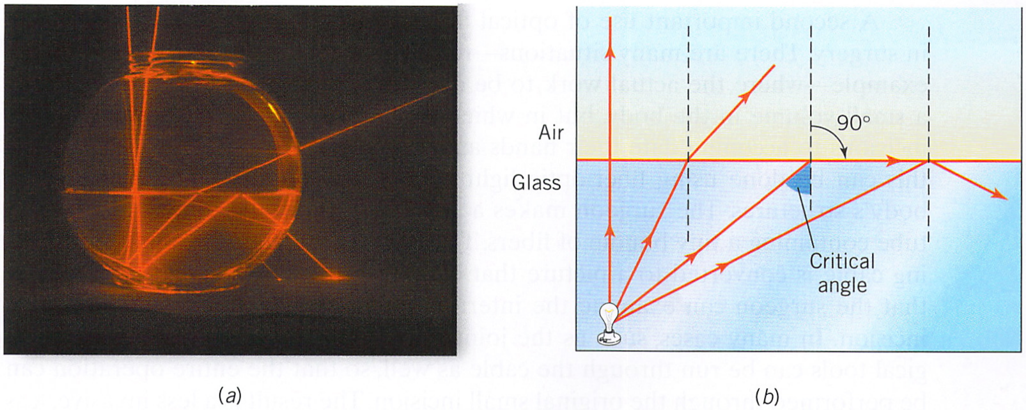


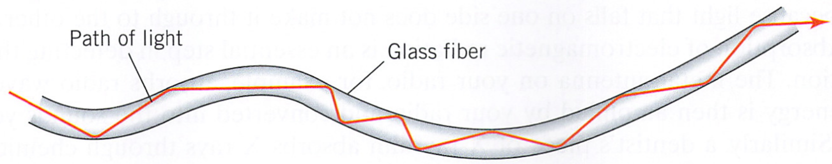
FIGURE 20-6. Total internal reflection occurs when the angle of incidence becomes larger than a critical value. In this case, the light is not able to leave the material but is reflected back inward.

as shown in Figure 20-6. If the angle of incidence becomes larger than this critical value, the light is not able to leave the material but is reflected back inward. This phenomenon, known as *total internal reflection,* is the basis for modern fiber-optic technology.

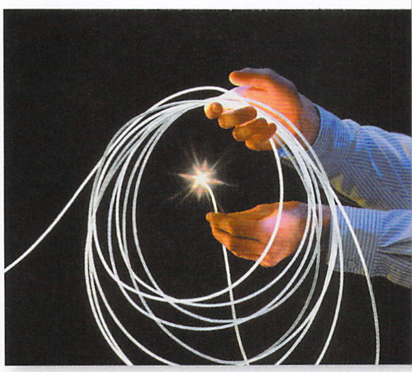
The basic working principle of **fiber optics,** shown in Figure 20-7, is that a beam of light enters a long glass fiber at one end, but traveling at such an angle that each time it reaches the glass–air surface, it is reflected back into the glass. Thus, whatever enters one end of the fiber comes out the other end.

Today, in the most efficient optical fibers, the density of the glass fiber is made to vary from the long central axis to the outside so that the light actually follows the kind of wavy path shown in Figure 20-7*a*. In this way optical fibers can transmit almost 100% of their light from one end to the other.

Fiber optics finds critical uses in many modern technologies. As we have seen in Chapter 19, the wavelength of visible light is quite short—only a few hundred billionths of a meter. This short wavelength makes it possible to pack a lot more information into a light signal of a given length than into much longer radio waves or waves traveling through copper wires. Consequently, if we send signals via light waves in optical fibers, we can pack a lot more information into each fiber and carry a much heavier load. A typical copper wire, for example, can transfer tens of thousands of phone conversations, while an optical fiber can carry upward of half a million. The first commercial optical-fiber phone line was installed in downtown Chicago in 1977; today the majority of long-distance phone calls are transmitted in this way.



(a)



(b)

FIGURE 20-7. (*a*) In an optical fiber, a beam of light enters a long glass fiber at one end, traveling at such an angle that each time it reaches the glass–air surface, it is reflected back into the glass. In modern optical fibers, the material is designed in such a way the the index of refraction of the glass is different near the edge than it is at the center. The light is bent gently as it approaches the edge rather than being reflected. Optical fibers can reflect almost 100% of a light beam from one end to the other. (*b*) Optical fibers used in microsurgery.

A second important use of optical fibers has been in medicine, particularly in surgery. There are many situations—removing torn cartilage from a joint, for example—where the actual work to be done in the surgical procedure involves a small volume in the body, but in which surgeons used to have to make large incisions to accommodate their hands and scalpels. Today, microsurgery such as this can be done using fiber-optic light sources to illuminate and observe the body's structures. The surgeon makes a small incision in the body and inserts a tube containing a tiny bundle of fibers. The light traveling out through the twisting cable is converted to a picture that can be shown on a TV-like monitor, so that the surgeon can examine the interior of the body without making a large incision. In many cases, such as the joint surgery already mentioned, small surgical tools can be run through the cable as well, so that the entire operation can be performed through the original small incision. The result is a less invasive, less traumatic experience for the patient and usually leads to a much more rapid recovery than conventional surgery. So common has this sort of procedure become that it is often referred to by the slang term "Band-Aid surgery" because after it is over only an ordinary Band-Aid is needed to cover the wound.

ABSORPTION AND TRANSMISSION

When electromagnetic waves travel through matter, they do not behave in the same way as they do in a vacuum. The waves, after all, consist of electric and magnetic fields, and matter consists of atoms made from electrically charged particles such as electrons. These electrons can absorb energy from the wave—for example, the wave's electric fields can accelerate the electrons. Depending on how the atom is put together and the way in which it is bonded to other atoms in the material, several things can happen.

The energy that the electron absorbs from the wave may be converted to many different forms, since all forms of energy are interchangeable (see Chapter 12). For example, the energy from the wave might eventually find its way into kinetic energy of atoms in the material. In this case, the electric and magnetic energy in the wave is reduced and the thermal energy in the material increases. The intensity of the electromagnetic wave diminishes as it passes through the material and the temperature of the material increases.

In some materials, all the energy in the wave is converted into thermal energy or other forms of energy and the wave simply disappears. In this case, we call the process **absorption.** Materials that absorb or scatter electromagnetic radiation that falls on them are said to be **opaque**—that is, they are materials that do not allow the radiation to pass through them. A sheet of metal, for example, is opaque to light because light that falls on one side does not make it through to the other.

Absorption of electromagnetic radiation is an essential step in detecting that radiation. The metal antenna on your radio, for example, absorbs radio waves; that energy is then amplified by your radio and converted into the sounds you hear. Similarly, a dentist's piece of X-ray film absorbs X rays through chemical reactions that ultimately produce lighter and darker regions on the film. Those light and dark areas correspond to parts of your teeth that absorb greater and lesser numbers of X rays and thus reveal cavities. But you don't need to rely on modern technology to make this point. Go outside on a sunny day and you'll find that your skin is an excellent absorber of both infrared radiation (which you feel as heat) and ultraviolet radiation (which gives you a sunburn).

Electromagnetic waves can undergo a very different fate than absorption when encountering matter. It is possible that the wave, even though it loses energy, actually emerges from the other side of the material. In this case we call the process **transmission** and say that the material is **transparent.** A pane of ordinary window glass is an example of a material that is transparent to visible light because light from the outside easily passes through so that you can see what is on the other side.

Think about everyday phenomena that use electromagnetic radiation and you'll realize that many materials must be transparent to these waves. For example, your radio works inside your house or school; that means that walls, floors, carpeting, and windows must be transparent to radio waves. Earth's atmosphere is transparent to a wide range of electromagnetic radiation, including most wavelengths of radio waves, microwaves, and visible light. Fortunately for us, the atmosphere effectively absorbs most harmful ultraviolet radiation and X rays.

Having made the distinction between transparent and opaque materials, however, we have to make a couple of points:

1. It is possible for a material to be transparent for one wavelength of radiation, but opaque for another. Ordinary window glass, for example, readily transmits radiation at the wavelengths of visible light but is opaque to radiation in the infrared. This effect explains the operation of a greenhouse, by which the Sun's radiation warms the interior of a greenhouse, which then emits infrared radiation. Much of that heat energy is prevented from escaping quickly back into space because the glass is opaque to that wavelength. A similar phenomenon is the basis for the greenhouse effect (see Chapter 11).

2. Many intermediate situations are possible between complete transparency and complete opacity. A pane of clean, high-quality window glass is almost completely transparent, but when it is dirty more of the incoming light is absorbed. It's still more or less transparent, but not as transparent as it was. This fact, after all, is why we routinely clean the windshields of our cars. Thus, it's better to think of transparent and opaque as two extremes on a continuum, with most materials falling somewhere in between.

REFRACTION

When light is transmitted through a material substance, its path and speed may change in significant ways. These changes in direction and speed are called **refraction,** and they form the basis of countless optical devices, including eyeglasses, cameras, microscopes, and binoculars.

Because of the fact that electromagnetic radiation interacts with atoms when it passes through different materials, the radiation moves through these materials more slowly than it does in a vacuum. An analogy (although not an exact one) may help you think about why an electromagnetic wave travels more slowly in matter than in a vacuum. Imagine that two travelers arrive at an airport on the East Coast of the United States, both bound for the same airport on the West Coast. One takes a direct cross-country flight; the other changes planes, first in Chicago and then in Denver, before coming to his destination. While both travelers move at exactly the same speed while they are in the air, the one on the direct flight clearly arrives at the destination more quickly. An outside observer would therefore say that the traveler on the direct flight was moving faster (had a higher velocity) than the one who changed planes.

In just the same way, the individual waves discussed here all move at the same speed as they would in a vacuum between atoms, but the net effect of the interference process is, on average, to slow the wave down.

Index of Refraction

If the speed of an electromagnetic wave in a particular material is v, then the **index of refraction,** n, of that material is given by the following expression:

1. In words:

The index of refraction of a material is the ratio of the speed of the wave in a vacuum divided by the speed of the wave in that material.

2. In an equation with words:

$$\text{Index of refraction} = \frac{\text{Speed in vacuum}}{\text{Speed in material}}$$

3. In an equation with symbols:

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

Since light always travels more slowly in materials than in a vacuum, the index of refraction is always a number greater than 1. A few typical values are given in the following table.

Material	n
Air	1.0003
Water	1.33
Ethyl alcohol	1.36
Crown glass	1.52
Table salt	1.53

EXAMPLE 20-1

Light in the Water

How fast does light travel in water?

SOLUTION: In a vacuum, light travels at a speed of 3×10^8 m/s. In water, the index of refraction is 1.33, as listed in the table. Then the definition of the index of refraction tells us that

$$1.33 = \frac{3 \times 10^8 \text{ m/s}}{v}$$

where v is the speed of light in water. This means that

$$v = \frac{3 \times 10^8 \text{ m/s}}{1.33}$$

$$= 2.25 \times 10^8 \text{ m/s}$$

This value is three-fourths of light's speed in a vacuum. ●

The fact that radiation travels at different speeds in different materials means that the direction of a wave's motion changes when it passes through a boundary between one material and another. This effect is the basis for refraction.

Another analogy may help you understand refraction. Imagine horses racing across an open meadow, with each horse running at exactly the same speed, so that they stay neck and neck as they move. You can think of the line of horses as marking the crest of a wave.

Now suppose that, as in Figure 20-8, there is a marsh along one edge of the field—a marsh in which the horses get bogged down and move more slowly. As each horse enters the marsh, it slows down, while the horses in the open field keep running at their original pace. The result, as shown, is that the line wheels around as more and more horses enter the marsh. Eventually, the horses are neck and neck again, but the line is moving in a different direction.

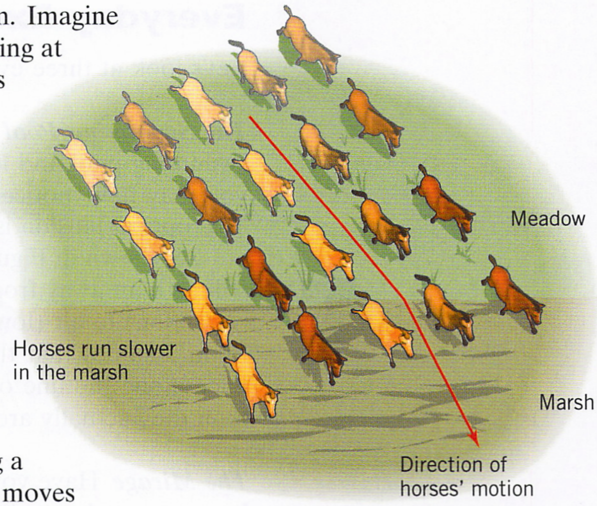


FIGURE 20-8. A line of horses traveling from a field to a marsh appears to change direction as the horses entering the marsh slow down. The same phenomenon is demonstrated by light rays traveling from a material of lower to higher index of refraction.

In just the same way, an electromagnetic wave entering a medium with a high index of refraction wheels around and moves in a different direction. The easiest way to picture the behavior of such a wave is to imagine each bit of the wavefront emitting its own little wave, with these waves undergoing interference to reconstruct the wave front farther along. As shown in Figure 20-9, while the wave is in a medium with a low index of refraction (i.e., a medium in which the speed of light is high), the wavefront moves forward because of the interference of the wavelets. When the wave reaches the second material, however, the wavelets generated by that part of the wavefront travel more slowly. Just like the line of horses encountering the marsh, the wavefront wheels around and changes direction.

If we trace the ray corresponding to the wave encountering the boundary, we get a diagram such as that shown in Figure 20-9*b*. We can make two qualitative statements about the behavior of radiation at a boundary:

1. When a wave moves from a medium with a low index of refraction to one with a high index of refraction, its direction of motion moves closer to a line perpendicular to the surface.

2. When a wave moves from a medium with a high index of refraction to one with a low index of refraction, its direction of motion moves farther from a line perpendicular to the surface.

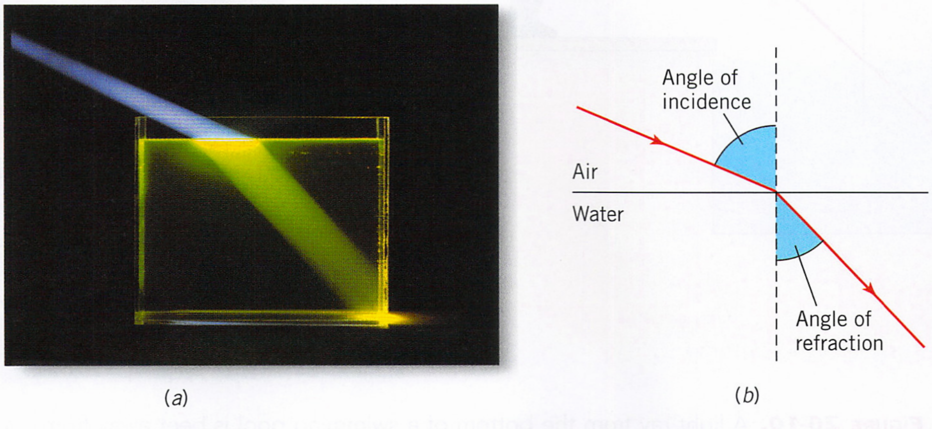


FIGURE 20-9. A light ray bends at the boundary of materials with higher and lower refractive indices.

Everyday Examples of Refraction

Let's look at three everyday examples of refraction.

The Swimming Pool You may have had the experience of standing next to a swimming pool and looking at a friend standing in the water. In this situation, you may have noticed that her legs appear to be shorter than they really are. This optical illusion is a consequence of refraction.

As shown in Figure 20-10, a light ray from the bottom of your friend's feet will be bent away from the perpendicular as it moves from water (high index of refraction) to air (low index of refraction). When this ray enters your eye, your brain assumes that the actual location of her foot can be obtained by tracing back along the line of the ray. Thus, to you, it appears that her feet are higher than they actually are.

The Mirage Have you ever had the experience of driving along a highway on a hot summer day and seeing a stretch of highway ahead of you that looks as if it were covered with water? If you have, you know that when you actually get to the "wet" spot, it turns out to be ordinary dry highway, while the "wet" spot has moved farther ahead. This phenomenon is an example of a *mirage*.

A mirage works like this: The air near the highway is heated and has a lower index of refraction than the cooler air higher up. Thus, light entering this air is bent away from the perpendicular, as shown in Figure 20-11. Because the air gets hotter the closer it is to the ground, this bending is a continuous process, since the light enters layers with successively lower indices of refraction.

Eventually, the direction of the incoming light is turned completely around,

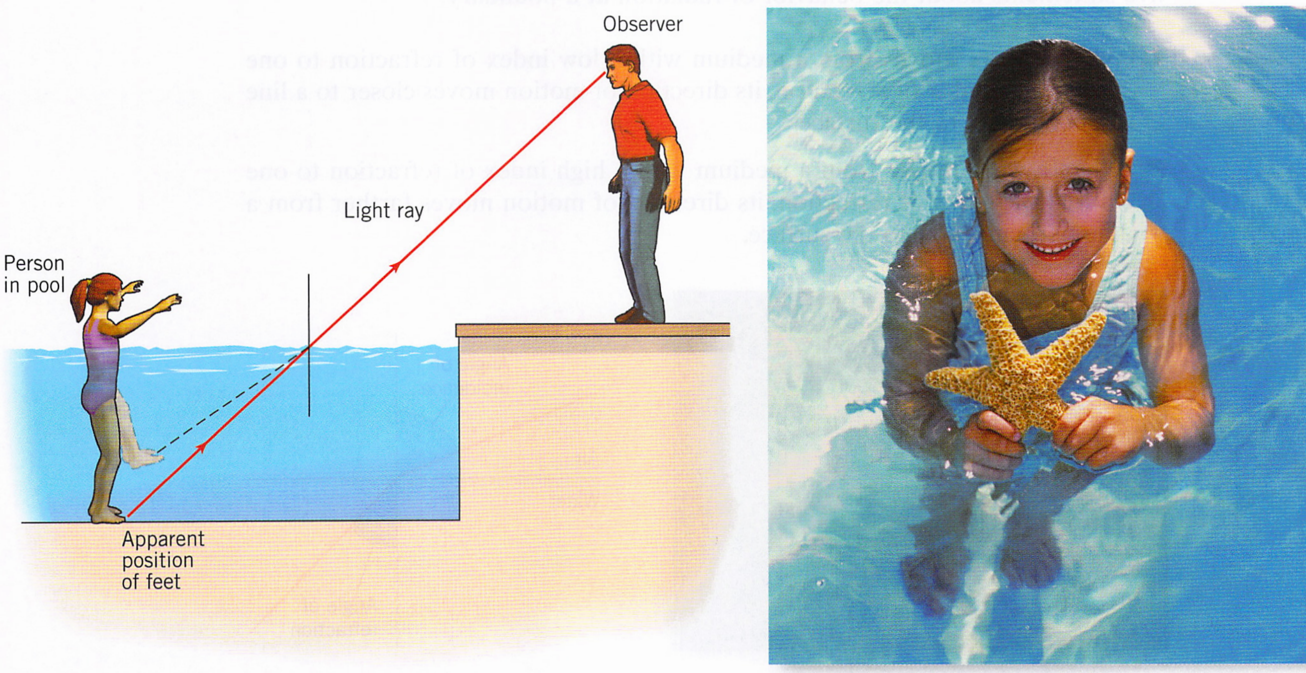
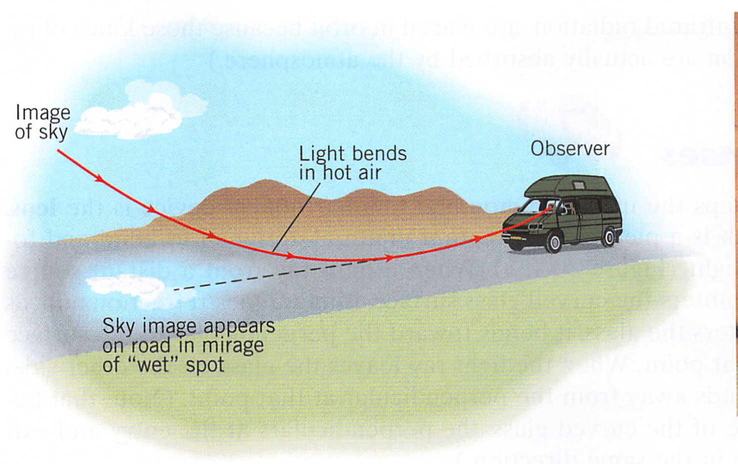


FIGURE 20-10. A light ray from the bottom of a swimming pool is bent away from the perpendicular as it moves from water (high index of refraction) to air (low index of refraction). To you it appears that the pool is shallower than it actually is.



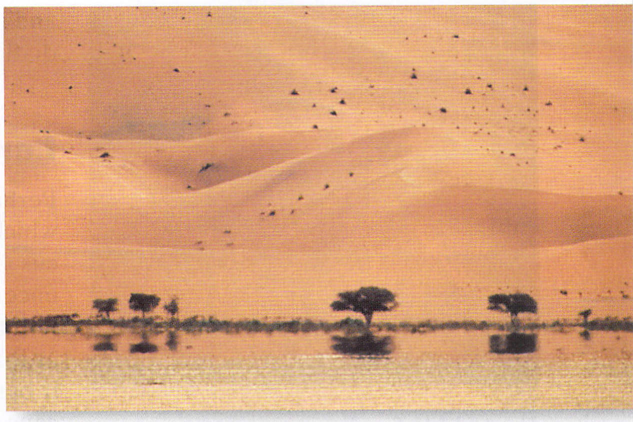


FIGURE 20-11. A mirage occurs when air near the ground is heated and has a lower index of refraction than the cooler air higher up. Thus, light entering this air is bent away from the perpendicular. What you see is light from the sky whose direction has been changed by refraction.

as shown. When the light rays enter your eye, you trace them backward and think that they are coming from a spot on the highway ahead of you. In actuality, you are seeing light from the sky—light whose direction has been changed by refraction.

Develop Your Intuition: A Green Mirage

If you are driving toward a forested mountain, the highway mirage may look green. Where do you suppose that light originated?

The green light originated on the mountainside and was refracted up to your eye. The green you see is actually the color of the leaves on the trees.

Twinkling Stars The fact that the index of refraction of air changes with temperature also explains another common experience, the twinkling of stars at night. Stars are very far away, so they can be thought of as point sources of light (because even though the stars are big, the distance to the stars is very much larger than the size of any star). As a ray of light makes its way through the atmosphere, it encounters currents of air of different temperatures and is refracted this way and that. Thus, the ray that finally comes to your eye in one instant has followed a circuitous course, as shown in Figure 20-12, and the star appears to be at the position labeled A. A ray coming through a split second later encounters a different pattern of air temperatures, however, so it follows a slightly different path and appears to be at the nearby position B. As a result of the movement of the atmosphere, then, the position of the star seems to shift around—a phenomenon that the eye interprets as twinkling.

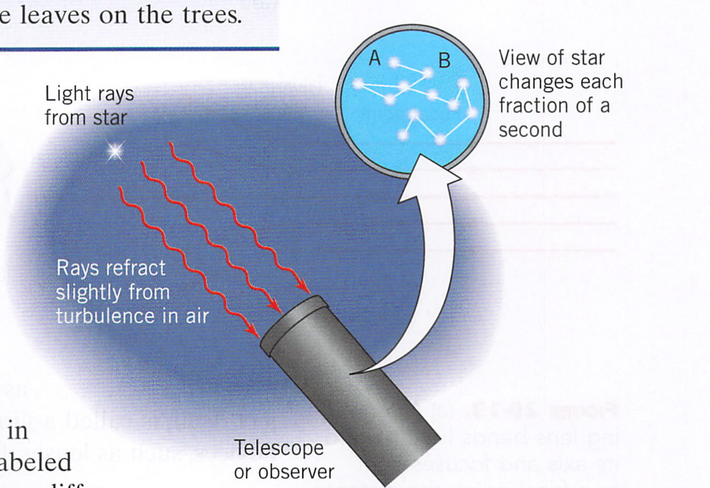


FIGURE 20-12. The twinkling of stars at night arises from the fact that the index of refraction of air changes with temperature. As a ray of light makes its way through the atmosphere, it encounters currents of air of different temperatures and is refracted this way and that. Your eye interprets this phenomenon as twinkling.

Needless to say, twinkling has always been a problem for astronomers, and it explains why they put so many major observatories above the atmosphere, where refraction will not take place. The Hubble Space Telescope is an excellent example of this approach. Located over 100 miles above Earth's surface, the Hubble Space Telescope intercepts light rays before they have a chance to be refracted by the atmosphere. (Other satellite observatories, such as those for X rays

The Hubble Space Telescope.

and infrared radiation, are placed in orbit because those kinds of radiation are actually absorbed by the atmosphere.)

Lenses

Perhaps the most common and familiar optical device is the **lens,** which is a piece of transparent material designed to bend and focus light (Figure 20-13*a*). When a light ray from a distant source encounters the curved glass surface, it undergoes refraction and, as it enters the glass, it bends toward the perpendicular to the surface at that point. When the light ray leaves the glass on the other side, it bends away from the perpendicular at that point. (Note that because of the curved glass, the perpendiculars at the entry and exit points do not go in the same direction.)

An observer standing on the other side of the lens sees the light ray coming at an angle, as shown, and assumes that the light originated at a point above the top of the actual object. Thus, the observer sees the object as larger than it actually is. This basic principle is employed in numerous devices, including magnifying glasses, eyeglasses, and binoculars.

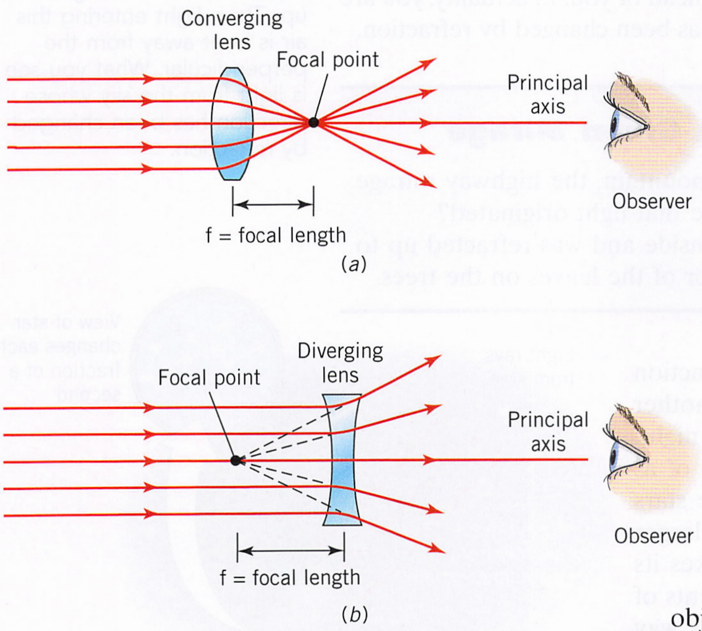


FIGURE 20-13. (*a*) A converging lens bends light toward its axis and focuses light to a focal point; the distance between the focal point and the lens is its focal length. (*b*) A diverging lens bends light away from the axis, so that someone looking through the lens sees what appears to be an object in back of the lens. Light rays moving along the axis in the center of the lens are not bent.

A lens like the one shown, which bends light rays toward its axis, is called a *converging lens.* If parallel rays of light from a distant source fall on the lens, then all the light is brought together at a single point, as shown in Figure 20-13*a*. The point at which all the light rays come together is called the *focal point* of the lens, and the distance between the focal point and the lens is called its *focal length.*

Another kind of device, shown in Figure 20-13*b*, is called a *diverging lens.* Rays of light entering this sort of lens are bent away from the central axis, so that someone looking through the lens sees what appears to be an object in back of the lens, as shown. An image such as this, where light rays do not actually originate on the object itself, is called a *virtual image.* A virtual image cannot be affected by other devices, such as lenses, farther along in the optical system.

Connection
Telescopes and Microscopes

Lenses occur in many important scientific instruments. In Figure 20-14, we sketch two kinds of telescopes. In Figure 20-14*a*, we see the sort of parabolic collecting mirror we have already discussed. Telescopes like this, based on the principle of reflection, are called *reflecting telescopes.* Another design, shown in Figure 20-14*b*, focuses light through a lens—an arrangement known as a *refracting telescope.*

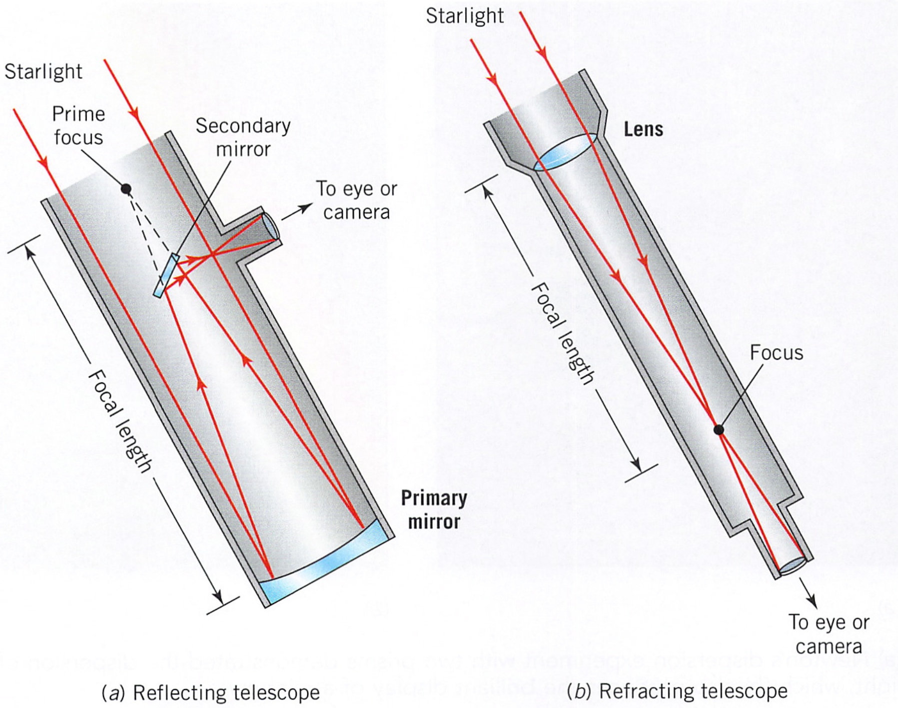


FIGURE 20-14. Two kinds of telescopes. (*a*) Telescopes based on the principle of reflection are reflecting telescopes. (*b*) Telescopes that focus light through lenses are refracting telescopes.

Because it is easier to build large mirrors than large lenses, the biggest astronomical telescopes—those intended to capture as much light as possible—are designed as reflectors. On the other hand, many small telescopes used by amateur astronomers and bird watchers are refractors.

The *microscope* is a device designed to magnify images. In a classical optical microscope such as the one shown in Figure 20-15, a strong light beam shines through a thin sample—a slide with biological tissue on it, for example, or a thin slice of rock—and is then focused through a series of converging lenses. The result is that the image is magnified, so that objects much too small to be seen with the naked eye become visible. ●

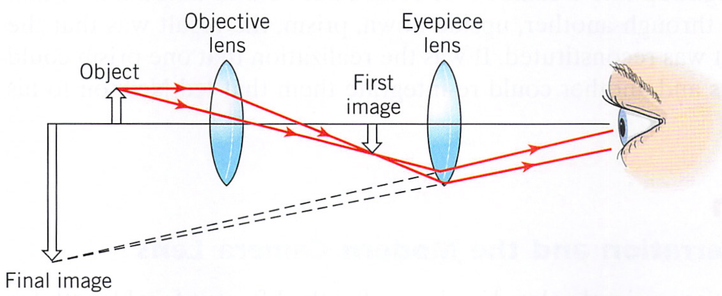
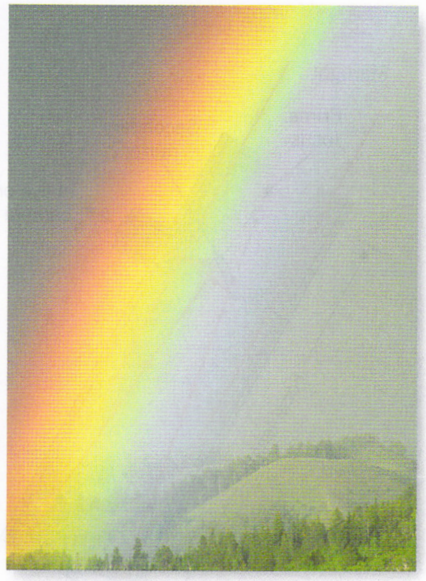


FIGURE 20-15. An optical microscope employs a sequence of lenses to magnify small objects.

(a)



(b)

(a) Newton's dispersion experiment with two prisms demonstrated the dispersion of light, which (b) also produces the brilliant display of a rainbow.

Dispersion

Thus far we have treated the index of refraction as a single number for a given material that is applicable to all wavelengths. If this were true, the world would be a far less colorful place than it is. Numerous optical phenomena, including majestic rainbows and the brilliant sparkle of diamonds, are the result of a process called *dispersion.*

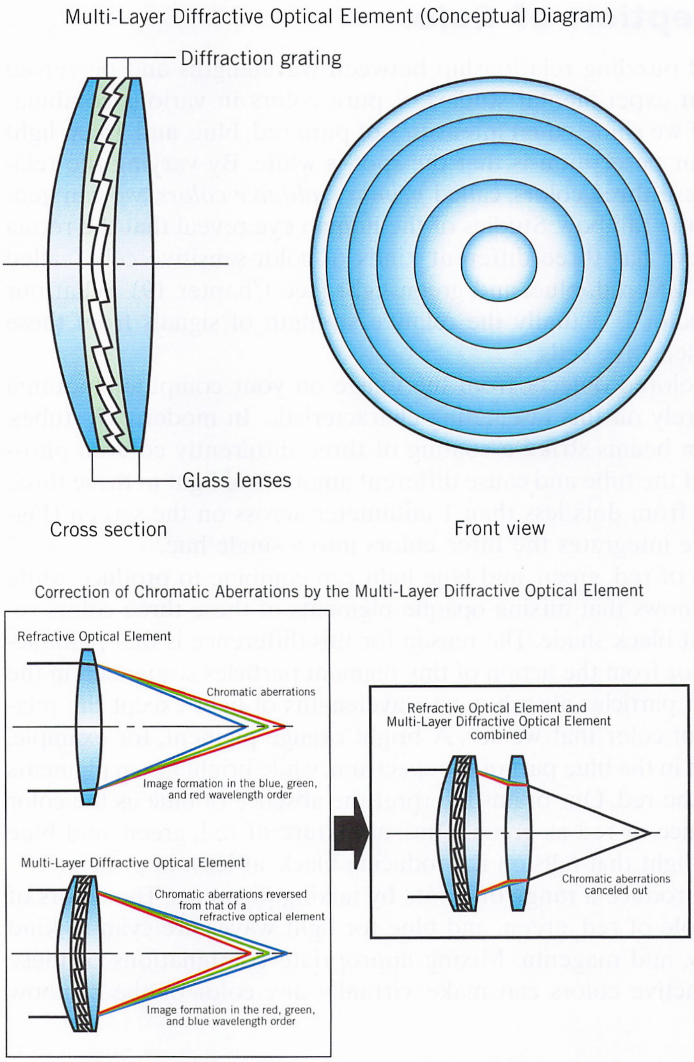
In general, the index of refraction of materials does depend on the wavelength of the radiation. When visible light enters glass, for example, long wavelengths are bent less than short ones. This phenomenon, known as **dispersion,** explains why a glass prism or raindrops in the atmosphere can break up sunlight, which is a mixture of all wavelengths, into a rainbow of colors. Longer-wavelength red light, for example, is bent least at both faces of the prism, so in the end it has been bent through a different angle than the other colors.

It's an interesting historical fact that Isaac Newton not only observed that a prism breaks sunlight up into a rainbow of colors, but he also noted that if that rainbow were put through another, upside-down, prism, the result was that the original white light was reconstituted. It was the realization that one prism could separate the colors and another could re-integrate them that led Newton to his theory of color.

Connection

Chromatic Aberration and the Modern Camera Lens

Because of dispersion, a simple glass lens has a slightly different focal length for different colors. In practical terms, this difference means that if such a lens were put into a camera, you would see halos of different colors surrounding every object in a picture. This unwanted effect is known as *chromatic aberration.*



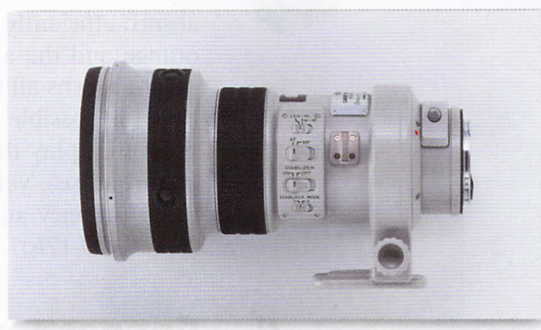


FIGURE 20-16. In modern cameras, chromatic aberration is corrected by placing a second lens made of a different glass behind the primary lens. A good camera lens today may have up to six nested lenses to correct for this and other kinds of aberrations.

In modern cameras, chromatic aberration is corrected by placing a second lens made of a different glass behind the primary lens, as shown in Figure 20-16. In fact, a good camera lens today may have up to six nested lenses to correct for this and other kinds of aberrations. ●

A WORLD OF COLORS

Color is one of the most familiar, yet most complex, optical phenomena. As we have seen in Chapter 19, the visible portion of the electromagnetic spectrum can be described simply in terms of the wavelength of the electromagnetic wave. The longest wavelengths correspond to red light, whereas the shortest wavelengths correspond to violet. All visible light consists of some combination of these wavelengths. However, it is important to realize that the phenomena our eyes and brains perceive as colors are related to wavelengths of light in a rather indirect way.

Human Perception of Color

The remarkable and puzzling relationship between wavelengths and perceived colors emerged from experimental studies of pure colors in various combinations. For example, if we shine equal intensities of pure red, blue, and green light on the same spot, our perception is that the spot is white. By varying the relative intensities of these three colors, called *primary additive colors,* we can generate every color of the rainbow. Studies of the human eye reveal that the retina in the back of the eye has three different kinds of color-sensitive cells, called "cones," that respond to red, blue, and green light (see Chapter 19). What our minds interpret as color is actually the relative strength of signals from these three kinds of light-sensitive cells.

Many familiar colored objects, from the image on your computer terminal to the comic pages, rely on this fascinating characteristic. In modern TV tubes, for example, electron beams strike a coating of three differently colored phosphors on the inside of the tube and cause different amounts of light in these three colors to be emitted from dots less than 1 millimeter across on the screen (Figure 20-17*a*). Your eye integrates the three colors into a single hue.

Although beams of red, green, and blue light can combine to produce white light, every painter knows that mixing opaque pigments of these three colors results in a dark, almost black shade. The reason for this difference is that paint acquires its brilliant color from the action of tiny pigment particles suspended in the liquid. These pigment particles absorb most wavelengths of light except the relatively narrow range of color that we see. A bright orange pigment, for example, typically absorbs light in the blue part of the spectrum, while bright green pigments absorb efficiently in the red. Our brains interpret the absence of blue as the color orange and the absence of red as green. Thus, a mixture of red, green, and blue paint absorbs all the light that falls on it, producing black, at least in principle.

It is possible to produce a range of colors by mixing pigments. The colors of paint that play the role of red, green, and blue for light waves are cyan (a kind of turquoise), yellow, and magenta. Mixing appropriate combinations of these three primary subtractive colors can make virtually any color of the rainbow (Figure 20-17*b*).

Connection

Four-Color Printing

A book such as this one, with many color pictures in it, is printed by a process called four-color printing. You might ask why we need four colors to make the pictures in a book or magazine when there are only three primary subtractive colors. The reason is a practical one. Although mixing the three colors together, as previously described, produces black in principle, in practice it is very difficult to get a pleasing shade of black in this way. Consequently, a fourth color, black, is added to the palette to produce color pictures that are pleasing to the eye. ●

The Physics of Color

All kinds of interactions between light and matter—scattering, transmission, and absorption—depend on the wavelength of the electromagnetic radiation. For example, a piece of green stained glass preferentially absorbs red wavelengths but is transparent to green wavelengths. Similarly, your favorite red sweater absorbs

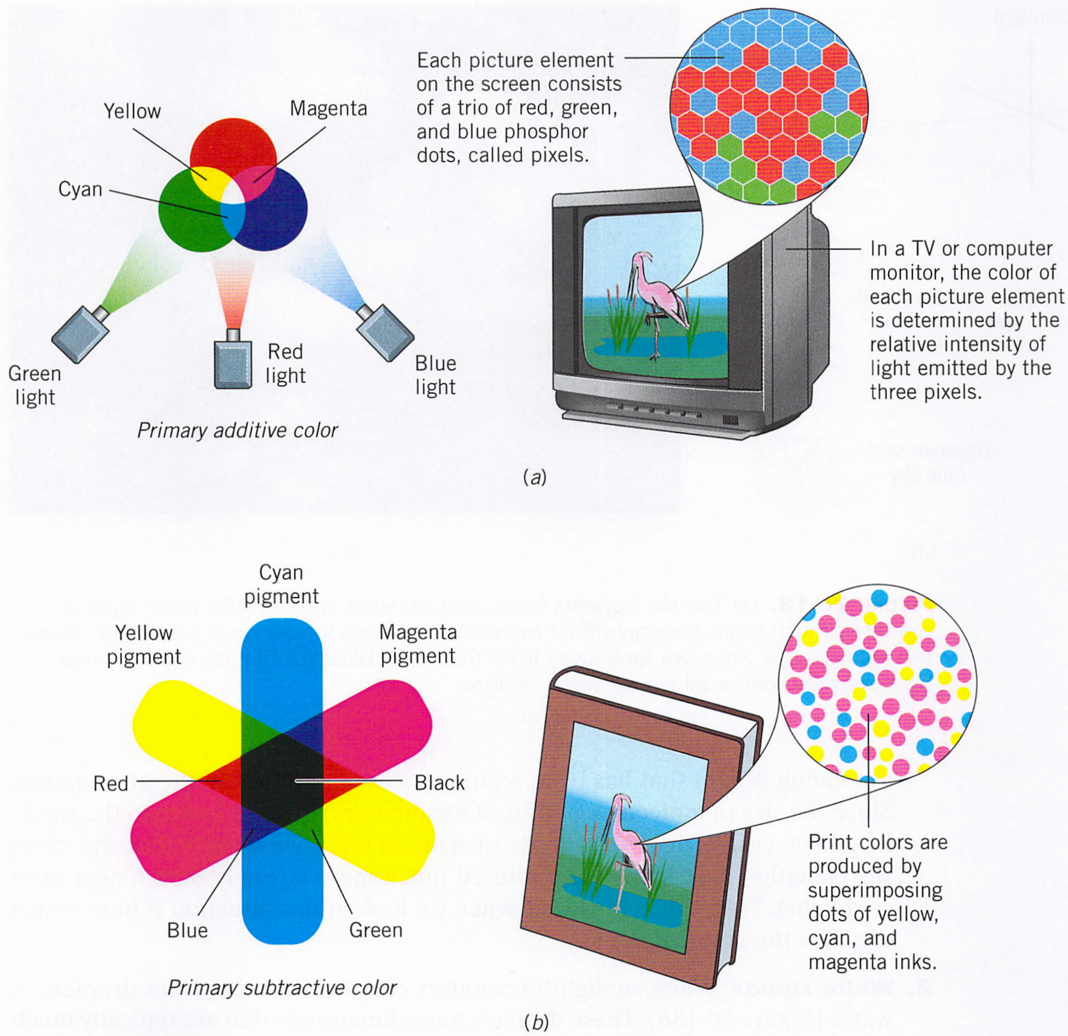


FIGURE 20-17. (*a*) The colors of many objects, including television screens, are produced by combining dots of the three primary additive colors—red, green, and blue. (*b*) Color printing combines dots of the three primary subtractive colors—cyan, yellow, and magenta.

green light but scatters red light. Every colored object absorbs, transmits, and scatters different wavelengths of light differently.

Let's consider three of the most familiar examples—blue sky, white clouds, and red sunsets—all of which are governed by the scattering of white light from the Sun. Two general rules govern the scattering of electromagnetic waves. First, if the object causing the scattering is much smaller than the wavelength of the radiation, then shorter wavelengths are scattered much more strongly than longer ones. Second, if the object causing the scattering is much larger than the wavelength of the radiation, then all wavelengths are scattered equally.

1. Blue sky Why does the daytime sky appear blue? As shown in Figure 20-18*a*, when you look at the sky in a direction away from the Sun, what you

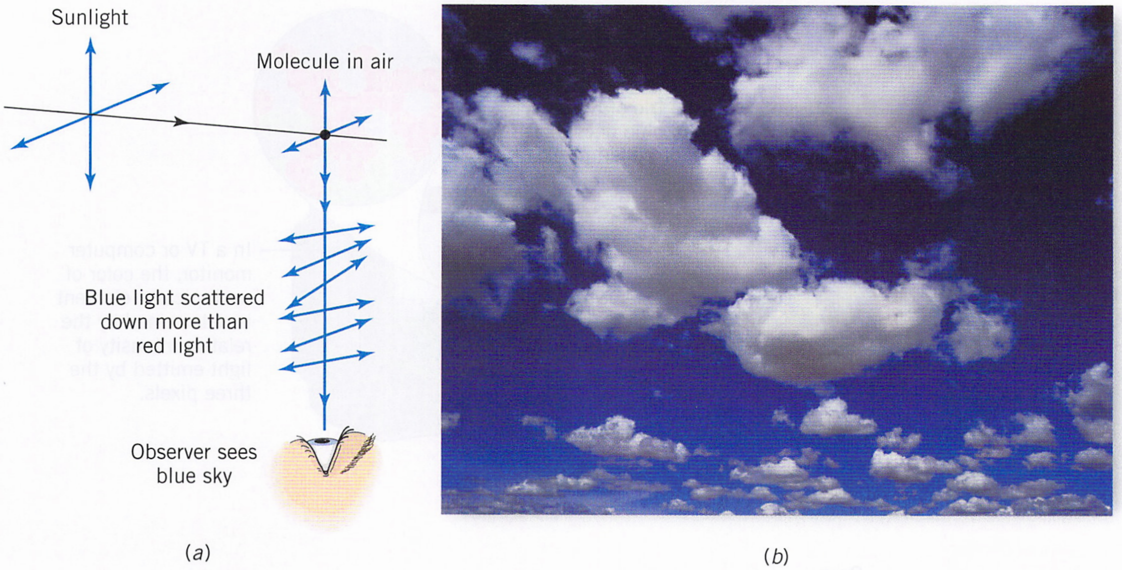


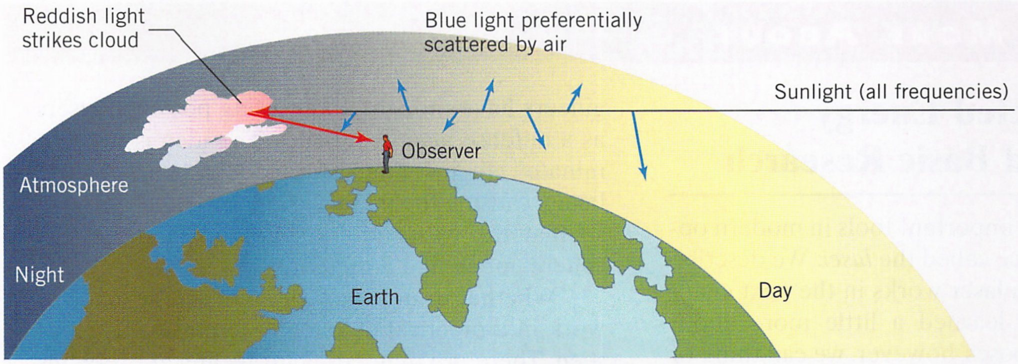
FIGURE 20-18. (*a*) The sky appears blue because short wavelengths (blue light) are scattered much more strongly off air molecules than are longer ones (red light). Thus, the light we see when we look away from the sun is blue. (*b*) Clouds appear white because they scatter all wavelengths of light.

are seeing is light that has been scattered from molecules in the atmosphere. Since the size of molecules (tenths of nanometers) is much less than the wavelength of visible light (hundreds of nanometers), we expect that the short wavelengths (blue light) are scattered much more strongly than longer ones (red light). Thus, the light we see when we look in this direction is blue, which explains the color of the sky.

2. **White clouds** When sunlight encounters clouds, it scatters from droplets of water (Figure 20-18*b*). These droplets have dimensions that are typically much larger than the wavelengths of visible light, although their size varies. The net result is that light of all colors is scattered equally from the cloud and the clouds appear white.

3. **Red sunsets** Light from the Sun is white—a collection of all visible wavelengths. As that light comes through the atmosphere, the blue light is scattered out of the beam (making the sky appear blue). What remains is light that is predominantly yellow, which explains the daytime appearance of the Sun. Toward sunset, however, the light from the setting Sun has to travel through much more of the atmosphere (Figure 20-19), so more scattering occurs. Once the blue has been removed from the beam, the yellow and green follow, leaving only the red light in the beam. This gradual filtering explains the appearance of the Sun at sunset.

You can see an interesting application of the rules for scattering by looking at the sky above a large city. Typically, the sky directly overhead looks blue, but near the horizon it is often a hazy white. The reason for this is that the sky above the city is normally full of tiny particles of dust and other material. Light



(a)

(b)

FIGURE 20-19. (a) Light from the Sun is white, but blue light is scattered out of the beam (making the sky appear blue). Toward sunset, however, the light from the Sun has to travel through much more of the atmosphere, so more scattering occurs. Once the blue has been removed from the beam, the yellow and green follow, leaving only the red light in the beam. (b) This gradual filtering explains the appearance of the Sun at sunset.

coming from the horizon, then, has travelled a long distance through these particles. It is a mixture of the normal blue light coming from atmospheric scattering and the many wavelengths resulting from scattering by the particles. As a result, the normal blue is washed out, and the sky appears a pale white.

THINKING MORE ABOUT

Optics: Directed Energy Weapons and Basic Research

One of the most important tools in modern optics is the device called the *laser.* We describe the details of how a laser works in the next chapter, after we have learned a little more about atoms. For our purposes, however, we can think of a laser as a device that produces a powerful beam of electromagnetic radiation, usually in the form of visible light.

You have undoubtedly seen lasers in use. They are often used as pointers in classroom lectures, for example—they produce a red spot on the screen—and they are used extensively to produce visual effects at rock concerts. They are also widely used as surgical tools in medicine, as we see in Chapter 21, and as cutting tools in industry, to name a few modern applications.

They also have a presence, although less benign, in science fiction. The phaser in the *Star Trek* series, for example, is a weapon modeled on the laser, as are countless clones in other movies and TV shows. The development of the laser as a weapon, however, is not just fiction. It has played a very real role in modern military research.

The basic idea behind what are called directed energy weapons is simple. An intense beam of electromagnetic radiation is directed toward a target, which absorbs the energy of the beam. If the beam is powerful enough, the target will be weakened—a metal target, for example, might actually melt. For this reason, some scientists and engineers have thought about using powerful lasers as a defense against missiles. The idea is to "illuminate" an incoming warhead with an intense beam, causing the metal casing to weaken enough so that the warhead will burn up in the atmosphere, much like a meteor.

Whether or not such a system can be made to work in a practical defense system remains to be seen. There are many difficult technical problems that would have to be overcome, and it is by no means clear that this would be the best system to develop. Nevertheless, the discussion about directed energy weapons illustrates an important point about basic research in physics and other sciences. When people at universities in the United States were developing the first lasers, they had no idea that these devices might someday improve surgical techniques in the nation's hospitals, much less be developed as weapons. In fact, one of the authors (JT) remembers hearing Arthur Schawlow, who shared the Nobel Prize for developing the laser, speculating that, possibly, it could be used to make a better device for erasing letters typed on paper (people still used typewriters rather than word processors in those days). He thought of his device primarily as a tool to do basic research in atomic physics, nothing more.

Every major discovery has applications far beyond what can be imagined at the beginning. Do you think scientists should consider what those uses might be before they begin research? Should there be government laws and regulations in this area? Why or why not?

Summary

Optics is the study of light and its interactions with matter. When electromagnetic radiation encounters matter, it can be **scattered, absorbed,** or **transmitted.** A **mirror** is an optical device that uses **reflection** to change the direction of light rays. Radio telescopes, radar receivers, satellite dishes, and X-ray telescopes are all examples of instruments that work by reflection.

A material that absorbs all the radiation of a given wavelength that falls on it is said to be **opaque,** while one that absorbs little of that radiation is said to be **transparent.** The ratio between the speed of light in a vacuum and its speed in a material is called the **index of refraction** of that material. When radiation passes a boundary between different materials, its direction changes. The ray moves closer to the perpendicular to the boundary if the wave is moving from a medium of low to high index of refraction and away from it when moving from a medium of low to high index of refraction. This bending effect is called **refraction.**

The laws of refraction govern the operation of **lenses** and of optical instruments such as microscopes and some telescopes. This phenomenon is the basis of **fiber optics,** a technology that is revolutionizing both communications and medicine.

Different wavelengths of radiation often have slightly different indices of refraction in materials, a phenomenon known as **dispersion.** Dispersion causes a prism to split white light into its constituent colors.

The color of a single ray of light is determined by its wavelength. All colors can be made from combinations of red, green, and blue light, which are the three primary additive colors. All colors can also be made by mixing cyan, magenta, and yellow pigments, which are the three primary subtractive colors.

Key Terms

absorption The conversion of electromagnetic wave energy into thermal energy, resulting in a reduction (partial or complete) of the wave strength. (p. 426)

dispersion The phenomenon that different wavelengths of light refract different amounts when entering a medium. (p. 434)

fiber optics A technology that uses long and thin glass fibers to carry light great distances using the principle of total internal reflection. (p. 425)

index of refraction Defined for a specific material, the ratio of the speed of light in a vacuum to the speed of light in that material; it is a measure of how much light slows down and bends as it enters the material. (p. 428)

lens A piece of transparent material designed to bend and focus light. (p. 432)

mirror A device that scatters light by reflection. (p. 421)

opaque materials Materials that absorb or scatter electromagnetic radiation. (p. 426)

optics The branch of physics dealing with the manipulation and analysis of electromagnetic waves. (p. 419)

ray The path taken by a beam of electromagnetic radiation, a line drawn perpendicular to the wavefront. (p. 419)

reflection The return of light from a surface on which it falls. (p. 421)

refraction The change in direction and speed of a wave as it enters a different medium. (p. 427)

scattering The process of changing the direction (and sometimes the properties) of a wave as it encounters an obstacle. (p. 421)

transmission The process of a wave passing through a material (even though it may lose some of its energy). (p. 427)

transparent materials Materials that transmit electromagnetic waves. (p. 427)

Key Equation

$$\text{Index of refraction} = \frac{\text{Speed in vacuum}}{\text{Speed in material}}$$

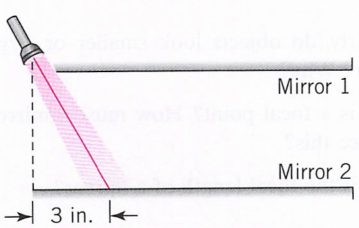
Review

1. What is meant by the term "optics"?
2. Is optics strictly concerned with visible light? Explain.
3. What are three ways that electromagnetic radiation interacts with matter?
4. What is a ray? Why is this description of the movement of an electromagnetic wave so useful?
5. Is the concept of a ray used only in connection with visible light?
6. What does it mean to say that a wave scatters? What exactly is a scattered wave, and in what direction does it move?
7. What is the angle of incidence of an incoming ray of radiation? The angle of reflection?
8. How is the angle of incidence related to the angle of reflection?
9. Do objects look smaller or larger in a concave mirror? Why?
10. Similarly, do objects look smaller or larger in a convex mirror? Why?
11. What is a focal point? How must a mirror be shaped to produce this?
12. What is the focal length of a mirror?

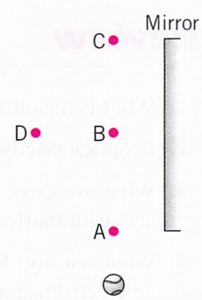
13. Why are parabolic mirrors frequently used in astronomy? What is meant by the term "light bucket"?
14. Infrared cameras capture electromagnetic radiation in the infrared part of the spectrum. Are these cameras considered optical instruments? List at least five other optical devices that are not concerned with visible light.
15. What are some of the technical difficulties associated with the construction of large telescope mirrors? How does active optics help mitigate some of these difficulties?
16. How does an electromagnetic wave behave in a vacuum? In a material? Is the energy of the wave conserved in each case? If not, what happens to it?
17. Fill a drinking glass with water and look through the water. Describe the different ways that light is interacting with matter.
18. Identify a substance that
    a. absorbs radio waves
    b. scatters microwaves
    c. transmits visible light
    d. absorbs x-rays
    e. scatters infrared radiation
19. What is absorption? What occurs to make a material opaque to light or to other electromagnetic radiation?
20. What is transmission? Can a material be transparent for one wavelength of radiation and opaque for another? Explain.
21. Propose an experiment to test whether lead is transparent to radio waves.
22. Describe the phenomenon of refraction. How and why does this occur?
23. What is the index of refraction of a material? Explain this in terms of a ratio.
24. What happens to the direction of a ray when it passes from a material with a high index of refraction, through a boundary, to a material with a low index of refraction? Similarly, what occurs in a transition from a low to a high index of refraction?
25. How does refraction account for a mirage? Explain.
26. Why do stars twinkle? What is the reason so many telescopes are placed as high in the atmosphere as possible?
27. What is a converging lens? A diverging lens? How does each work?
28. What is the difference between a reflecting telescope and a refracting telescope? Where is each commonly used?
29. What type of lens is used in a microscope? How does this magnify the image of the specimen?
30. What is meant by the term "total internal reflection"? How does this principle explain the workings of fiber optics?
31. Give several examples of the use of fiber optics. What makes it such a valuable technology?
32. What is dispersion? How does this account for the colors generated by a prism?
33. Explain the phenomenon of chromatic aberration. How is this corrected in photographic lenses?
34. What happens when you shine equal intensities of red, blue, and green light on the same spot? What happens when you mix paints from these three colors together? Why are the outcomes different?
35. What is a primary additive color? A primary subtractive color?
36. Why is the sky blue?
37. Why are the clouds white?
38. Why are sunsets red?
39. How are most colors we see like many of the sounds we hear?

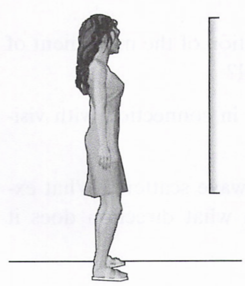
Questions

1. How does the smoothness of a mirror affect the clarity of the image you see? What is the difference between a set of parallel rays reflected off a very smooth mirror and the same rays reflected off a more bumpy mirror made of the exact same material?
2. Two large plane mirrors are aligned so that they are parallel and facing each other, as shown. A flashlight beam strikes the bottom mirror, as shown. Where will the flashlight beam hit the bottom mirror the second time?



3. A baseball is sitting near a plane mirror, as shown. At which of the marked locations could an observer stand and see the image of the baseball?

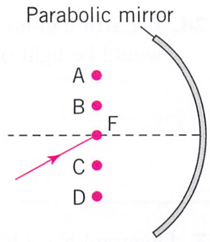




4. Sally stands in front of a plane mirror, as shown. Do you think she is able to see her feet in the mirror, or does she need a full-length mirror?

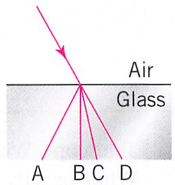
5. As you walk toward a full-length plane mirror, your image walks toward you. If your speed is 1 meter per second, what is the speed of your image?

6. A laser beam passes through the focal point of a concave parabolic mirror, labeled F in the figure. After the beam reflects off the mirror, which other point will the beam pass through?



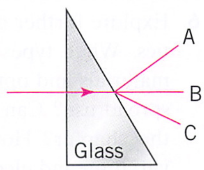
7. In a nighttime infrared image of a heated house, the windows glow brightly. However, this book claims that glass is opaque to infrared radiation. Resolve this apparent dilemma. (*Hint:* Think about the difference between the heat conduction properties of the walls and the glass windows.)

8. The figure shows a beam of light striking a flat interface between air and glass. Which is the correct refracted beam, A, B, C, or D?



9. Diamonds have a very high index of refraction. How does this help to account for their sparkle? How does the cutting of diamonds into facets increase the sparkle you see?

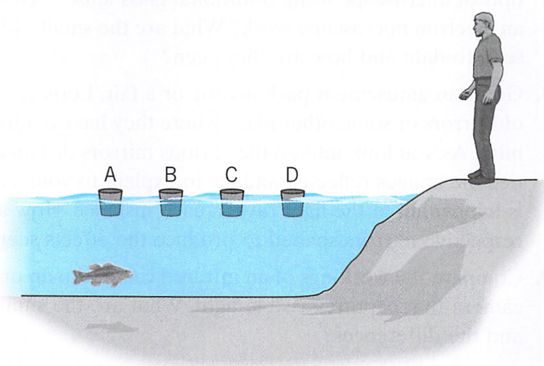
10. Light passes through a triangular-shaped piece of glass as shown. Which is the correct emerging beam, A, B, or C? How would your answer change if the glass were submerged in a liquid that had the same index of refraction as the glass?



11. If the atmosphere did not scatter light, what would you see when you looked at the daytime sky? Explain.

12. If the atoms and molecules in the sky had about 10 times their present size, would you expect the daytime sky to be blue? If not, what color would you expect? Explain.

13. A man is standing by the lake looking at a piece of cork floating on the surface. At that moment, he notices a fish in the same line of sight as the cork. The figure shows the actual position of the fish. Where is the cork?



14. Why do people wear light-colored clothing in summer and dark-colored clothing in winter?

15. What is the frequency range of light seen when you look at a white-colored object? A black-colored one?

16. Why do stained-glass windows look gray from the inside of a church at night but bright from the outside?

17. For a house window to be as energy efficient as possible, which wavelengths of the electromagnetic spectrum should it be transparent to, and which wavelengths should it be more opaque to?

18. What kind of electromagnetic radiation can you detect with your body?

19. Why don't planets twinkle the way stars do? (*Hint:* How big do planets appear, as compared to stars?)

20. How does a concave mirror change the image seen as compared to a flat plane mirror? Is the image enlarged or reduced? Why does this image differ from a flat plane mirror?

21. What shape are the security mirrors often placed high in the corners of stores, and why are they shaped that way?

22. Some of the mirrors you might see in an amusement park make some parts of you seem large, while at the same time making other parts seem smaller. How is this accomplished?

23. Is a lens used to capture an image different from a lens used to project that image back onto a screen for viewing? Explain.

24. When you focus an optical instrument such as a camera or microscope, what are you actually doing to the lens and what happens to the focal point of the image?

25. Why is the image projected onto the back of the retina in your eye upside down? How can we see something as right side up if this is the case?

26. In movies that involve a character lost in the wilderness somewhere, you often see the hero vainly try to spear a fish in a river or tidal basin. Even if his aim is good, how should he aim to spear the fish? Due to refraction, is the fish actually located nearer or farther from where he sees it?

27. In many weapons systems, including aircraft, fiber optics is used to transmit information. Why might fiber optics be particularly useful in a military application such as a battlefield environment?

28. If you left a glass fiber-optic cable unshielded by any plastic covering, should the light still be able to travel through the cable? Explain.

29. A polar bear actually has translucent colorless fur and black skin. What are the benefits it derives from this and how is this similar to the workings of fiber optics?

30. Which parts of the electromagnetic spectrum, if any, scatter all wavelengths equally from atoms and molecules?

31. It sometimes happens that in cities located on a coast a hazy white layer can be seen over the city, but the layer is much less pronounced, or even absent, over the water. Explain why this should be so.

32. If you swim just below the surface of a pool and look straight up, you will see the sky. However, if you look at a glancing angle to the surface of the water, you will see a reflection of the bottom of the pool. What's going on?

33. In order to have a wide field of view, the passenger-side mirror on an automobile or truck is curved outward (it is a convex mirror). Why is the driver-side mirror not usually convex?

34. If Earth had no atmosphere the days would be shorter (it would be light out for a shorter time each day). Why?

Problems

1. How fast does light travel through crown glass? Take the index of refraction of crown glass to be 1.52 and the speed of light to be 3×10^8 m/s.

2. If the speed of light through material Z is 2.5×10^8 m/s, what is this material's index of refraction?

3. Diamond has a high index of refraction at about 2.4, which helps account for its sparkle. How fast does light travel through a diamond? Using Problem 1, which material, diamond or crown glass, bends a light ray more as it passes from air into the respective material?

Investigations

1. Next time you see a rainbow after a sun shower, note the orientation of the rainbow in relation to the light from the Sun. Which direction is the Sun coming from in relation to the rainbow and in which direction does there seem to still be rain? Research the origin of rainbows. When do they occur, and what is the role of reflection and refraction in creating them?

2. Examine a microwave oven or, better yet, obtain an old broken oven that you can take apart. Locate the source of microwaves. Which materials in the oven transmit microwaves? Which ones scatter microwaves? Do you think any of the components absorb microwaves? Why?

3. The eye is a very sophisticated and remarkable instrument through which we interpret much of the physical world. How does it work? What is its structure and how and where does it focus the incoming light rays to form the images we see? In terms of the concepts discussed in this chapter, what happens when light comes into a normal healthy eye? How is the eye similar to a camera and how does it differ?

4. Continuing Investigation 3, find out what is actually happening when a person is nearsighted, farsighted, or has an astigmatism. Where is the focal point in each of these conditions in relation to where it ought to be if the eye were normal, and how is the lens of the eye misshapen so that this occurs? What types of lenses are used to correct these conditions, and how and where do these lenses refocus images onto the retina so that the focus is better? How does the surgical procedure "radial keratotomy" work to correct vision permanently?

5. Search the Web or the library for images created by the Hubble Space Telescope. Compare these images to images of the stars from the best terrestrial telescopes. How do they differ, if at all? Investigate the history of the Hubble Space Telescope. What types of optical technologies are on board? What exactly plagued it in its early years? How was this initially corrected for? What have been some of its key discoveries, and how much of the universe has been seen with it?

6. Explore further the history of the development of fiber optics. What types of technological advances in terms of materials and optical instruments helped facilitate its widespread use? Can you find examples of its use not given in the chapter? How does fiber optics react to temperature variation and electrical interference, and how easy would it be to eavesdrop on such a communication system compared to other traditional communication mediums? How difficult is it to connect a fiber-optic cable to other cables and devices in telephone systems? Is this a problem? Finally, what is its future, as you see it?

7. Go into a classroom where a microscope is available, examine it, and use it. How many lenses are there and how do you focus them? What happens to the rays of light as they hit the object and then move through the microscope to your eye? What are the smallest images seen with a traditional optical microscope using traditional glass lenses? How does an electron microscope work? What are the smallest images seen to date and how are they seen?

8. Go to an amusement park nearby or a fair. Look for a Hall of Mirrors or some other place where they have a mirror exhibit. As you look into all the various mirrors displayed, notice the images reflected and try to explain to yourself what is happening to the light rays in each instance. How are the respective mirrors shaped to produce the effects seen?

9. Compare the workings of an infrared camera to an ordinary camera that captures visible light. What are the similarities and the differences?

WWW Resources

See the *Physics Matters* home page at **www.wiley.com/college/trefil** for valuable web links.

1. **http://www.phy.ntnu.edu.tw/java/Rainbow/rainbow.html** A site that discusses and models the dispersion of light through raindrops, creating the curved spectrum known as a rainbow.
2. **http://www.phy.ntnu.edu.tw/java/Lens/lens_e.html** The classic thin lens and mirror simulator, this applet shows how lenses and mirrors make use of the laws of reflection and refraction to create various kinds of images.
3. **http://www.phy.ntnu.edu.tw/java/optics/prism_e.html** A demonstration of how refraction and reflection occur in a prism, including calculated intensities of reflected and refracted beams. The index of refraction is controllable.
4. **http://www.exploratorium.edu/light_walk/index.html** The famous walk through the physics of pinhole images from the San Francisco Exploratorium.
5. **http://www.phy.ntnu.edu.tw/java/image/rgbColor.html** An applet that allows the mixing of colored light, the mixing of pigments, and the use of filters to demonstrate color production and separation.
6. **http://school.discovery.com/lessonplans/interact/electromagneticspectrum.hml** A brief introduction to the electromagnetic spectrum from Discovery School.