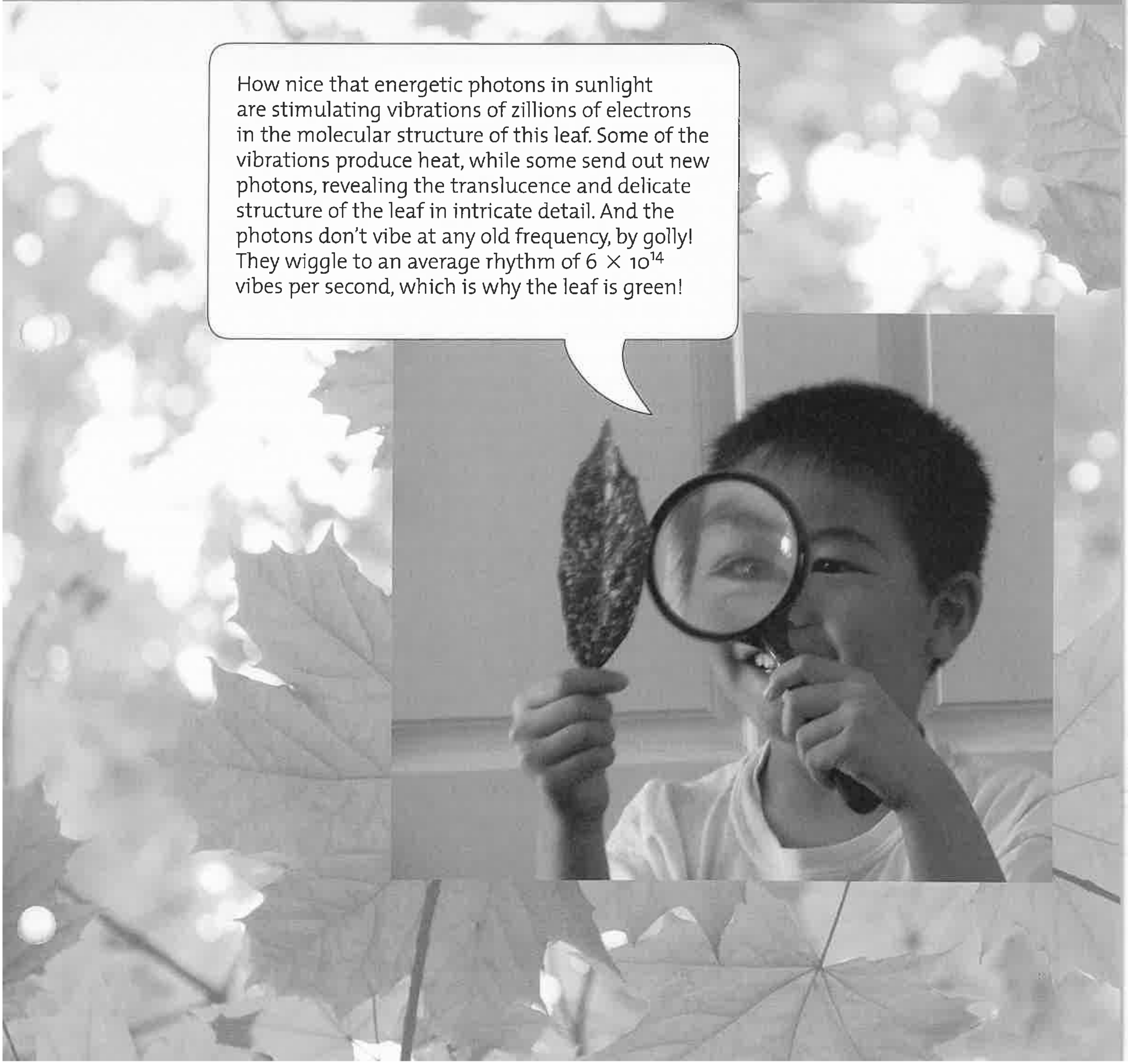
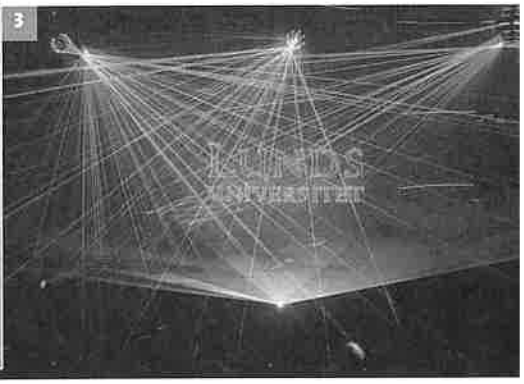
Part Six
Light



26 Properties of Light



1 Looking down from the space station MIR at a solar eclipse on Earth. 2 Bob and Leslie Abrams (my daughter) assist Dave Wall with an optics experiment. 3 Physics students at Lund University in Sweden are introduced to optics by being treated to a laser show each semester.

James Clerk Maxwell, born in 1831, was a Scottish mathematician and theoretical physicist. His parents did not meet and marry until they were well into their thirties, which was unusual at that time, and his mother was nearly 40 when he was born. James was an only surviving child, his older sister dying in infancy.

Maxwell maintained an unquenchable curiosity from an early age. His mother recognized his potential and took responsibility for his early education, which in the Victorian era was largely the job of the woman of the house. Unfortunately, she died of abdominal cancer when Maxwell was only 8. His education was then overseen by his father, who hired a 16-year-old tutor for young Maxwell. The tutor treated him harshly, chiding him for being slow and wayward. After his father dismissed the tutor, Maxwell was sent to the prestigious Edinburgh Academy.

Ten-year-old Maxwell, raised in isolation on his father's countryside estate, didn't fit in well at school. With no space in the first-year class, he was obliged to join the second-year class with classmates a year his senior. His mannerisms and Galloway accent struck the other boys as rustic, and arriving on his first day at school wearing home-made shoes and tunic earned him the unkind nickname of "Dafty." Maxwell, however, never seemed to have resented the epithet, bearing it without complaint for many years.

At an early age, Maxwell was fascinated by geometry. His academic work remained unremarkable until, at the age of 13, he won the school's mathematical medal and first prizes for English and poetry. At age 14, Maxwell wrote a paper describing a mechanical means of drawing mathematical curves with a piece of twine and the properties of curves with two or more foci. His genius showed in this work on "oval curves," which was presented to the Royal Society of Edinburgh, but not by Maxwell. Since he was deemed too young, he entrusted the paper to a professor of natural philosophy at Edinburgh University.

Maxwell left Edinburgh Academy at the age of 16 and began attending classes at the University of Edinburgh. He had the opportunity to attend Cambridge after his first term but decided instead to complete the full course of his undergraduate studies at the local university. Maxwell soon found his classes undemanding, and he immersed himself in private study during free time at the university, and particularly in visits back home. There he experimented with improvised chemical and electromagnetic apparatus. His chief preoccupation at the time was polarized light. He constructed shaped blocks of gelatin, subjecting them to various stresses, and with a pair of polarizing prisms viewed the resulting colored fringes in the gelatin. Maxwell had discovered photoelasticity, a means of determining the stress distribution within physical structures.

At age 18, Maxwell contributed two papers to the Royal Society of Edinburgh. Although the work was impressive, as with his schoolboy paper on oval curves, he was considered too young to stand at the rostrum and make the presentation himself. Maxwell's papers were instead delivered by his tutor.

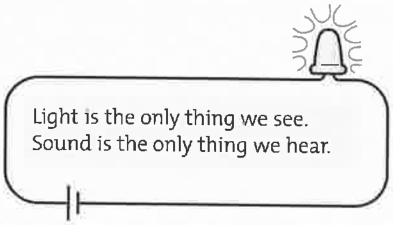
In October 1850, already an accomplished mathematician, Maxwell left Scotland for Cambridge University and soon joined Trinity College, where in 1854 he graduated with a degree in mathematics. Maxwell decided to remain at Trinity after graduating and, aside from tutoring and examining duties, to pursue scientific interests such as color, hydrostatics, optics, and Saturn's rings at his own leisure.

In 1859, after moving to Marischal College in Aberdeen, Scotland, Maxwell married Katherine Mary Dewar, the daughter of the college's principal. In that same year, he won a prize for concluding that the rings of Saturn consist of small particles—a conclusion verified more than a century later in the space age. Maxwell had a near-fatal bout of smallpox soon thereafter and headed south to London with his wife. He took a position at King's College, which turned out to be the most productive period of his career. There he displayed the world's first colored photograph and developed ideas on the viscosity of gases. His most significant achievement, however, was the development of electromagnetic theory, synthesizing all previous unrelated observations, experiments, and equations of electricity, magnetism, and even optics into one consistent theory. Around 1862, he calculated that the speed of propagation of an electromagnetic field is approximately that of the speed of light, and he wrote, "We can scarcely avoid the conclusion that light consists in the transverse undulations of the same medium which is the cause of electric and magnetic phenomena."

Whereas Newton's work first unified mechanics, Maxwell's work in electromagnetism has been called the "second great unification in physics." Maxwell died of abdominal cancer at the age of 48.

Electromagnetic Waves

Recall from the previous chapter how Maxwell discovered that light is the oscillation of electric and magnetic fields. You know that if you shake the end of a stick back and forth in still water, you will produce waves on the surface of the water. Maxwell taught us that if you similarly shake an electrically charged rod to and fro in empty space, you will produce waves in space. The vibrating electric and magnetic fields regenerate each other to make up an **electromagnetic wave,** which emanates (moves outward) from the vibrating charge. There is only one speed, it turns out, for which the electric and magnetic fields remain in perfect balance, reinforcing each other as they carry energy through space. Let's see why this is so.



Light is the only thing we see.
Sound is the only thing we hear.

FIGURE 26.1

Shake an electrically charged object to and fro, and you produce an electromagnetic wave.

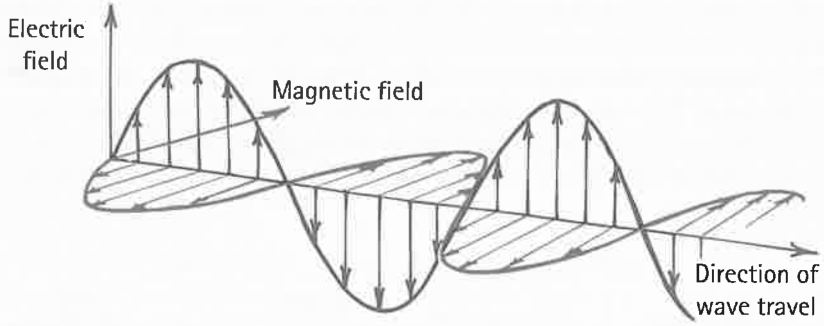


FIGURE 26.2

INTERACTIVE FIGURE

The electric and magnetic fields of an electromagnetic wave are perpendicular to each other and to the direction of motion of the wave.

ELECTROMAGNETIC WAVE VELOCITY

Unlike other moving objects, electromagnetic waves traveling through free space never change speed. Why this is so involves electromagnetic induction and energy conservation. If light were to slow down, its changing electric field would generate a weaker magnetic field, which, in turn, would generate a weaker electric field, and so on, until the wave dies out. Energy would be lost and none would be transported from one place to another. So light cannot travel slower than it does.

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- Our study of light begins by investigating its electromagnetic properties. In the next chapter, we'll discuss its appearance—color. In Chapter 28, we'll learn how light behaves—how it reflects and refracts. Then we'll learn about its wave nature in Chapter 29 and its quantum nature in Chapters 30 and 31.

Maxwell "with his own thinking" calculated the speed of light. Some 100 years later, in 1969, millions of people watching the first Moon landing on TV listened to conversations between the astronauts and mission control on Earth. When viewers perceived a distinct time delay between the messages, they heard the effect of Maxwell's speed "with their own ears."

If light were to speed up, the changing electric field would generate a stronger magnetic field, which, in turn, would generate a stronger electric field, and so on, a crescendo of ever-increasing field strength and ever-increasing energy—clearly a no-no with respect to energy conservation. At only one speed does mutual induction continue indefinitely, carrying energy forward without loss or gain. From his equations of electromagnetic induction, Maxwell calculated the value of this critical speed and found it to be 300,000 kilometers per second. In his calculation, he used only the constants in his equations determined by simple laboratory experiments with electric and magnetic fields. He didn't *use* the speed of light. He *found* the speed of light!

Maxwell quickly realized that he had discovered the solution to one of the greatest mysteries of the universe—the nature of light. He discovered that light is simply electromagnetic radiation within a particular frequency range, 4.3×10^{14} to 7×10^{14} vibrations per second. Such waves activate the "electrical antennae" in the retina of the eye. The lower-frequency waves appear red, and the higher-frequency waves appear violet.[1] Maxwell realized, at the same time, that electromagnetic radiation of *any* frequency propagates at the same speed as light.

CHECK POINT

The unvarying speed of electromagnetic waves in space is a remarkable consequence of what central principle in physics?

Check Your Answer

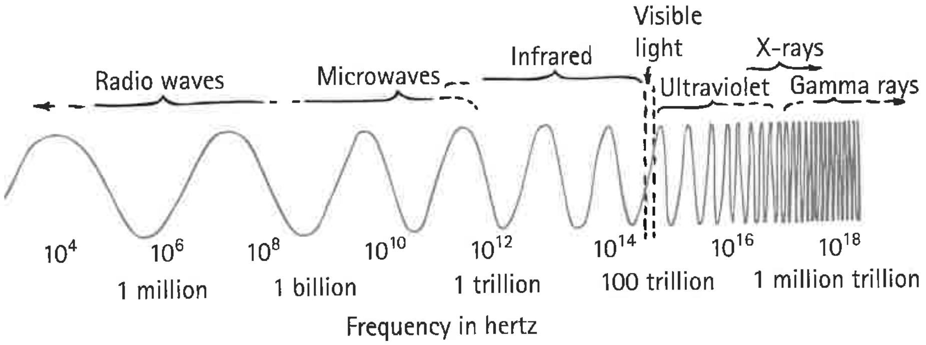
The conservation of energy.

The Electromagnetic Spectrum

In a vacuum, all electromagnetic waves move at the same speed and differ from one another in their frequency. The classification of electromagnetic waves according to frequency is the **electromagnetic spectrum** (Figure 26.3). Electromagnetic waves have been detected with a frequency as low as 0.01 hertz (Hz). Electromagnetic waves with frequencies of several thousand hertz (kHz) are classified as very low frequency radio waves. One million hertz (MHz) lies in the middle of the AM radio band. The very high frequency (VHF) television band of waves starts at about 50 MHz, and FM radio waves are between 88 and 108 MHz. Cell phones operate on either 800 MHz or 1900 MHz. Then come ultrahigh frequencies

FIGURE 26.3

INTERACTIVE FIGURE



The electromagnetic spectrum is a continuous range of waves extending from radio waves to gamma rays. The descriptive names of the sections are merely a historical classification, for all waves are the same in nature, differing principally in frequency and wavelength; all travel at the same speed.

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[1] It is common to describe sound and radio waves by *frequency* and light by *wavelength*. In this book, however, we favor the single concept of frequency in describing light.

(UHF), followed by microwaves, beyond which are infrared waves, often called "heat waves." Further still is visible light, which makes up less than 1 millionth of 1% of the measured electromagnetic spectrum. The lowest frequency of light visible to our eyes appears red. The highest frequencies of visible light, which are nearly twice the frequency of red light, appear violet. Still higher frequencies are ultraviolet. These higher-frequency waves cause sunburns. Higher frequencies beyond ultraviolet extend into the X-ray and gamma-ray regions. There are no sharp boundaries between the regions, which actually overlap each other. The spectrum is separated into these arbitrary regions for classification.

The concepts and relationships we treated earlier in our study of wave motion (Chapter 19) apply here. Recall that the frequency of a wave is the same as the frequency of the vibrating source. The same is true here: The frequency of an electromagnetic wave as it vibrates through space is identical to the frequency of the oscillating electric charge generating it.[2] Different frequencies correspond to different wavelengths—waves of low frequency have long wavelengths and waves of high frequencies have short wavelengths. For example, since the speed of the wave is 300,000 km/s, an electric charge oscillating once per second (1 Hz) will produce a wave with a wavelength of 300,000 km. This is because only one wavelength is generated in 1 second. If the frequency of oscillation were 10 Hz, then 10 wavelengths would be formed in 1 second, and the corresponding wavelength would be 30,000 km. A frequency of 10,000 Hz would produce a wavelength of 30 km. So the higher the frequency of the vibrating charge, the shorter the wavelength of radiant energy.[3]

We tend to think of space as empty, but only because we cannot see the montages of electromagnetic waves that permeate every part of our surroundings. We see some of these waves, of course, as light. These waves constitute only a microportion of the electromagnetic spectrum. We are unconscious of radio and cell-phone waves, which engulf us every moment. Free electrons in every piece of metal on Earth's surface continually dance to the rhythms of these waves. They jiggle in unison with the electrons being driven up and down along their transmitting antennae. A radio or television receiver is simply a device that sorts and amplifies these tiny currents. There is radiation everywhere. Our first impression of the universe is one of matter and void, but actually the universe is a dense sea of radiation occupied only occasionally by specks of matter.

CHECK POINT

Are we correct to say that a radio wave is a low-frequency light wave? And that a radio wave is also a sound wave?

Check Your Answers

Yes and no: Both a radio wave and a light wave are electromagnetic waves emitted by vibrating electrons; radio waves have lower frequencies than light waves, so a radio wave may be considered to be a low-frequency light wave (and a light wave, similarly, can be considered to be a high-frequency radio wave). But a sound wave is a mechanical vibration of matter and is fundamentally different from an electromagnetic wave. So a radio wave is definitely not a sound wave.

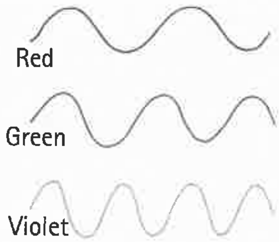

FIGURE 26.4

INTERACTIVE FIGURE

Relative wavelengths of red, green, and violet light. Violet light has nearly twice the frequency of red light and half the wavelength.

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- For quality reception of electromagnetic waves, a conventional antenna has to be about one-quarter wavelength long. That's why, in early mobile devices, antennas had to be pulled out before the device was used. Nathan Cohen, a professor at Boston University, was troubled by a rule in Boston at the time that prohibited the use of large external antennas on buildings. So he fashioned a small antenna by folding aluminum foil into a compact fractal shape (a Van Koch figure—check the Web for more on fractals). It worked. He then engineered and patented many practical fractal antennas, as did Carles Fuente, an inventor in Spain. Both formed fractal-antenna companies.

  Fractals are fascinating shapes that can be split into parts, each of which is (or approximates) a reduced copy of the whole. In any fractal, similar shapes appear at all levels of magnification. Common fractals in nature include snowflakes, clouds, lightning bolts, shorelines, and even cauliflower and broccoli.

  The fractal antenna, like other fractals, has a shape that repeats itself. Because of its folded self-similar design, a fractal antenna can be compressed into a small space, and in fact, be built into the body of the device—it can also simultaneously operate at different frequencies. This means that the same antenna can be used for cell-phone conversations and for GPS navigation.

  How nice that an iPhone or BlackBerry fits in your pocket. Cheers for compact fractal antennas!

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[2] This is a rule of classical physics, valid when charges are oscillating over dimensions that are large compared with the size of a single atom (for instance, in a radio antenna). Quantum physics permits exceptions. Radiation emitted by a single atom or molecule can differ in frequency from the frequency of the oscillating charge within the atom or molecule.

[3] The relationship is $c = f\lambda$, where c is the wave speed (constant), f is the frequency, and λ is the wavelength.

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Light and Transparent Materials

Transparent Materials

When light is transmitted through matter, some of the electrons in the matter are forced into vibration. In this way, vibrations in the emitter are transmitted to vibrations in the receiver. This is similar to the way sound is transmitted (Figure 26.5).

FIGURE 26.5

Just as a sound wave can force a sound receiver into vibration, a light wave can force electrons in materials into vibration.

Atoms are like optical tuning forks that resonate at certain frequencies.

The way a receiving material responds when light is incident upon it depends on the frequency of the light and on the natural frequency of the electrons in the material. Visible light vibrates at a very high frequency, more than 100 trillion times per second (more than 10^{14} Hz). If a charged object is to respond to these ultrafast vibrations, it must have very, very little inertia. Because the mass of electrons is so tiny, they can vibrate at this rate.

Such materials as glass and water allow light to pass through in straight lines. We say they are **transparent** to light. To understand how light travels through a transparent material, visualize the electrons in the atoms of transparent materials as if they were connected to the nucleus by springs (Figure 26.6).[4] When a light wave is incident upon them, the electrons are set into vibration.

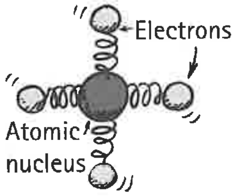

FIGURE 26.6

The spring model of light. The electrons of atoms in glass have certain natural frequencies of vibration and behave as if they were connected to the atomic nucleus by springs.

Materials that are springy (elastic) respond more to vibrations at some frequencies than at others (Chapter 20). Bells ring at a particular frequency, tuning forks vibrate at a particular frequency, and so do the electrons of atoms and molecules. The natural vibration frequencies of an electron depend on how strongly it is attached to its atom or molecule. Different atoms and molecules have different "spring strengths." Electrons in the atoms of glass have a natural vibration frequency in the ultraviolet range. Therefore, when ultraviolet waves shine on glass, resonance occurs and the vibration of electrons builds up to large amplitudes, just as pushing someone at the resonant frequency on a swing builds to a large amplitude. The energy received by any glass atom is either reemitted or passed on to neighboring atoms by collisions. Resonating atoms in the glass can hold onto the energy of the ultraviolet light for quite a long time (about 100 millionths of a second). During this time, the atom makes more than 1 million vibrations, and it collides with neighboring atoms and gives up its energy as heat. Thus, glass is not transparent to ultraviolet light.

At lower wave frequencies, such as those of visible light, electrons in the glass atoms are forced into vibration, but at lower amplitudes. The atoms hold the energy

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[4] Electrons, of course, are not really connected by springs. Their "vibration" is actually orbital as they move around the nucleus, but the "spring model" helps us to understand the interaction of light with matter. Physicists devise such conceptual models to understand nature, particularly at the submicroscopic level. The worth of a model lies not in whether it is "true," but in whether it is useful. A good model not only is consistent with and explains observations but also predicts what may happen. If predictions of the model are contrary to what happens, the model is usually either refined or abandoned. The simplified model that we present here—of an atom whose electrons vibrate as if on springs, with a time interval between absorbing energy and reemitting energy—is quite useful for understanding how light passes through transparent solids.

for a shorter time, with less chance of collision with neighboring atoms, and with less energy transformed to heat. The energy of vibrating electrons is reemitted as light. Glass is transparent to all the frequencies of visible light. The frequency of the reemitted light that is passed from atom to atom is identical to the frequency of the light that produced the vibration in the first place. However, there is a slight time delay between absorption and reemission.

It is this time delay that results in a lower average speed of light through a transparent material (Figure 26.7). Light travels at different average speeds through different materials. We say *average speeds* because the speed of light in a vacuum, whether in interstellar space or in the space between molecules in a piece of glass, is a constant 300,000 km/s. We call this speed of light *c*.[5] The speed of light in the atmosphere is slightly less than in a vacuum, but it is usually rounded off as *c*. In water, light travels at 75% of its speed in a vacuum, or 0.75*c*. In glass, light travels at about 0.67*c*, depending on the type of glass. In a diamond, light travels at less than half its speed in a vacuum, only 0.41*c*. When light emerges from these materials into the air, it travels at its original speed, *c*.

Different materials have different molecular structures and therefore absorb or reflect light from various spectral ranges differently.

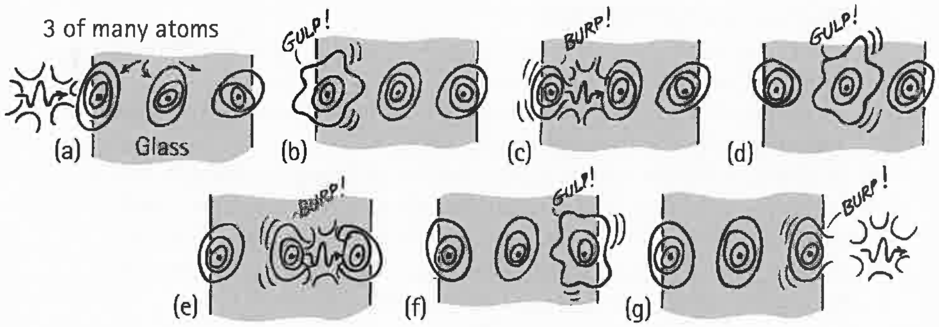

FIGURE 26.7

A wave of visible light incident upon a pane of glass sets up vibrations in the glass atoms that produce a chain of absorptions and reemissions, which pass the light energy through the material and out the other side. Because of the time delay between absorptions and reemissions, the light travels more slowly through the glass than through empty space.

In glass, infrared waves, with frequencies lower than those of visible light, cause not only the electrons, but entire atoms or molecules to vibrate. This vibration increases the internal energy and temperature of the structure, which is why infrared waves are often called *heat waves*. So we see that glass is transparent to visible light, but not to ultraviolet and infrared light.

FIGURE 26.8

When the raised ball is released and hits the others, the ball that emerges at the opposite side is not the ball that initiates the transfer of energy. Likewise, light that emerges from a pane of glass is not the same light that was incident on the glass.

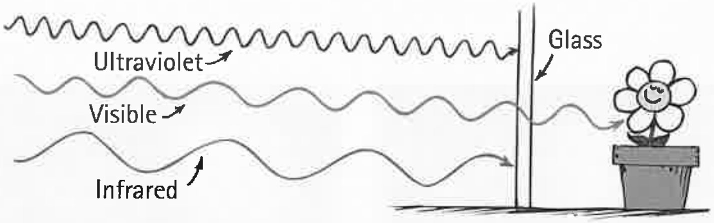

FIGURE 26.9

Glass blocks both infrared and ultraviolet, but it is transparent to visible light.

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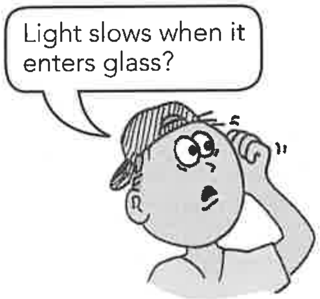
[5] The presently accepted value is 299,792 km/s, rounded to 300,000 km/s. (This corresponds to 186,000 mi/s.)



CHECK POINT

1. Why is glass transparent to visible light but opaque to ultraviolet and infrared?
2. Pretend that, while walking across a conference room, you make several momentary stops along the way to greet people who are "on your wavelength." How is this analogous to light traveling through glass?
3. In what way is it not analogous?

Check Your Answers

1. Because the natural vibration frequency for electrons in glass is the same as the frequency of ultraviolet light, resonance occurs when ultraviolet waves shine on glass. The absorbed energy is passed on to other atoms as heat, not reemitted as light, making the glass opaque at ultraviolet frequencies. In the range of visible light, the forced vibrations of electrons in the glass are at smaller amplitudes—vibrations are more subtle, reemission of light (rather than the generation of heat) occurs, and the glass is transparent. Lower-frequency infrared light causes whole molecules, rather than electrons, to resonate; again, heat is generated and the glass is opaque to infrared light.
2. Your average speed across the room is less than it would be in an empty room because of the time delays associated with your momentary stops. Likewise, the speed of light in glass is less than in air because of the time delays caused by the light's interactions with atoms along its path.
3. In walking across the room, it is you who begin and complete the walk. This is not analogous to light traveling through glass because, according to our model for light passing through a transparent material, the light absorbed by the first electron that is made to vibrate is not the same light that is reemitted—even though the two, like identical twins, are indistinguishable.

FIGURE 26.10

Metals are shiny because light that shines on them forces free electrons into vibration, and these vibrating electrons then emit their "own" light waves as reflection.

Opaque Materials

Most things around us are **opaque**—they absorb light without reemitting it. Books, desks, chairs, and people are opaque. Vibrations given by light to their atoms and molecules are turned into random kinetic energy—into internal energy. These materials become slightly warmer.

Metals are opaque. Because the outer electrons of atoms in metals are not bound to any particular atom, they are free to wander with very little restraint throughout the material (which is why metal conducts electricity and heat so well). When light shines on metal and sets these free electrons into vibration, their energy does not

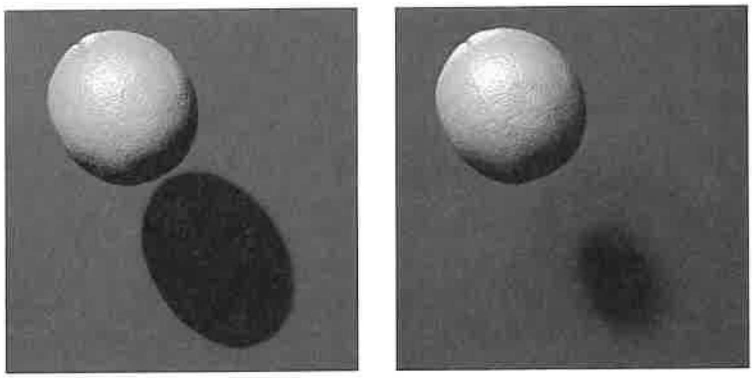


FIGURE 26.11

A small light source produces a sharper shadow than a larger source.

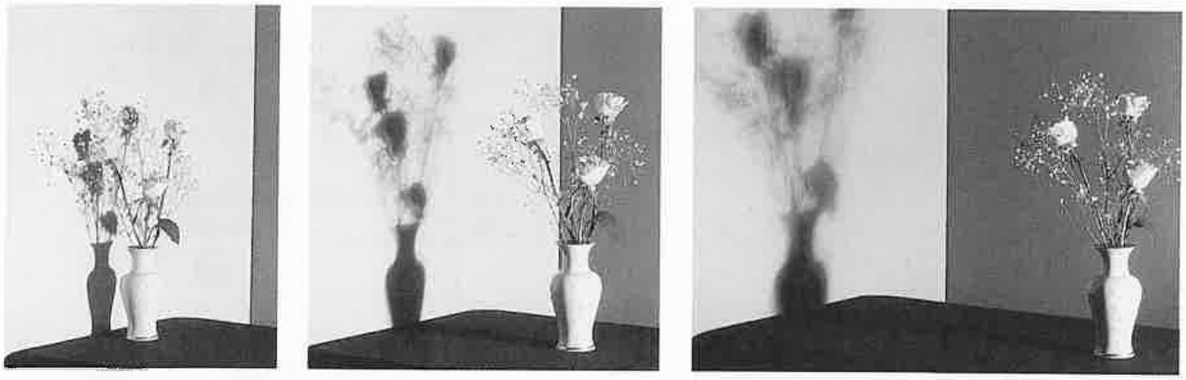


FIGURE 26.12

An object held close to a wall casts a sharp shadow because light coming from slightly different directions does not spread much behind the object. As the object is moved farther away from the wall, penumbras are formed and the umbra becomes smaller. When the object is farther away, the shadow is less distinct. When the object is very far away (not shown), no shadow is evident because all the penumbras mix together into a big blur.

"spring" from atom to atom in the material but, instead, is reflected. That's why metals are shiny.

Earth's atmosphere is transparent to some ultraviolet light, to all visible light, and to some infrared light, but it is opaque to high-frequency ultraviolet light. The small amount of ultraviolet that does get through is responsible for sunburns. If it all got through, we would be fried to a crisp. Clouds are semitransparent to ultraviolet, which is why you can get a sunburn on a cloudy day. Dark skin absorbs ultraviolet before it can penetrate too far, whereas it travels deeper in fair skin. With mild and gradual exposure, fair skin develops a tan and increases protection against ultraviolet light. Ultraviolet light is also damaging to the eyes—and to tarred roofs. Now you know why tarred roofs are covered with gravel.

Have you noticed that things look darker when they are wet than they do when they are dry? Light incident on a dry surface bounces directly to your eye, while light incident on a wet surface bounces around inside the transparent wet region before it reaches your eye. What happens with each bounce? Absorption! So more absorption of light occurs in a wet surface, and the surface looks darker.

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- Higher-frequency ultraviolet, called UV-A, is close to visible light and isn't harmful. Lower-frequency ultraviolet, called UV-C, would be harmful if it reached us, but is almost completely stopped by the atmosphere's ozone layer. It is the intermediate ultraviolet, UV-B, that can cause eye damage, sunburn, and skin cancer.

SHADOWS

A thin beam of light is often called a *ray*. When we stand in the sunlight, some of the light is stopped while other rays continue in a straight-line path. We cast a **shadow**—a region where light rays do not reach. If you are close to your own shadow, the outline of your shadow is sharp because the Sun is so far away. Either a large, far-away light source or a small, nearby light source will produce a sharp shadow. A large, nearby light source produces a somewhat blurry shadow (Figure 26.11). There is usually a dark part on the inside and a lighter part around the edges of a shadow. A total shadow is called an **umbra** and a partial shadow is called a **penumbra.** A penumbra appears where some of the light is blocked but where other light fills it in (Figure 26.12). A penumbra also occurs where light from a broad source is only partially blocked.

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Tutorial
Eclipses

Both Earth and the Moon cast shadows when sunlight is incident upon them. When the path of either of these bodies crosses into the shadow cast by the other, an eclipse occurs (Figure 26.13). A dramatic example of the umbra and penumbra occurs when the shadow of the Moon falls on Earth during a **solar eclipse.** Because of the large size of the Sun, the rays taper to provide an umbra and a surrounding penumbra (Figure 26.14). If you stand in the umbra part of the shadow, you experience darkness

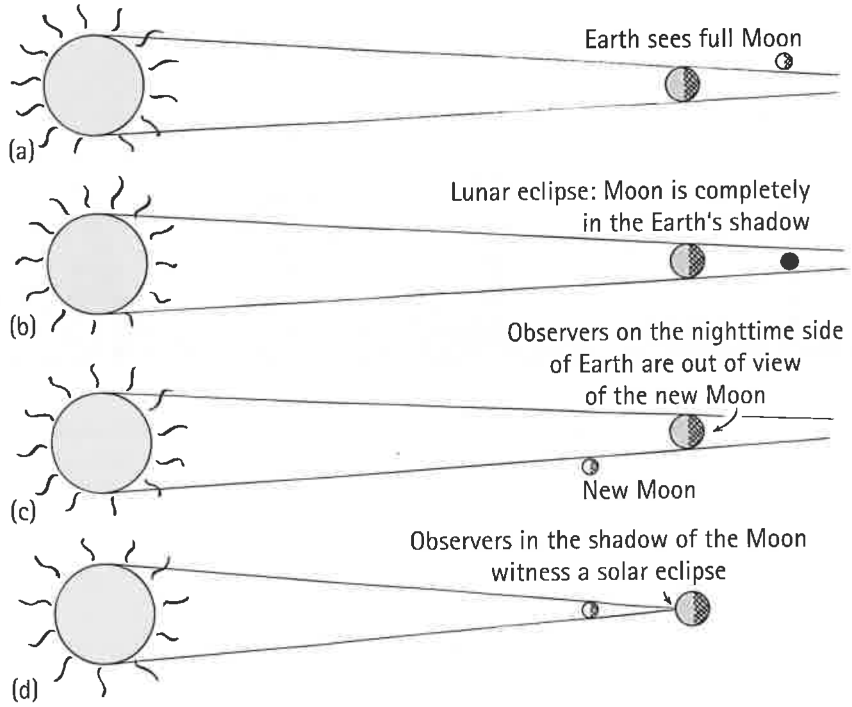

FIGURE 26.13

INTERACTIVE FIGURE

(a) A full Moon is seen when Earth is between the Sun and the Moon. (b) When this alignment is perfect, the Moon is in Earth's shadow, and a lunar eclipse is produced. (c) A new Moon occurs when the Moon is between the Sun and Earth. (d) When this alignment is perfect, the Moon's shadow falls on part of Earth to produce a solar eclipse.

during the day—a total eclipse. If you stand in the penumbra, you experience a partial eclipse, for you see a crescent of the Sun (recall the photos of partial-eclipse crescents in Chapter 1, and recall the opening photo in this chapter of a solar eclipse as viewed from the space station MIR). In a **lunar eclipse,** the Moon passes into the shadow of Earth.

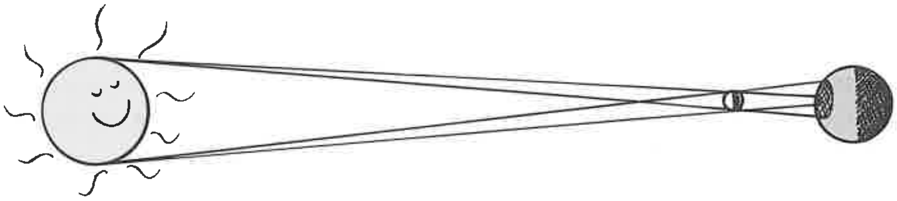

FIGURE 26.14

INTERACTIVE FIGURE

Details of a solar eclipse. A total eclipse is seen by observers in the umbra, and a partial eclipse is seen by observers in the penumbra. Most Earth observers see no eclipse at all.

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- People are cautioned not to look at the Sun at the time of a solar eclipse because the brightness and the ultraviolet light of direct sunlight are damaging to the eyes. This good advice is often misunderstood by those who then think that sunlight is more damaging at this special time. But staring at the Sun when it is high in the sky is harmful whether or not an eclipse occurs. In fact, staring at the bare Sun is more harmful than when part of the Moon blocks it! The reason for special caution at the time of an eclipse is simply that more people are interested in looking at the Sun during this time.

CHECK POINT

1. Which type of eclipse—a solar eclipse, a lunar eclipse, or both—is dangerous to view with unprotected eyes?
2. Why are lunar eclipses more commonly seen than solar eclipses?

Check Your Answers

1. Only a solar eclipse is harmful because one views the Sun directly. During a lunar eclipse, one views a very dark Moon. It is not completely dark because Earth's atmosphere acts as a lens and bends some light into the shadow region. Interestingly, this is the light of red sunsets and sunrises all around the world, which is why the Moon appears a faint, deep red during a lunar eclipse.
2. Because the shadow of the relatively small Moon on the large Earth covers a very small part of Earth's surface, only a relatively few people are in the shadow of the Moon in a solar eclipse. But the shadow of Earth that covers the Moon during a lunar eclipse is in view of everybody who can see the Moon in the nighttime sky.

Seeing Light—the Eye

Light is the only thing we see with the most remarkable optical instrument known—the eye (Figure 26.15). As light enters the eye, it moves through the transparent cover called the *cornea,* which does about 70% of the necessary bending of the light before it passes through an opening in the *iris* (colored part of the eye). The opening is called the *pupil.* The light then reaches the *crystalline lens,* which fine tunes the focusing of light that passes through a gelatinous fluid called *vitreous humor.* Light then passes to the retina.

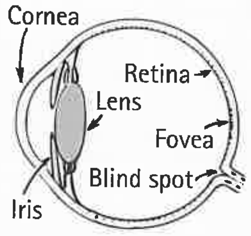

FIGURE 26.15
The human eye.

The *retina* covers the back two-thirds of the eye and is responsible for the wide field of vision that we experience. For clear vision, light must focus directly on the retina. When light focuses in front of or behind the retina, vision is blurry. Until very recently, the retina was more sensitive to light than any artificial detector ever made. The retina is not uniform. In the middle is the *macula,* and a small depression in the center is the *fovea,* the region of most distinct vision. Behind the retina is the *optic nerve,* which transmits signals from the photoreceptor cells to the brain.

Much greater detail can be seen at the fovea than at the side parts of the eye. There is also a spot in the retina where the nerves carrying all the information exit along the optic nerve; this is the *blind spot.* You can demonstrate that you have a blind spot in each eye if you hold this book at arm's length, close your left eye, and look at Figure 26.16 with your right eye only. You can see both the round dot and the X at this distance. If you now move the book slowly toward your face, with your right eye fixed upon the dot, you'll reach a position about 20–25 cm from your eye where the X disappears. Now repeat with only the left eye open, looking this time at the X, and the dot will disappear. When you look with both eyes open, you are not aware of the blind spot, mainly because one eye "fills in" the part to which the other eye is blind. Amazingly, the brain fills in the "expected" view even with one eye open. Repeat the exercise of Figure 26.16 with small objects on various backgrounds. Note that, instead of seeing nothing, your brain gratuitously fills in the appropriate background. So you not only see what's there—you also see what's *not* there!

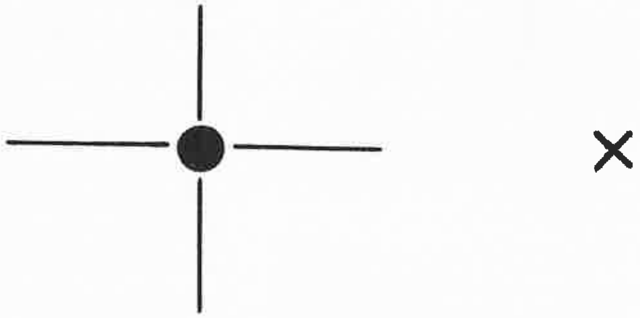

FIGURE 26.16
The blind-spot experiment. Close your left eye and look with your right eye at the round dot. Adjust your distance and find the blind spot that erases the X. Switch eyes and look at the X and the dot disappears. Does your brain fill in crossed lines where the dot was?

The retina is composed of tiny antennae that resonate to the incoming light. There are two basic kinds of antennae, the rods and the cones (Figure 26.17). As the names imply, some of the antennae are rod-shaped and some cone-shaped. The rods predominate toward the periphery of the retina, while cones are denser toward the fovea. Rods handle vision in low light and the cones handle color vision and detail. There are three types of cones: those that are stimulated by low-frequency light, those that are stimulated by light of intermediate frequencies, and those that are stimulated by light of higher frequencies. The cones are very dense in the fovea itself, and, since they are packed so tightly, they are much finer or narrower there than elsewhere in the retina. We see color most acutely by focusing an image on the fovea, where there are no rods. Primates and a species of ground squirrel are the only mammals that have the three types of cones and experience full color vision. The retinas of other mammals consist primarily of rods, which are sensitive only to lightness or darkness, like a black-and-white photograph or movie.

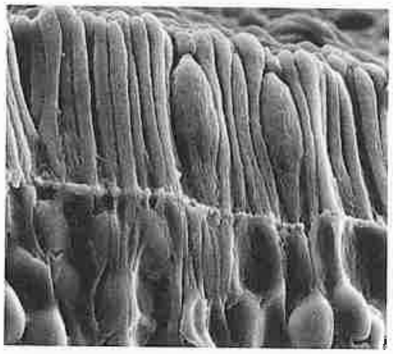

FIGURE 26.17
Magnified view of the rods and cones in the human eye.

In the human eye, the number of cones decreases as we move away from the fovea. It's interesting that the color of an object disappears if it is viewed on the periphery of the visual field. This can be tested by having a friend enter your periphery of vision with some brightly colored objects. You will find that you can see the objects before you can see what color they are.

Another interesting observation is that the periphery of the retina is very sensitive to motion. Although our vision is poor from the corner of our eye, we are sensitive to anything moving there. We are "wired" to look for something jiggling to the side of our visual field, a feature that must have been important in our evolutionary development. So have your friend shake those brightly colored objects when she brings them into the periphery of your vision. If you can just barely see the objects when they shake, but not at all when they're stationary, then you won't be able to tell what color they are (Figure 26.18). Try it and see!

Another distinguishing feature of the rods and cones is the intensity of light to which they respond. The cones require more energy than the rods before they will "fire" an impulse through the nervous system. If the intensity of light is very low, the things we see have no color. We see low intensities with our rods. Dark-adapted vision is almost entirely due to the rods, while vision in bright light is due to the cones. Stars, for example, look white to us. Yet most stars are actually brightly colored. A time exposure of the stars with a camera reveals reds and red-oranges for the "cooler" stars and blues and blue-violets for the "hotter" stars. The starlight is too weak, however, to fire the color-perceiving cones in the retina. So we see the stars with our rods and perceive them as white or, at best, as only faintly colored. Females have a slightly lower threshold of firing for the cones, however, and can see a bit more color than males. So if she says she sees colored stars and he says she doesn't, she is probably right!

We find that the rods "see" better than the cones toward the blue end of the color spectrum, and the reverse is true at the other end of the spectrum. As far as the rods are concerned, a deep red object might as well be black. Thus, if you have two colored objects—say, one blue and one red—the blue one will appear much brighter than the red in dim light, although the red one might be much brighter than the blue one in bright light. The effect is quite intriguing. Try this: In a dark room, find a magazine or something that has colors, and, before you know for sure what the colors are, judge the lighter and darker areas. Then bring the magazine into the light. You should see a remarkable shift between the brightest and dimmest colors.[6]

The rods and cones in the retina are not connected directly to the optic nerve, but, quite amazingly, are connected to many other cells that are joined to one another. While many of these cells are interconnected, only a few carry information to the optic nerve. Through these interconnections, a certain amount of information is combined from several visual receptors and "digested" in the retina. In this way, the light signal is "thought about" before it goes to the optic nerve and thence to the main body of the brain. So some brain functioning occurs in the eye itself. The eye does some of our "thinking" for us. This thinking is betrayed by the iris, the colored part of the eye that expands and contracts and regulates the size of the pupil, admitting more or less light as the intensity of light changes. It so happens that the expansion or contraction of the iris is related to our emotions. If we see, smell, taste, or hear something that is pleasing to us, our pupils automatically increase in size. If we see, smell, taste, or hear something repugnant to us, our pupils automatically contract. Many card players have betrayed the value of a hand by the size of their pupils! (The study of the size of the pupil as a function of attitudes is called *pupilometrics.*)

fyi

- Animals with 360° vision without turning their heads include rabbits and hares because of their big protruding eyes on the sides of their heads. But they have depth perception only where the view from each eye overlaps a bit in front of their heads and behind them.

FIGURE 26.18

On the periphery of your vision, you can see an object and its color only if it is moving.

Eyes differ for different creatures. Mostly cones and only a few rods are in the retina of a chicken, who doesn't see dim light well. Bees have cones that are sensitive to ultraviolet light. The giant squid has the largest eyes in the world.

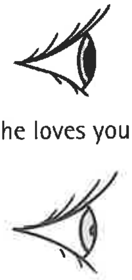

FIGURE 26.19

The size of your pupils depends on your mood.

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[6] This phenomenon is called the *Purkinje effect* after the Czech physiologist who discovered it.

The brightest light that the human eye can perceive without damage is some 500 million times brighter than the dimmest light that can be perceived. Look at a nearby lightbulb. Then turn to look into a dimly lit closet. The difference in light intensity may be more than a million to one. Because of an effect called *lateral inhibition,* we don't perceive the actual differences in brightness. The brightest places in our visual field are prevented from outshining the rest, for whenever a receptor cell on our retina sends a strong brightness signal to our brain, it also signals neighboring cells to dim their responses. In this way, we even out our visual field, which allows us to discern detail in very bright areas and in dark areas as well. (Camera film is not so good at this. A photograph of a scene with strong differences of intensity may be overexposed in one area and underexposed in another.) Lateral inhibition exaggerates the difference in brightness at the edges of places in our visual field. Edges, by definition, separate one thing from another. So we accentuate differences. The gray rectangle on the left in Figure 26.20 appears darker than the gray rectangle on the right when the edge that separates them is in our view. But cover the edge with your pencil or your finger, and they look equally bright. That's because both rectangles *are* equally bright; each rectangle is shaded lighter to darker, moving from left to right. Our eye concentrates on the boundary where the dark edge of the left rectangle joins the light edge of the right rectangle, and our eye–brain system assumes that the rest of the rectangle is the same. We pay attention to the boundary and ignore the rest.

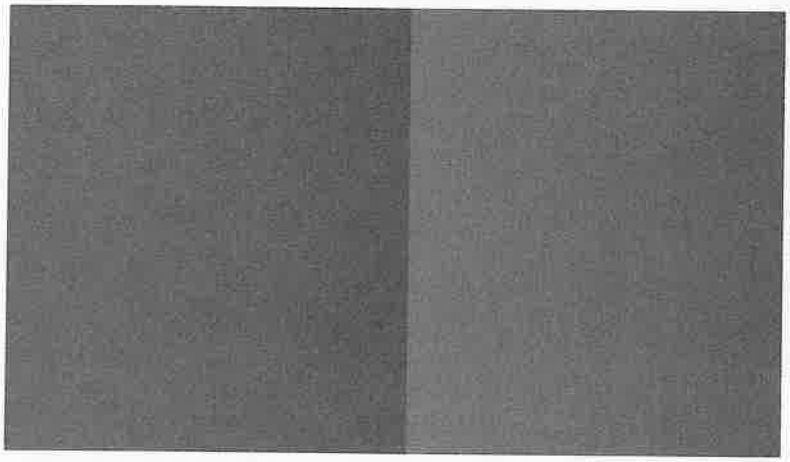


FIGURE 26.20

Both rectangles are equally bright. Cover the boundary between them with your pencil and see.

Questions to ponder: Is the way the eye selects edges and makes assumptions about what lies beyond similar to the way in which we sometimes make judgments about other cultures and other people? Don't we, in the same way, tend to exaggerate the differences on the surface while ignoring the similarities and subtle differences within?

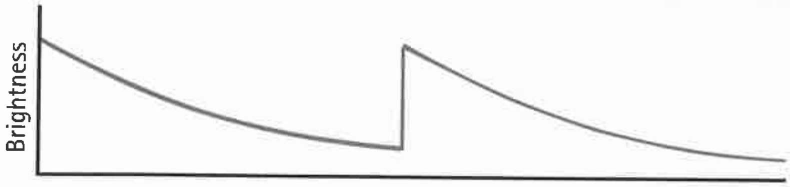
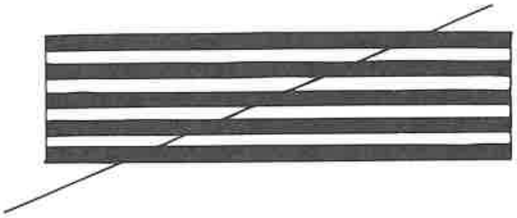


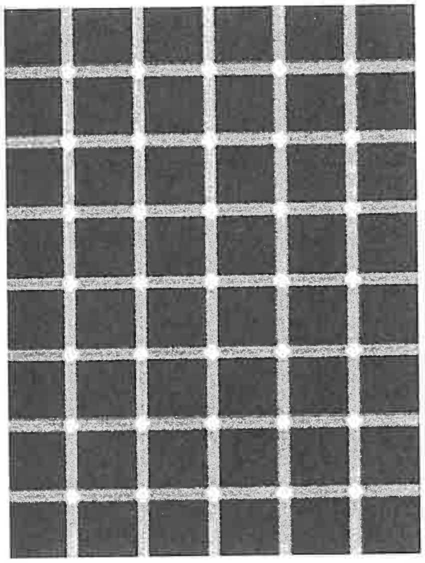
FIGURE 26.21

Graph of brightness levels for the rectangles in Figure 26.20.

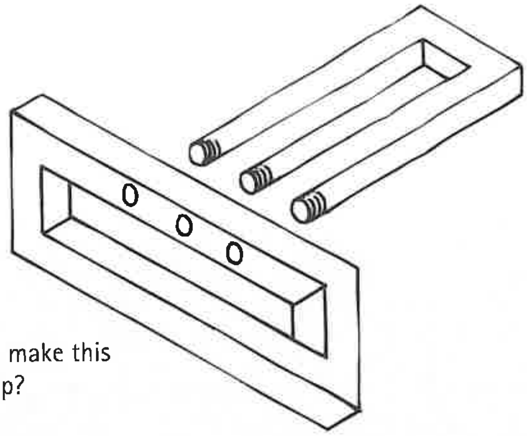


Is the slanted line really broken?

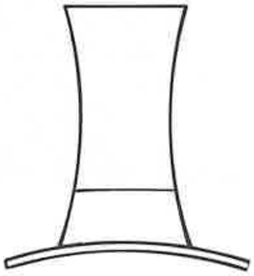
Are the dashes on the right really shorter?



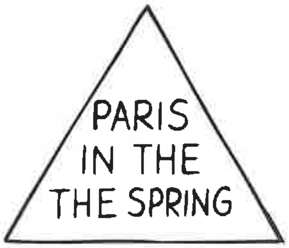
Can you count the black dots?



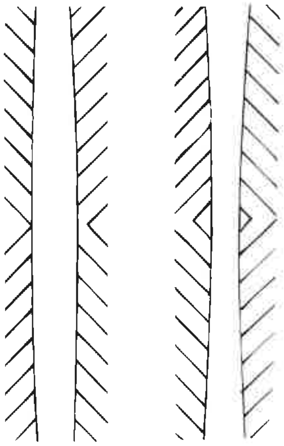
Could you make this in the shop?



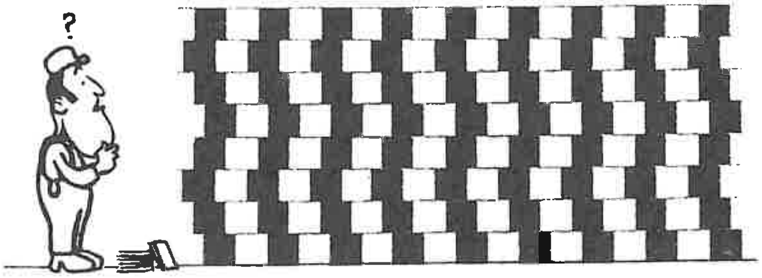
Is the hat taller than the brim is wide?



What does this sign read?



Are the vertical lines parallel?



Are the rows of tiles really crooked?

FIGURE 26.22
Optical illusions.

SUMMARY OF TERMS

Electromagnetic wave An energy-carrying wave emitted by a vibrating charge (often electrons) that is composed of oscillating electric and magnetic fields that regenerate one another.

Electromagnetic spectrum The range of electromagnetic waves extending in frequency from radio waves to gamma rays.

Transparent The term applied to materials through which light can pass in straight lines.

Opaque The term applied to materials that absorb light without reemission and thus through which light cannot pass.

Shadow A shaded region that appears where light rays are blocked by an object.

Umbra The darker part of a shadow where all the light is blocked.

Penumbra A partial shadow that appears where some but not all of the light is blocked.

Solar eclipse An event wherein the Moon blocks light from the Sun and the Moon's shadow falls on part of Earth.

Lunar eclipse An event wherein the Moon passes into the shadow of Earth.

REVIEW QUESTIONS

Electromagnetic Waves

1. What does a *changing magnetic field* induce?
2. What does a *changing electric field* induce?
3. What produces an electromagnetic wave?
4. How is the fact that an electromagnetic wave in space never slows down consistent with the conservation of energy?
5. How is the fact that an electromagnetic wave in space never speeds up consistent with the conservation of energy?
6. What do electric and magnetic fields contain and transport?

The Electromagnetic Spectrum

7. What is the principal difference between a *radio wave* and *light?* Between *light* and an *X-ray?*
8. About how much of the measured electromagnetic spectrum does light occupy?
9. What is the color of visible light of the lowest frequencies? Of the highest frequencies?
10. How does the frequency of a radio wave compare to the frequency of the vibrating electrons that produce it?
11. How is the wavelength of light related to its frequency?
12. What is the wavelength of a wave that has a frequency of 1 Hz and travels at 300,000 km/s?
13. What do we mean when we say that outer space is not really empty?

Transparent Materials

14. The sound coming from one tuning fork can force another to vibrate. What is the analogous effect for light?
15. In what region of the electromagnetic spectrum is the resonant frequency of electrons in glass?
16. What is the fate of the energy in ultraviolet light that is incident upon glass?
17. What is the fate of the energy in visible light that is incident upon glass?
18. How does the frequency of reemitted light in a transparent material compare with the frequency of the light that stimulates its reemission?
19. How does the average speed of light in glass compare with its speed in a vacuum?
20. Why are infrared waves often called *heat waves?*

Opaque Materials

21. Why do opaque materials become warmer when light shines on them?
22. Why are metals shiny?
23. Why do wet objects normally look darker than the same objects when dry?
24. Distinguish between an *umbra* and a *penumbra.*
25. Do Earth and the Moon always cast shadows? What do we call the occurrence where one passes within the shadow of the other?

Seeing Light—the Eye

26. Distinguish between the *rods* and *cones* of the eye and between their functions.

PROJECTS

1. Compare the size of the Moon on the horizon with its size higher in the sky. One way to do this is to hold at arm's length various objects that will just barely block out the Moon. Experiment until you find something just right, perhaps a thick pencil or a pen. You'll find that the object will be less than a centimeter, depending on the length of your arms. Is the Moon really bigger when it is near the horizon?
2. Which eye do you use more? To test which you favor, hold a finger up at arm's length. With both eyes open, look past it at a distant object. Now close your right eye. If your finger appears to jump to the right, then you use your right eye more. Check with friends who are both left-handed and right-handed. Is there a correlation between dominant eye and dominant hand?

EXERCISES

1. A friend says, in a profound tone, that light is the only thing we can see. Is your friend correct?
2. Your friend goes on to say that light is produced by the connection between electricity and magnetism. Is your friend correct?
3. What is the fundamental source of electromagnetic radiation?
4. Which have the longest wavelengths—light waves, X-rays, or radio waves?
5. Which has the shorter wavelengths, ultraviolet or infrared? Which has the higher frequencies?
6. How is it possible to take photographs in complete darkness?
7. What is it, exactly, that waves in a light wave?
8. We hear people talk of "ultraviolet light" and "infrared light." Why are these terms misleading? Why are we less likely to hear people talk of "radio light" and "X-ray light"?
9. Knowing that interplanetary space consists of a vacuum, what is your evidence that electromagnetic waves can travel through a vacuum?
10. What is the principal difference between a gamma ray and an infrared ray?
11. What is the speed of X-rays in a vacuum?
12. Which travels faster through a vacuum—an infrared ray or a gamma ray?
13. Your friend says that microwaves and ultraviolet light have different wavelengths but travel through space at the same speed. Do you agree or disagree?
14. Your friend says that any radio wave travels appreciably faster than any sound wave. Do you agree or disagree, and why?
15. Your friend says that outer space, instead of being empty, is chock full of electromagnetic waves. Do you agree or disagree?
16. Are the wavelengths of radio and television signals longer or shorter than waves detectable by the human eye?
17. Suppose a light wave and a sound wave have the same frequency. Which has the longer wavelength?
18. Which requires a physical medium in which to travel—light, sound, or both? Explain.
19. Do radio waves travel at the speed of sound, or at the speed of light, or somewhere in between?
20. When astronomers observe a supernova explosion in a distant galaxy, they see a sudden, simultaneous rise in visible light and other forms of electromagnetic radiation. Is this evidence to support the idea that the speed of light is independent of frequency? Explain.
21. What are the similarities and differences between radio waves and light?
22. A helium–neon laser emits light of wavelength 633 nanometers (nm). Light from an argon laser has a wavelength of 515 nm. Which laser emits the higher-frequency light?
23. Why would you expect the speed of light to be slightly less in the atmosphere than in a vacuum?
24. If you fire a bullet through a board, it will slow down inside and emerge at a speed that is less than the speed at which it entered. Does light, then, similarly slow down when it passes through glass and also emerge at a lower speed? Defend your answer.
25. Pretend that a person can walk only at a certain pace—no faster, no slower. If you time her uninterrupted walk across a room of known length, you can calculate her walking speed. If, however, she stops momentarily along the way to greet others in the room, the extra time spent in her brief interactions gives an *average* speed across the room that is less than her walking speed. How is this similar to light passing through glass? In what way does it differ?
26. Is glass transparent or opaque to light of frequencies that match its own natural frequencies? Explain.
27. Short wavelengths of visible light interact more frequently with the atoms in glass than do longer wavelengths. Does this interaction time tend to speed up or to slow down the average speed of short-wavelength light in glass?
28. What determines whether a material is transparent or opaque?
29. You can get a sunburn on a cloudy day, but you can't get a sunburn even on a sunny day if you are behind glass. Explain.
30. Suppose that sunlight falls both on a pair of reading glasses and on a pair of dark sunglasses. Which pair of glasses would you expect to become warmer? Defend your answer.
31. Why does a high-flying airplane cast little or no shadow on the ground below while a low-flying airplane casts a sharp shadow?
32. Only some of the people on the daytime side of Earth can witness a solar eclipse when it occurs, whereas all the people on the nighttime side of Earth can witness a lunar eclipse when it occurs. Why is this so?
33. Do planets cast shadows? What is your evidence?
34. Lunar eclipses are always eclipses of a full Moon. That is, the Moon is always seen full just before and after Earth's shadow passes over it. Why is this? Why can we never have a lunar eclipse when the Moon is in its crescent or half-moon phase?
35. In 2004, the planet Venus passed between Earth and the Sun. What kind of eclipse, if any, occurred?
36. What astronomical event would be seen by observers on the Moon at the time Earth experiences a lunar eclipse? At the time Earth experiences a solar eclipse?
37. Light from a location on which you concentrate your attention falls on your fovea, which contains only cones. If you wish to observe a weak source of light, like a faint star, why should you not look *directly* at the source?
38. Why do objects illuminated by moonlight lack color?
39. Why do we not see color at the periphery of our vision?
40. Why should you be skeptical when your sweetheart holds you and looks at you with constricted pupils and says, "I love you"?
41. From your experimentation with Figure 26.16, is your blind spot located noseward from your fovea or to the outside of it?
42. Can we infer that a person with large pupils is generally happier than a person with small pupils? If not, why not?
43. The intensity of light decreases as the inverse square of the distance from the source. Does this mean that light energy is lost? Explain.

44. Light from a camera flash weakens with distance in accord with the inverse-square law. Comment on an airline passenger who takes a flash photo of a city at nighttime from a high-flying plane.

45. Ships determine the ocean depth by bouncing sonar waves from the ocean bottom and measuring the round-trip time. How do some airplanes similarly determine their distance to the ground below?

46. The planet Jupiter is more than 5 times as far from the Sun as planet Earth. How does the brightness of the Sun appear at this greater distance?

47. When you look at the night sky, some stars are brighter than others. Can you correctly say that the brightest stars emit more light? Defend your answer.

48. When you look at a distant galaxy through a telescope, how is it that you're looking backward in time?

49. When we look at the Sun, we are seeing it as it was 8 minutes ago. So we can only see the Sun "in the past." When you look at the back of your own hand, do you see it "now" or in "the past"?

50. "20/20 vision" is an arbitrary measure of vision—meaning that you can read what an average person can read at a distance of 20 feet in daylight. What is this distance in meters?

PROBLEMS

1. In 1676, the Danish astronomer Ole Roemer had one of those "aha" moments in science. He concluded from accumulated observations of eclipses of Jupiter's moon at different times of the year that light must travel at finite speed and needed 1300 s to cross the diameter of Earth's orbit around the Sun. Using 300,000,000 km for the diameter of Earth's orbit, calculate the speed of light based on Roemer's 1300-s estimate. How does it differ from a modern value for the speed of light?

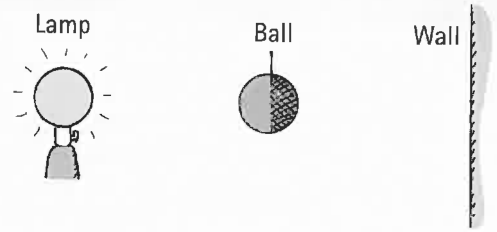
2. More than 200 years later, Albert A. Michelson sent a beam of light from a revolving mirror to a stationary mirror 15 km away. Show that the time interval between light leaving and returning to the revolving mirror was 0.0001 s.

3. The Sun is 1.50×10^{11} m from Earth. How long does it take for the Sun's light to reach Earth? How long does it take light to cross the diameter of Earth's orbit? Compare this time with the time measured by Roemer in the 17th century (Problem 1).

4. Show that it would take 2.5 s for a pulse of laser light to reach the Moon and to bounce back to Earth.

5. The nearest star beyond the Sun is Alpha Centauri, 4.2×10^{16} m away. If we were to receive a radio message from this star today, show that it would have been sent 4.4 years ago.

6. A ball with the same diameter as a lightbulb is held halfway between the bulb and a wall, as shown in the sketch. Construct light rays (similar to those in Figure 26.14) and show that the diameter of the umbra on the wall is the same as the diameter of the ball and that the diameter of the penumbra is 3 times the diameter of the ball.



7. A certain radar installation tracks airplanes by transmitting electromagnetic radiation of wavelength 3 cm. (a) Show that the frequency of this radiation is 10 GHz. (b) Show that the time required for a pulse of radar waves to reach an airplane 5 km away and return is 3.3×10^{-5} s.

• **8.** The wavelength of light changes as light goes from one medium to another, while the frequency remains the same. Is the wavelength longer or shorter in water than in air? Explain in terms of the equation speed = frequency × wavelength. A certain blue-green light has a wavelength of 600 nm (6×10^{-7} m) in air. What is its wavelength in water, where light travels at 75% of its speed in air? In Plexiglas, where light travels at 67% of its speed in air?

CHAPTER 26 ONLINE RESOURCES

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- 26.2, 26.3, 26.4, 26.13, 26.14

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- Eclipses

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- Light and Transparent Materials

Quizzes

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27 Color

1 Carlos Vasquez displays a variety of colors when he is illuminated by only red, green, and blue lamps. 2 The color blue in the sky is due to the scattering of sunlight from the air; the cyan color of water is due to absorption of the infrared and red portions of sunlight by the water. 3 A photo of science author Suzanne Lyons with her children Tristan and Simone. 4 A negative of the same photo shows its complementary colors.

Isaac Newton's first became famous not due to his laws of motion, nor even due to his law of universal gravitation. Newton's fame began with his study of light. In about 1665 while studying the images of heavenly bodies formed by a lens, he noted coloration at the edges of the images. To investigate this, he darkened his room and allowed a beam of sunlight to pass through a small circular hole in the shutter that produced a circular patch of white light on the opposite wall. He then placed a triangular glass prism in the beam of light and observed that the white light split into the colors of the rainbow.

Newton showed that inside a beam of sunlight are all the colors of the rainbow. White light is a composition of the rainbow colors. And furthermore, he showed that a rainbow is the outcome of similar dispersion of sunlight by water drops in the sky.

With a second prism he found that these colors could be recombined to make white light again. In his middle years, he was elected to the Royal Society, where he exhibited the world's first reflector telescope. It can still be seen, preserved at the library of the Royal Society in London with the inscription: "The first reflecting telescope, invented by Sir Isaac Newton, and made with his own hands."

Color in Our World

Roses are red and violets are blue; colors intrigue artists and physics types too. To the physicist, the colors of objects are not in the substances of the objects themselves or even in the light they emit or reflect. Color is a physiological experience and is in the eye of the beholder. So when we say that light from a rose is red, in a stricter sense we mean that it *appears* red. Many organisms, including people with defective color vision, do not see the rose as red at all.

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Tutorial
Color

The colors we see depend on the frequency of the light we see. Lights of different frequencies are perceived as different colors; the lowest-frequency light we can detect appears to most people as the color red and the highest frequency as violet. Between them range the infinite number of hues that make up the color spectrum of the rainbow. By convention, these hues are grouped into the seven colors of red, orange, yellow, green, blue, indigo, and violet. These colors together appear white. The white light from the Sun is a composite of all the visible frequencies.

Selective Reflection

Except for such light sources as lamps, lasers, and gas discharge tubes (which we will treat in Chapter 30), most of the objects around us reflect rather than emit light. They reflect only part of the light that is incident upon them, the part that gives them their color. A rose, for example, doesn't emit light; it reflects light (Figure 27.1). If we pass sunlight through a prism and then place a deep-red rose in various parts of the spectrum, the petals appear brown or black in all parts of the spectrum except in the red. In the red part of the spectrum, the petals appear red, but the green stem and leaves appear black. This shows that the red petals have the ability to reflect red light but not light of other colors; likewise, the green leaves have the ability to reflect green light but not light of other colors. When the rose is held in white light, the petals appear red and the leaves appear green because the petals reflect the red part of the white light and the leaves reflect the green part. To understand why objects reflect specific colors of light, we must turn our attention to the atom.

FIGURE 27.1
The colors of things depend on the colors of the light that illuminates them.

Light is reflected from objects in a manner similar to the way in which sound is "reflected" from a tuning fork when a nearby tuning fork sets it into vibration. One tuning fork can make another vibrate even when the frequencies are not matched, although at significantly reduced amplitudes. The same is true of atoms and molecules. The outer electrons that buzz about the atomic nucleus can be forced into vibration by the oscillating electric fields of electromagnetic waves.[1] Once vibrating, these electrons send out their own electromagnetic waves, just as vibrating acoustical tuning forks send out sound waves.

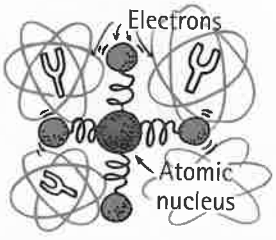

FIGURE 27.2
The outer electrons in an atom vibrate and resonate just as weights on springs would do. As a result, atoms and molecules behave somewhat like optical tuning forks.

Different materials have different natural frequencies for absorbing and emitting electromagnetic radiation. In one material, electrons oscillate readily at certain frequencies; in another material, they oscillate readily at different frequencies. At the resonant frequencies at which the amplitudes of oscillation are large, light is absorbed; but at frequencies below and above the resonant frequencies, light is reemitted. If the material is transparent, the reemitted light passes through it. If the material is opaque, the light passes back into the medium from which it came. This is reflection.

Usually, a material absorbs light of some frequencies and reflects the rest. If a material absorbs most of the visible light that is incident upon it but reflects red, for example, it appears red. That's why the petals of a red rose are red and the stem is green. The atoms of the petals absorb all visible light except red, which they reflect;

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[1] The words *oscillation* and *vibration* both refer to periodic motion—motion that regularly repeats.

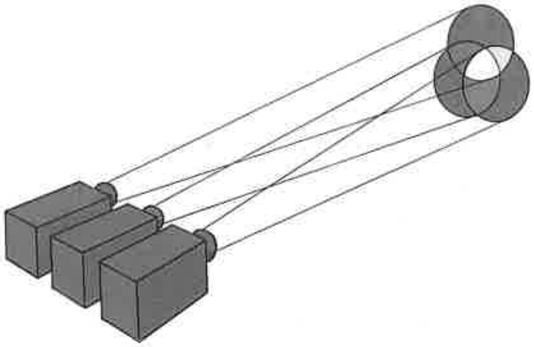

FIGURE 27.9

INTERACTIVE FIGURE

Color addition by the mixing of colored lights. When three projectors shine red, green, and blue light on a white screen, the overlapping parts produce different colors. White is produced where all three colors overlap.

the image. Cyan, yellow, and magenta appear where pairs of dots overlap. A close examination of the image on a TV screen will reveal the assemblage of tiny spots, each less than a millimeter across. When the screen is lit, the mixtures of RGB colors at a distance provide a complete range of colors, plus white.

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Videos

Yellow-Green Peak of Sunlight

Colored Shadows

It's interesting to note that the "black" you see in the darkest scenes on a TV screen is simply the color of the unlit screen itself, which is more a light gray than black. Because our eyes are sensitive to the contrast with the illuminated parts of the screen, we see this gray as black.

CHECK POINT

If white light is all the colors added together, is black simply the absence of light?

Check Your Answer

Yes.

COMPLEMENTARY COLORS

Here's what happens when two of the three additive primary colors are combined:

Red + blue = magenta

Red + green = yellow

Blue + green = cyan

We say that magenta is the opposite of green; yellow is the opposite of blue; and cyan is the opposite of red. Now, when we add each of these colors to its opposite, we get white.

Magenta + green = white (= red + blue + green)

Yellow + blue = white (= red + green + blue)

Cyan + red = white (= blue + green + red)

When two colors are added together to produce white, they are called **complementary colors.** Every hue has some complementary color that when added to it will result in white.

The fact that a color and its complement combine to produce white light is nicely used in lighting stage performances. Blue and yellow lights shining on performers, for example, produce the effect of white light—except where one of the two colors is absent, as in the shadows. The shadow of one lamp, say the blue, is illuminated by the yellow lamp and appears yellow. Similarly, the shadow cast by the yellow lamp appears blue. This is a most interesting effect. We see this effect in Figure 27.10, where red, green, and blue light shine on the golf ball. Note the shadows cast by the ball. The middle shadow is cast by the green spotlight and is not dark because it is illuminated by the red and blue lights, which make magenta. The shadow cast by the blue light appears yellow because it is illuminated by red and green light. Can you see why the shadow cast by the red light appears cyan?

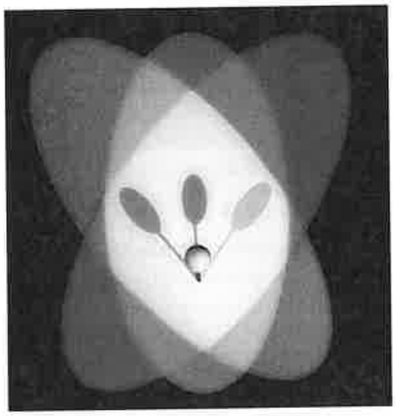


FIGURE 27.10

INTERACTIVE FIGURE

The white golf ball appears white when illuminated with red, green, and blue lights of equal intensities. Why are the shadows of the ball cyan, magenta, and yellow?

CHECK POINT

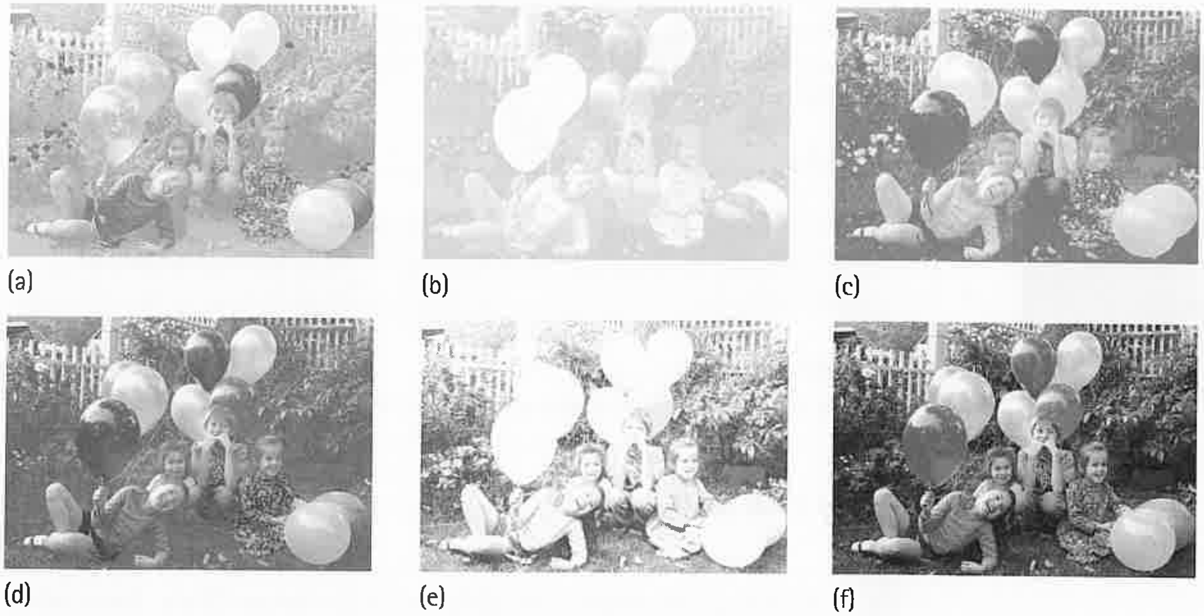
1. From Figure 27.9, find the complements of cyan, of yellow, and of red.
2. Red + blue = ____
3. White − red = ____
4. White − blue = ____

Check Your Answers

1. Red, blue, cyan
2. Magenta
3. Cyan
4. Yellow

Mixing Colored Pigments

Every artist knows that if you mix red, green, and blue paint, the result will not be white but a muddy dark brown. Red and green paint certainly do not combine to form yellow, as is the rule for mixing colored lights. Mixing pigments in paints and dyes is entirely different from mixing lights. Pigments are tiny particles that absorb specific colors. For example, pigments that produce the color red absorb the complementary color cyan. So something painted red absorbs mostly cyan, which is why it reflects red. In effect, cyan has been *subtracted* from white light. Something painted blue absorbs yellow, and so reflects all the colors except yellow. Take yellow away from white and you've got blue. The colors cyan, yellow, and magenta are the **subtractive primaries.** The variety of colors in the colored photographs in this or any other book are the result of cyan, yellow, and magenta dots. Light illuminates the book, and light of some frequencies is subtracted from the light reflected. The rules of color subtraction differ from the rules of light addition.



(a) (b) (c)

(d) (e) (f)

FIGURE 27.11

Only four colors of ink are used to print color illustrations and photographs—(a) magenta, (b) yellow, (c) cyan, and black. When magenta, yellow, and cyan are combined, they produce (d). Addition of black (e) produces the finished result (f).

FIGURE 27.12
Dyes or pigments, as in the three transparencies shown, absorb and effectively subtract light of some frequencies and transmit only part of the spectrum. The subtractive primary colors are cyan, yellow, and magenta. When white light passes through overlapping sheets of these colors, light of all frequencies is blocked (subtracted) and we have black. Where only cyan and yellow overlap, light of all frequencies except green is subtracted. Various proportions of cyan, yellow, and magenta dyes will produce nearly any color in the spectrum.

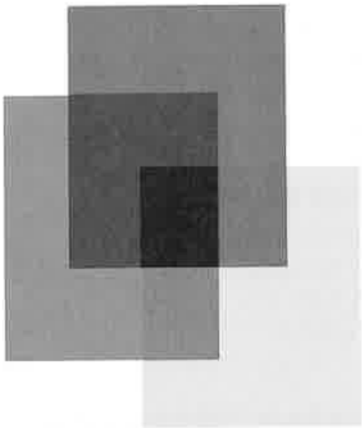


FIGURE 27.13
The rich colors of Sneezlee represent many frequencies of light. The photo, however, is a mixture of only cyan, yellow, magenta, and black (CYMK).

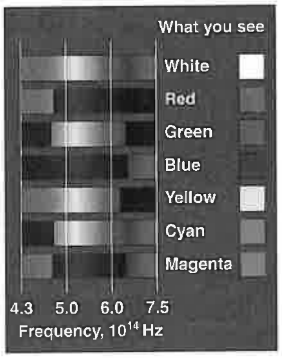


FIGURE 27.14
The approximate ranges of the frequencies we sense as the additive primary colors and the subtractive primary colors.

Color printing is an interesting application of color mixing. Three photographs (color separations) are taken of the illustration to be printed: one through a magenta filter, one through a yellow filter, and one through a cyan filter. Each of the three negatives has a different pattern of exposed areas that corresponds to the filter used and the color distribution in the original illustration. Light is shone through these negatives onto metal plates specially treated to hold printer's ink only in areas that have been exposed to light. The ink deposits are regulated on different parts of the plate by tiny dots. Inkjet printers deposit various combinations of cyan, yellow, magenta, and black inks. This is CMYK printing (K indicates black). Interestingly, the three colors can produce black, but that takes more ink and has a color cast; hence the black ink, which does a better job. Examine the color in any of the figures in this or any book with a magnifying glass and see how the overlapping dots of these colors show a wide range of colors. Or look at a billboard up close.

We see that all the rules of color addition and subtraction can be deduced from Figures 27.9, 27.10, and 27.12.

When we look at the colors on a soap bubble or soap film, we see cyan, yellow, and magenta predominantly. What does this tell us? It tells us that some primary colors have been subtracted from the original white light! (How this happens will be discussed in Chapter 29.)

CHECK POINT

For the projection of light, the primary colors are RGB. For light we see by reflection from opaque surfaces, the primary colors are CMY. Is this correct?

Check Your Answer

Yes! And for reflected light, toss in black with the dyes to get primo images.

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Video
Why the Sky Is Blue and Why the Sunset Is Red

Why the Sky Is Blue

Not all colors are the result of the addition or subtraction of light. Some colors, like the blue of the sky, are the result of selective scattering. Consider the analogous case of sound: If a beam of a particular frequency of sound is directed to a tuning fork of similar frequency, the tuning fork is set into vibration and redirects the beam in multiple directions. The tuning fork *scatters* the sound. A similar process occurs with the scattering of light from atoms and particles that are far apart from one another, as they are in the atmosphere.[2]

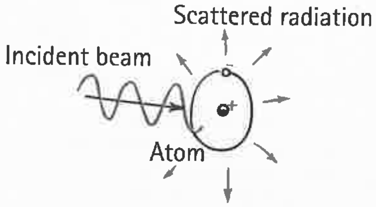

FIGURE 27.15

A beam of light falls on an atom and increases the vibrational motion of electrons in the atom. The vibrating electrons reemit the light in various directions. Light is scattered.

Recall Figure 27.2, where we learned that atoms behave like tiny optical tuning forks and reemit light waves that shine on them. Molecules and larger collections of atoms do the same. The tinier the particle, the greater the amount of higher-frequency light it will reemit. This is similar to the way small bells ring with higher notes than larger bells. The nitrogen and oxygen molecules that make up most of the atmosphere are like tiny bells that "ring" with high frequencies when energized by sunlight. Like sound from the bells, the reemitted light is sent in all directions. When light is reemitted in all directions, we say the light is *scattered.*

Of the visible frequencies of sunlight, violet is scattered the most by nitrogen and oxygen in the atmosphere, followed in order by blue, green, yellow, orange, and red. Red is scattered only a tenth as much as violet. Although violet light is scattered more than blue, our eyes are not very sensitive to violet light. Therefore, the blue scattered light is what predominates in our vision, and we see a blue sky.

FIGURE 27.16

In clean air, the scattering of high-frequency light provides a blue sky. When the air is full of particles larger than molecules, lower-frequency light is also scattered, which adds to the blue to give a whitish sky.

The blue of the sky varies in different locations under different conditions. A principal factor is the water-vapor content of the atmosphere. On clear, dry days, the sky is a much deeper blue than on clear days with high humidity. In locations where the upper air is exceptionally dry, such as Italy and Greece, beautifully blue skies have inspired painters for centuries. Where the atmosphere contains a lot of particles of dust and other particles larger than oxygen and nitrogen molecules, light of the lower frequencies is also scattered strongly. This makes the sky less blue, and it takes on a whitish appearance. After a heavy rainstorm when the particles have been washed away, the sky becomes a deeper blue.

The grayish haze in the skies over large cities is the result of particles emitted by car and truck engines and by factories. Even when idling, a typical gasoline-burning automobile engine emits more than 100 billion particles per second. Most particles are invisible, but they act as tiny centers to which other particles adhere. These are the primary scatterers of lower-frequency light. The largest of these particles absorb rather than scatter light, and a brownish haze is produced. Yuk!

CHECK POINT

Distant dark mountains are bluish. What is the source of this blueness? (*Hint:* What is between us and the mountains we see?)

Check Your Answer

If we look at distant dark mountains, very little light from them reaches us, and the blueness of the atmosphere between us and them predominates. The blueness we attribute to the mountains is actually the blueness of the low-altitude "sky" between us and the mountains!

Why Sunsets Are Red

Light that isn't scattered is light that is transmitted. Because red, orange, and yellow light are the least scattered by the atmosphere, light of these lower frequencies is better transmitted through the air. Red, which is scattered the least—

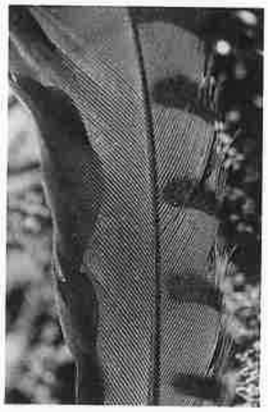

FIGURE 27.17

There are no blue pigments in the feathers of a blue jay. Instead, there are tiny alveolar cells in the barbs of its feathers that scatter light—mainly high-frequency light. So a blue jay is blue for the same reason the sky is blue—scattering.

---

[2] This type of scattering, called *Rayleigh scattering,* occurs whenever the scattering particles are much smaller than the wavelength of incident light and have resonances at frequencies higher than those of the scattered light. Scattering is more complex than our simplified treatment here.

Isn't it true that knowing why the sky is blue and why sunsets are red *adds* to their beauty? Knowledge doesn't subtract—it adds.

and, therefore, is transmitted the most—passes through more atmosphere than any other color. So the thicker the atmosphere through which a beam of sunlight travels, the more time there is to scatter all the higher-frequency components of the light. This means that the light that makes it through best is red. As Figure 27.18 shows, sunlight travels through more atmosphere at sunset, and that is why sunsets (and sunrises) are red.

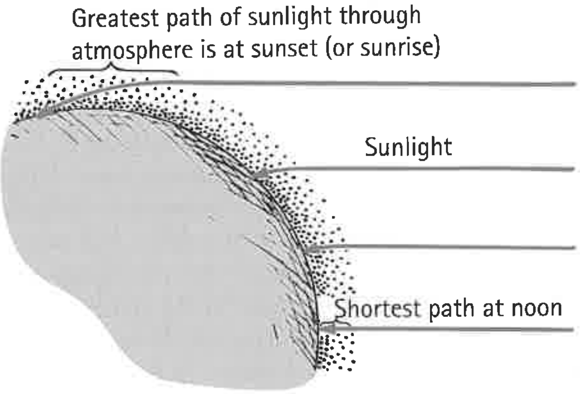

FIGURE 27.18

INTERACTIVE FIGURE

A sunbeam must travel through more of the atmosphere at sunset than at noon. As a result, more blue is scattered from the beam at sunset than at noon. By the time a beam of initially white light reaches the ground, only light of the lower frequencies survives to produce a red sunset.

fyi

- Atmospheric soot heats Earth's atmosphere by absorbing light, while cooling local regions by blocking sunlight from reaching the ground. Soot particles in the air may trigger severe rains in one region and cause droughts and dust storms in another.

At noon, sunlight travels through the least amount of atmosphere to reach Earth's surface. Only a small amount of high-frequency light is scattered from the sunlight, enough to make the Sun look yellowish. As the day progresses and the Sun descends lower in the sky, the path through the atmosphere is longer, and more violet and blue are scattered from the sunlight. The removal of violet and blue leaves the transmitted light redder. The Sun becomes progressively redder, going from yellow to orange and finally to a red-orange at sunset. Sunsets and sunrises are unusually colorful following volcanic eruptions because particles larger than atmospheric molecules are then more abundant in the air.[3]

FIGURE 27.19

The sunset sky is red because of the absence of high-frequency light that has been scattered beyond the horizon.

---

[3] Sunsets and sunrises would be unusually colorful if particles larger than atmospheric molecules were more abundant in the air. This was the case all over the world for three years following the eruption, in 1883, of the volcano Krakatau (or Krakatoa) in what is now Indonesia, when micrometer-sized particles were spewed out in abundance and spread throughout the world's atmosphere. This occurred to a lesser extent following the 1991 eruption of Mount Pinatubo in the Philippines. Next?

Practicing Physics

You can simulate a sunset with a fish tank full of water in which you've dropped a tiny bit of milk. A few drops will do. Then shine a flashlight beam through the water and you'll see that it looks bluish from the side. Milk particles are scattering the higher frequencies of light in the beam. Light emerging from the far end of the tank will have a reddish tinge. That's the light that wasn't scattered.

The colors of the sunset are consistent with our rules for color mixing. When blue is subtracted from white light, the complementary color that is left is yellow. When higher-frequency violet is subtracted, the resulting complementary color is orange. When medium-frequency green is subtracted, magenta is left. The combinations of resulting colors vary with atmospheric conditions, which change from day to day, giving us a variety of sunsets to enjoy.

CHECK POINT

1. If molecules in the sky scattered low-frequency light more than high-frequency light, what color would the sky be? What color would sunsets be?
2. Distant snow-covered mountains reflect a lot of light and are bright. Very distant ones look yellowish. Why? (*Hint:* What happens to the reflected white light as it travels from the mountains to us?)

Check Your Answers

1. If low-frequency light were scattered, the noontime sky would appear reddish-orange. At sunset, more reds would be scattered by the longer path of the sunlight, and the sunlight would be predominantly blue and violet. So sunsets would appear blue!
2. Bright snow-covered mountains appear yellow because the blue in the white light they reflect is scattered on its way to us. By the time the light reaches us, it is weak in the high frequencies and strong in the low frequencies—hence, it is yellowish. Snow-covered mountains much farther away have an orange tinge for the same reason a sunset appears orange.

Why do we see the scattered blue when the background is dark but not when the background is bright? Because the scattered blue is faint. A faint color will show itself against a dark background but not against a bright background. For example, when we look from Earth's surface at the atmosphere against the darkness of space, the atmosphere is sky blue. But astronauts above who look down through the same atmosphere to the bright surface of Earth do not see the same blueness.

fyi

- A new brown paint is now available that reflects infrared but absorbs visible light. Since over half the power of sunlight is in the infrared, roofs covered with this paint are called "cool roofs," for they reduce energy spent on air conditioning. The same "cool" color on cars, sidewalks, and road pavements also adds to the greening of the planet.

Why Clouds Are White

Water droplets in a variety of sizes make up clouds. The different-size droplets produce a variety of scattered frequencies: The tiniest scatter more blue than other colors; slightly larger droplets scatter light of slightly higher frequencies, such as green; and still larger droplets scatter more red. The overall result is a white cloud. Electrons close to one another in a droplet vibrate together and in step, which results in a greater intensity of scattered light than from the same number of electrons vibrating separately. Hence, clouds are bright! Larger assortments of droplets absorb much of the light incident upon them, and so the intensity of the scattered light is less. This contributes to the darkness of clouds composed of larger droplets.

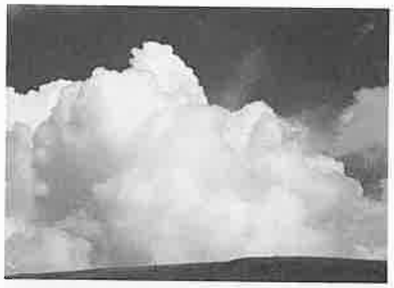

FIGURE 27.20

A cloud is composed of water droplets of various sizes. The tiniest droplets scatter blue light, slightly larger ones scatter green light, and still larger ones scatter red light. The result is a white cloud.

Further increase in the size of the droplets causes them to fall as raindrops, and we have rain.

The next time you find yourself admiring a crisp blue sky, or delighting in the shapes of bright clouds, or watching a beautiful sunset, think about all those ultra-tiny optical tuning forks vibrating away—you'll appreciate these everyday wonders of nature even more!

Why Water Is Greenish Blue

We often see a beautiful deep blue when we look at the surface of a lake or the ocean. But that isn't the color of water; it's the reflected color of the sky. The color of water itself, as you can see by looking at a piece of white material under water, is a pale greenish blue.

Although water is transparent to light of nearly all the visible frequencies, it strongly absorbs infrared waves. This is because water molecules resonate to the frequencies of infrared. The energy of the infrared waves is transformed into internal energy in the water, which is why sunlight warms water. Water molecules resonate somewhat in the visible red, which causes red light to be a little more strongly absorbed in water than blue light. Red light is reduced to one-quarter of its initial brightness by 15 meters of water. There is very little red light in the sunlight that penetrates below 30 meters of water. When red is removed from white light, what color remains? This question can be asked in another way: What is the complementary color of red? The complementary color of red is cyan—a bluish-green color. In seawater, everything at these depths has a cyan color.

Many crabs and other sea creatures that appear black in deep water are found to be red when they are raised to the surface. At these depths, black and red look the same. Apparently the selection mechanism of evolution could not distinguish between black and red at such depths in the ocean.

fyi

- The fall colors of some trees is due to removal of sugars and starches from leaves to tree roots for winter storage. As green is withdrawn from leaves, yellow begins to show, which can change to red, orange, or purple by the acidity of other chemical substances in the leaf. So each fall, the trees prepare for winter "sleep" in a cloak of flaming glory.

FIGURE 27.21

Water is cyan because it absorbs red light. The froth in the waves is white because, like clouds, it is composed of a variety of tiny water droplets that scatter light of all the visible frequencies.

Whereas the bluish-green color of water is produced by selective absorption of light, the intriguingly vivid blue of lakes in the Canadian Rocky Mountains is due to scattering.[4] The lakes are fed by runoff from melting glaciers that contain fine particles of silt, called rock flour, which remain suspended in the water. Light scatters from these tiny particles and gives the water its eerily vivid color (Figure 27.22). (Tourists who photograph these lakes are advised to inform their photo processors *not* to adjust the color to a 'real' blue!)

Interestingly enough, the color we see is not in the world around us—the color is in our heads. The world is filled with a montage of vibrations—electromagnetic

FIGURE 27.22

The extraordinary blue of lakes in the Canadian Rocky Mountains is produced by scattering from extremely fine particles of glacial silt suspended in the water.

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[4] Scattering by small, widely spaced particles in the irises of blue eyes, rather than any pigments, accounts for their color. Absorption by pigments accounts for brown eyes.

waves that stimulate the sensation of color when the vibrations interact with the cone-shaped receiving antennae in the retinas of our eyes. How nice that eye–brain interactions produce the beautiful colors we see.

CHECK POINT

Of these sources of blue light (a) TV screen, (b) the sky, (c) lakes of the Canadian Rockies, which are due to scattering?

Check Your Answer

(b) and (c).

SUMMARY OF TERMS

Additive primary colors The three colors—red, blue, and green—that, when added in certain proportions, produce any other color in the visible-light part of the electromagnetic spectrum and can be mixed equally to produce white light.

Complementary colors Any two colors that, when added, produce white light.

Subtractive primary colors The three colors of absorbing pigments—magenta, yellow, and cyan—that, when mixed in certain proportions, reflect any other color in the visible-light part of the electromagnetic spectrum.

REVIEW QUESTIONS

Color in Our World

1. What is the relationship between the frequency of light and its color?

Selective Reflection

2. What occurs when the outer electrons that buzz about the atomic nucleus encounter electromagnetic waves?
3. What happens to light when it falls upon a material that has a natural frequency equal to the frequency of the light?
4. What happens to light when it falls upon a material that has a natural frequency above or below the frequency of the light?

Selective Transmission

5. What color light is transmitted through a piece of red glass?
6. What is a *pigment?*
7. Which warms more quickly in sunlight—a colorless or a colored piece of glass? Why?

Mixing Colored Light

8. What is the evidence for the statement that white light is a composite of all the colors of the spectrum?
9. What is the color of the peak frequency of solar radiation?
10. To what color of light are our eyes most sensitive?
11. What is a *radiation curve?*
12. What frequency ranges of the radiation curve do red, green, and blue light occupy?
13. Why are red, green, and blue called the *additive primary colors?*

Complementary Colors

14. What is the resulting color of equal intensities of red light and cyan light combined?
15. Why are red and cyan called *complementary colors?*

Mixing Colored Pigments

16. When something is painted red, what color is most absorbed?
17. What are the *subtractive primary colors?*
18. If you look with a magnifying glass at pictures printed in full color in this or other books or magazines, you'll notice three colors of ink plus black. What are these colors?

Why the Sky Is Blue

19. Which interact more with high-pitched sounds—small bells or large bells?
20. Which interact more with high-frequency light—small particles or large particles?
21. Why is it incorrect to say the sky is blue because oxygen and nitrogen molecules are blue in color?
22. Why does the sky sometimes appear whitish?

Why Sunsets Are Red

23. Why does the Sun look reddish at sunrise and sunset but not at noon?
24. Why does the color of sunsets vary from day to day?

Why Clouds Are White

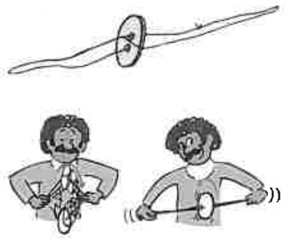
25. What is the evidence for a variety of droplet sizes in a cloud?
26. What is the effect on the color of a cloud when it contains an abundance of large droplets?

Why Water Is Greenish Blue

27. What part of the electromagnetic spectrum is most absorbed by water?
28. What part of the *visible* electromagnetic spectrum is most absorbed by water?
29. What color results when red is subtracted from white light?
30. Why does water appear cyan?

PROJECTS

1. Stare at a piece of colored paper for 45 seconds or so. Then look at a plain white surface. The cones in your retina receptive to the color of the paper become fatigued, so you see an afterimage of the complementary color when you look at a white area. This is because the fatigued cones send a weaker signal to the brain. All the colors produce white, but all the colors minus one produce the complement to the missing color. Try it and see!
2. Cut a disk a few centimeters or so in diameter from a piece of cardboard; punch two holes a bit off-center, big enough to loop a piece of string as shown in the sketch. Twirl the disk as shown, so the string winds up like a rubber band on a model airplane. Then, if you tighten the string by pulling outward, the disk will spin. If half the disk is colored yellow and the other half blue, when it is spun the colors will be mixed and appear nearly white. (How close to white depends on the hues of the colors). Try this for other complementary colors.



3. Fashion a cardboard tube covered at each end with metal foil. Punch a hole in each end with a pencil, one about 3 or so millimeters in diameter and the other twice as big. Place your eye to the small hole and look through the tube at the colors of things against the black background of the tube. You'll see colors that look very different from how they appear against ordinary backgrounds.
4. Write a letter to Grandma and tell her what details you've learned that explain why the sky is blue, sunsets are red, and clouds are white. Discuss whether or not this information adds to or decreases your perception of the beauty of nature.

EXERCISES

1. What color of visible light has the longest wavelength? The shortest wavelength?
2. In a boutique store with only fluorescent lighting, a customer insists on taking dresses into the daylight at the doorway to check their color. Is she being reasonable? Explain.
3. Why is red paint red?
4. Why will the leaves of a red rose be warmed more than the petals when illuminated with red light? How does this relate to people in the hot desert wearing white clothes?
5. If the sunlight were somehow green instead of white, what color clothing would be most advisable on an uncomfortably hot day? On a very cold day?
6. Why do we not list black and white as colors?
7. Why are the interiors of optical instruments intentionally black?
8. Fire engines used to be red. Yellow-green is now the preferred color. Why the change?
9. What is the usual color of common tennis balls, and why?
10. The radiation curve of the Sun (Figures 27.7 and 27.8) show that the brightest light from the Sun is yellow-green. Why, then, do we see the Sun as whitish instead of yellow-green?
11. What color does red cloth appear to be when illuminated by sunlight? By light from a neon sign? By cyan light?
12. Why does a white piece of paper appear white in white light, red in red light, blue in blue light, and so on for every color?
13. A spotlight is coated so that it won't transmit yellow light from its white-hot filament. What color is the emerging beam of light?
14. How could you use the spotlights at a play to change the performers' clothes suddenly from yellow to black?
15. Suppose that two flashlight beams are shone on a white screen, one through a pane of blue glass and the other through a pane of yellow glass. What color appears on the screen where the two beams overlap? Suppose, instead, that the two panes of glass are placed in the beam of a single flashlight. What colors then appear?
16. Does color television operate by color addition or by color subtraction? Defend your answer.
17. On a TV screen, red, green, and blue spots of fluorescent materials are illuminated at a variety of relative intensities to produce a full spectrum of colors. What dots are activated to produce yellow? Magenta? White?
18. What colors of ink do color ink-jet printers use to produce a full range of colors? Do the colors form by color addition or by color subtraction?
19. Your friend reasons that magenta and yellow paint mixed together will produce red because magenta is a combination of red and blue and yellow is a combination of red and green—and that the color in common is red. Do you agree or disagree, and why?
20. Science author Suzanne Lyons is shown with son Tristan wearing red and daughter Simone wearing green in the opening set of photos for this chapter. Note that the

negative of the photo shows these colors differently. What is your explanation?

21. Streetlights that use high-pressure sodium vapor produce light that is mainly yellow with some red. Why are dark blue police cars not advisable in a community that uses these streetlights?
22. In which of these cases will a ripe banana appear black—when illuminated with red, yellow, green, or blue light?
23. What color of light will be transmitted through overlapping cyan and magenta filters?
24. Look at your red, sunburned feet when they are under water. Why don't they look as red as when they are above water?
25. Why does the blood of injured deep-sea divers look greenish-black in underwater photographs taken with natural light, but red when flash is used?
26. By reference to Figure 27.9, complete the following equations:
    Yellow light + blue light = __________ light
    Green light + ____________ light = white light
    Magenta + yellow + cyan = __________ light
27. Check Figure 27.9 to see if the following three statements are accurate. Then fill in the last statement. (All colors are combined by the addition of light.)
    Red + green + blue = white
    Red + green = yellow = white − blue
    Red + blue = magenta = white − green
    Green + blue = cyan = white − ________
28. Your friend says that red and cyan light produce white light because cyan is green + blue, and so red + green + blue = white. Do you agree or disagree, and why?
29. When white light is shone on red ink dried on a glass plate, the color that is transmitted is red. But the color that is reflected is not red. What is it?
30. Stare intently at an American flag. Then turn your view to a white area on a wall. What colors do you see in the image of the flag that appears on the wall?
31. Why can't we see stars in the daytime?
32. Why is the sky a darker blue when you are at high altitudes? (*Hint:* What color is the "sky" on the Moon?)
33. There is no atmosphere on the Moon to produce scattering of light. How does the daytime sky of the Moon appear when viewed from the Moon's surface?
34. Can stars be seen from the Moon's surface in the "daytime" when the Sun is shining?
35. What is the color of the setting Sun as seen on the Moon?
36. At the beach, you can get a sunburn while under the shade of an umbrella. What is your explanation?
37. Pilots sometimes wear glasses that transmit yellow light and absorb light of most other colors. Why does this help them see more clearly?
38. Does light travel faster through the lower atmosphere or through the upper atmosphere?
39. Your friend says that the reason the distant dark mountains appear blue is because you're looking at the sky between you and the mountains. Do you agree or disagree?
40. Why does smoke from a campfire look blue against trees near the ground but yellow against the sky?
41. Comment on the statement "Oh, that beautiful red sunset is just the leftover colors that weren't scattered on their way through the atmosphere."
42. If the sky on a certain planet in the solar system were normally orange, what color would sunsets be?
43. Volcanic emissions spew fine ashes in the air that scatter red light. What color does a full Moon appear to be through these ashes?
44. Tiny particles, like tiny bells, scatter high-frequency waves more than low-frequency waves. Large particles, like large bells, mostly scatter low-frequency waves. Intermediate-size particles and bells mostly scatter waves of intermediate frequencies. How does this relate to the whiteness of clouds?
45. Why is the foam of root beer white, while the beverage is dark brown?
46. Very big particles, like droplets of water, absorb more radiation than they scatter. How does this relate to the darkness of rain clouds?
47. How would the whiteness of snow appear if Earth's atmosphere were several times denser?
48. The atmosphere of Jupiter is more than 1000 km thick. From the surface of Jupiter, would you expect to see a white Sun?
49. Red sunrises occur for the same reason as red sunsets. But sunsets are usually more colorful than sunrises—especially near cities. What is your explanation?
50. You're explaining to a youngster at the seashore why the water is cyan colored. The youngster points to the whitecaps of overturning waves and asks why they are white. What is your answer?

CHAPTER 27 ONLINE RESOURCES

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Interactive Figures

- 27.9, 27.10, 27.18

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- Why the Sky Is Blue and Why the Sunset Is Red

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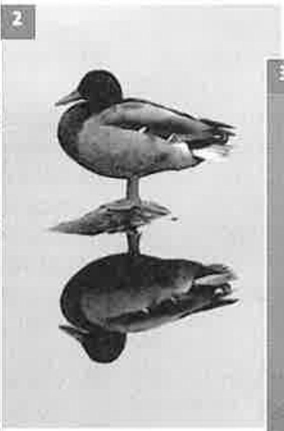
28 Reflection and Refraction



1 Peter Hopkinson boosts class interest using this zany demonstration of standing astride a large mirror as he lifts his right leg while his unseen left leg provides support behind the mirror. 2 Why do the legs of the duck, but not its feet, show in the reflected view of the center photo? 3 Physics teacher Fred Myers stands between parallel mirrors and takes a photo of his daughter McKenzie, now a design engineer.

French lawyer and mathematician Pierre de Fermat (pronounced fer-mah) was born in 1601. He attended the University of Toulouse before moving to Bordeaux in his twenties. He was fluent in Latin, Greek, Italian, and Spanish and was well recognized for his written verse in several languages. In 1629, he produced important mathematical work on the ideas of maxima and minima, which turned out to be useful to Newton, as well as to Leibniz, when they independently developed calculus. Through his correspondence with Blaise Pascal in 1654, Fermat helped lay the fundamental groundwork for the theory of probability.

To mathematicians, Fermat is best remembered for his famous "Last Theorem," a special case of which states that the sum of two cubes of whole numbers cannot be the cube of another whole number. For more than 300 years, mathematicians were tantalized by a marginal note in Latin in one of Fermat's books, which is translated as "I have a truly marvelous proof of this proposition which this margin is too narrow to contain." Not until 1994 was the theorem proved (by Andrew Wiles of Princeton University) using methods unavailable to Fermat, so it seems unlikely that Fermat really did have a proof. This doesn't diminish the genius that he showed in many other ways.

Fermat had a unique way of looking at paths of light. He stated that of all the possible paths that light can travel from one point to another, it travels the path that requires the least time. Reflection and refraction, the chief topics of this chapter, are nicely understood with this principle.

Reflection

Most of the things we see around us do not emit light of their own. They are visible because they reemit light reaching their surface from a primary source, such as the Sun or a lamp, or from a secondary source, such as the illuminated sky. When light falls on the surface of a material, it is either reemitted without change in frequency or is absorbed into the material and converted to heat.[1] We say light is *reflected* when it is returned into the medium from which it came—the process is **reflection.**

When sunlight or lamplight illuminates this page, electrons in the atoms of the paper and ink vibrate more energetically in response to the oscillating electric fields of the illuminating light. The energized electrons reemit the light by which you see the page. When the page is illuminated by white light, the paper appears white, which reveals that the electrons reemit all the visible frequencies. Very little absorption occurs. The ink is a different story. Except for a bit of reflection, it absorbs all the visible frequencies and therefore appears black.

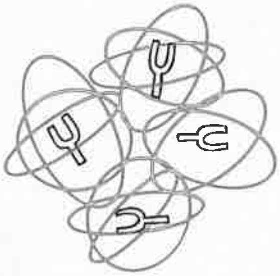


FIGURE 28.1

Light interacts with atoms as sound interacts with tuning forks.

Principle of Least Time[2]

The idea that light takes the quickest path in going from one place to another, as mentioned on the previous page, was formulated by Pierre Fermat. His idea is now called **Fermat's principle of least time.**

We can understand reflection by Fermat's principle. Consider the following situation. In Figure 28.2, we see two points, A and B, and an ordinary plane mirror beneath. How can we get from A to B most quickly, that is, in the shortest time? The answer is simple enough—go straight from A to B! But, if we add the condition that the light must strike the mirror in going from A to B in the shortest time, the answer is not so easy. One way would be to go as quickly as possible to the mirror and then to B, as shown by the solid lines in Figure 28.3. This gives us a short path to the mirror but a very long path from the mirror to B. If we instead consider a point on the mirror a little to the right, we slightly increase the first distance, but we considerably decrease the second distance, and so the total path length shown by the dashed lines—and therefore the travel time—is less. How can we find the exact point on the mirror for which the time is least? We can find it very nicely by a geometric trick.

We construct, on the opposite side of the mirror, an artificial point, B′, which is the same distance "through" and below the mirror as the point B is above the mirror (Figure 28.4). The shortest distance between A and this artificial point B′ is simple enough to determine: It's a straight line. Now this straight line intersects the mirror at a point C, the precise point of reflection for the shortest path and hence the path of least time for the passage of light from A to B. Inspection will show that the distance from C to B equals the distance from C to B′. We see that the length of the path from A to B′ through C is equal to the length of the path from A to B bouncing off point C along the way.

Inspection of Figures 28.4 and 28.5 and a little geometrical reasoning will show that the angle of incident light from A to C is equal to the angle of reflection from C to B.

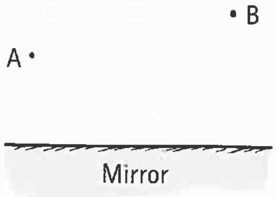


FIGURE 28.2

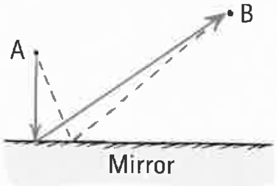


FIGURE 28.3

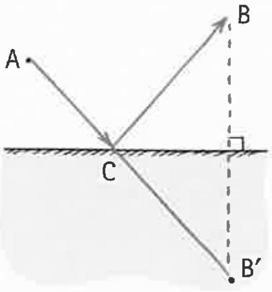


FIGURE 28.4

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[1] Another less common fate is absorption followed by reemission at lower frequencies—fluorescence (Chapter 30).

[2] This material and many of the examples of least time are adapted from R. P. Feynman, R. B. Leighton, and M. Sands, *The Feynman Lectures on Physics*, Vol. I, Chap. 26 (Reading, MA: Addison-Wesley, 1963).

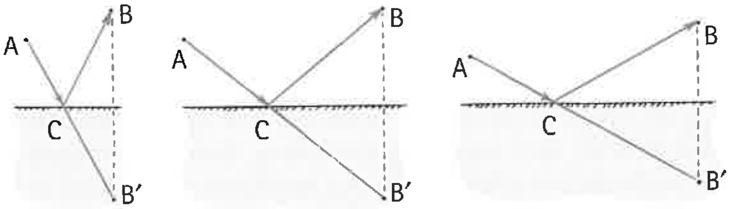


FIGURE 28.5
Reflection.

Law of Reflection

As Fermat showed, the angle of incident light will be the same as the angle of reflected light. This is the **law of reflection,** and it holds for all angles (Figure 28.5):

The angle of incidence equals the angle of reflection.

The law of reflection is illustrated with arrows representing light rays in Figure 28.6. Instead of measuring the angles of incident and reflected rays from the reflecting surface, it is customary to measure them from a line perpendicular to the plane of the reflecting surface. This imaginary line is called the *normal.* The incident ray, the normal, and the reflected ray all lie in the same plane. Such reflection from a smooth surface is called *specular* reflection. Mirrors produce excellent specular reflections.

White coatings on roofs reflect up to 85% of incident light, which on hot summer days greatly reduces air conditioning costs and carbon emissions. On cold winter days where heat is desirable, however, this is not such a good idea. But for regions with hot summers and mild winters, paint your rooftops white! (As mentioned in Chapter 27, there are also new brown paints that aid cooling by reflecting infrared light.)

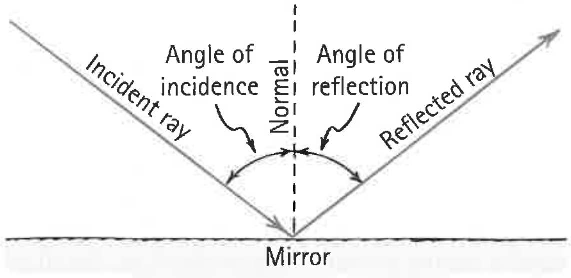


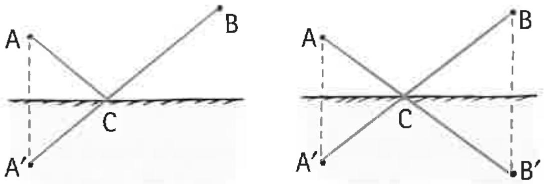
FIGURE 28.6
INTERACTIVE FIGURE
The law of reflection.

CHECK POINT

The construction of artificial points B′ in Figures 28.4 and 28.5 shows how light encounters point C in reflecting from A to B. By similar construction, show that light originating from B reflects to A also encounters the same point C.

Check Your Answer

Construct an artificial point A′ as far below the mirror as A is above; then draw a straight line from B to A′ to find C, as shown at the left. Both constructions superimposed, at right, show that C is common to both. We see that light will follow the same path if it goes in the opposite direction. Whenever you see somebody else's eyes in a mirror, be assured that they can also see yours.



PLANE MIRRORS

Suppose a candle flame is placed in front of a plane mirror. Rays of light radiate from the flame in all directions. Figure 28.7 shows only four of the infinite number of rays leaving one of the infinite number of points on the candle. These rays diverge from the candle flame and encounter the mirror, where they are reflected at angles equal to their angles of incidence. The rays diverge from the mirror and appear to emanate from a particular point behind the mirror (where the dashed lines intersect). An observer sees an image of the flame at this point. The light rays do not actually originate from this point, so the image is called a *virtual image.* The image is as far behind the mirror as the object is in front of the mirror, and image and object have the same size. When you view yourself in a mirror, for example, the size of your image is the same as the size your twin would appear if located the same distance behind the mirror as you are in front—as long as the mirror is flat (we call a flat mirror a *plane mirror*).

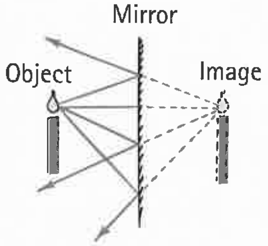


FIGURE 28.7

A virtual image is formed behind the mirror and is located at the position where the extended reflected rays (dashed lines) converge.

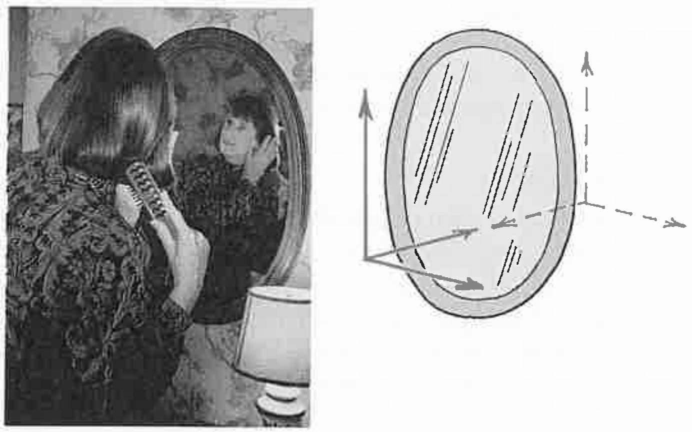


FIGURE 28.8

Marjorie's image is as far behind the mirror as she is in front. Note that she and her image have the same color of clothing—evidence that light doesn't change frequency upon reflection. Interestingly, her left–right axis is no more reversed than her up–down axis. The axis that *is* reversed, as shown to the right, is front–back. That's why it seems her left hand faces the right hand of her image.

When the mirror is curved, the sizes and distances of object and image are no longer equal. We will not discuss curved mirrors in this text, except to say that the law of reflection still applies. A curved mirror behaves as a succession of flat mirrors, each at a slightly different angular orientation from the one next to it. At each point, the angle of incidence is equal to the angle of reflection (Figure 28.9). Note that, in a curved mirror, unlike in a plane mirror, the normals (shown by the dashed black lines to the left of the mirror) at different points on the surface are not parallel to one another.

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Video
Image Formation in a Mirror

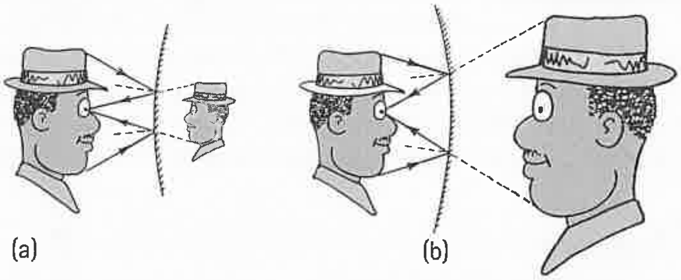

FIGURE 28.9

(a) The virtual image formed by a *convex* mirror (a mirror that curves outward) is smaller and closer to the mirror than the object.
(b) When the object is close to a *concave* mirror (a mirror that curves inward like a "cave"), the virtual image is larger and farther away than the object. In either case, the law of reflection applies to each ray.

Whether the mirror is plane or curved, the eye–brain system cannot ordinarily differentiate between an object and its reflected image. So the illusion that an object exists behind a mirror (or in some cases in front of a concave mirror) is merely due to the fact that the light from the object enters the eye in exactly the same manner, physically, as it would have entered if the object really were at the image location.

Only part of the light that strikes a surface is reflected. On a surface of clear glass, for example, and for normal incidence (light perpendicular to the surface), only about 4% is reflected from each surface. On a clean and polished aluminum or silver surface, however, about 90% of incident light is reflected.

CHECK POINT

1. What evidence can you cite to support the claim that the frequency of light does not change upon reflection?
2. If you wish to take a picture of your image while standing 5 m in front of a plane mirror, for what distance should you set your camera to provide the sharpest focus?

Check Your Answers

1. The color of an image is identical to the color of the object forming the image. When you look at yourself in a mirror, for example, the color of your eyes doesn't change.
2. Set your camera for 10 m; the situation is equivalent to standing 5 m in front of an open window and viewing your twin standing 5 m beyond the window.

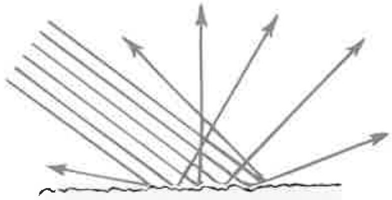

FIGURE 28.10

Diffuse reflection. Although each ray obeys the law of reflection, the many different surface angles that light rays encounter in striking a rough surface cause reflection in many directions.

DIFFUSE REFLECTION

When light is incident on a rough or granular surface, it is reflected in many directions. This is called *diffuse reflection* (Figure 28.10). If the surface is so smooth that the distances between successive elevations on the surface are less than about one-eighth the wavelength of the light, there is very little diffuse reflection, and the surface is said to be *polished.* A surface, therefore, may be polished for radiation of a long wavelength but not polished for light of a short wavelength. The wire-mesh "dish" shown in Figure 28.11 is very rough for light waves and so is hardly mirrorlike; but for long-wavelength radio waves, it is "polished" and therefore an excellent reflector. Reflection off the walls of your room is a good example of diffuse reflection. The light reflects back to the room, but produces no mirror images. Unlike specular reflection, diffuse reflection does not produce a mirror image.

FIGURE 28.11

The open-mesh parabolic dish is a diffuse reflector for short-wavelength light but a polished reflector for long-wavelength radio waves.

Light reflecting from this page is diffuse. The page may be smooth to a radio wave, but is rough to a light wave. Rays of light that strike this page encounter millions of tiny flat surfaces facing in all directions. The incident light therefore is reflected in all directions, which enables us to see objects from any direction or position. You can see the road ahead of your car at night, for instance, because of diffuse reflection by the road surface. When the road is wet, diffuse reflection is less, and it is more difficult to see. Most of our environment is seen by diffuse reflection.

FIGURE 28.12

A magnified view of the surface of ordinary paper.

CHECK POINT

How can the surface of water in a lake exhibit both specular and diffuse reflection?

Check Your Answer

Where the water is very still and the surface smooth, reflected images occur. This is specular reflection. Where the water is rough and doesn't show reflected images, the reflection is diffuse.

Refraction

Recall, from Chapter 26, that the average speed of light is lower in glass and other transparent materials than through empty space. Light travels at different speeds in different materials.[3] It travels at 300,000 km/s in a vacuum, at a slightly lower speed in air, and at about three-fourths that speed in water. In a diamond, light travels at about 40% of its speed in a vacuum. When light bends in passing obliquely from one medium to another, we call the process **refraction.** It is a common observation that a ray of light bends and takes a longer path when it encounters glass or water at an oblique angle. But the longer path taken is nonetheless the path requiring the least time. A straight-line path would take a longer time. We can illustrate this with the following situation.

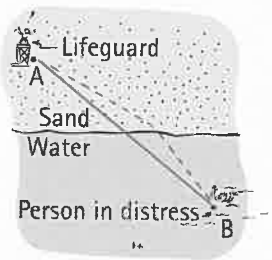

FIGURE 28.13

Refraction.

Imagine that you are a lifeguard at a beach and you spot a person in distress in the water. We show the relative positions of you, the shoreline, and the person in distress in Figure 28.13. You are at point A, and the person is at point B. You can run faster than you can swim. Should you travel in a straight line to get to B? A little thought will show that a straight-line path would not be the best choice because, if you instead spent a little bit more time traveling farther on land, you would save a lot more time in swimming a lesser distance in the water. The path of shortest time is shown by the dashed-line path, which clearly is not the path of the shortest distance. The amount of bending at the shoreline depends, of course, on how much faster you can run than swim. The situation is similar for a ray of light incident upon a body of water, as shown in Figure 28.14. The angle of incidence is larger than the angle of refraction by an amount that depends on the relative speeds of light in air and in water.

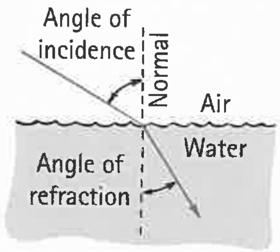

FIGURE 28.14

INTERACTIVE FIGURE

Refraction.

Consider the pane of thick window glass in Figure 28.15. When light goes from point A through the glass to point B, it will go in a straight-line path. In this case, light encounters the glass perpendicularly, and we see that the shortest distance through both air and glass corresponds to the shortest time. But what about light that goes from point A to point C? Will it travel in the straight-line path shown by the dashed line? The answer is *no,* because if it did so it would be spending more time inside the glass, where light travels more slowly than in air. The light will instead take a less-inclined path through the glass. The time saved by taking the resulting shorter path through the glass more than compensates for the added time required to travel the slightly longer path through the air. The overall path is the path of least time—the quickest path. The result is a parallel displacement of the light beam, because the angles in and out are the same. You'll notice this displacement when you look through a thick pane of glass at an angle. The more your angle of viewing differs from perpendicular, the more pronounced the displacement.

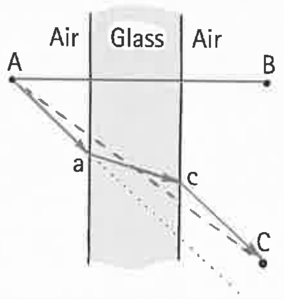

FIGURE 28.15

Refraction through glass. Although dashed line AC is the shortest path, light takes a slightly longer path through the air from A to a, then a shorter path through the glass to c, and then to C. The emerging light is displaced but parallel to the incident light.

Another example of interest is the prism, in which opposite faces of the glass are not parallel (Figure 28.16). Light that goes from point A to point B will not follow the straight-line path shown by the dashed line, because too much time would be spent in the glass. Instead, the light will follow the path shown by the solid line—a path that is a bit farther through the air—and pass through a thinner section of the glass to make its trip to point B. By this reasoning, one might think that the light

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[3] Just how much the speed of light differs from its speed in a vacuum is given by the index of refraction, n, of the material:

$$n = \frac{\text{speed of light in vacuum}}{\text{speed of light in material}}$$

For example, the speed of light in a diamond is 124,000 km/s, and so the index of refraction for diamond is $n = \frac{300{,}000 \text{ km/s}}{124{,}000 \text{ km/s}} = 2.42$. For a vacuum, $n = 1$.

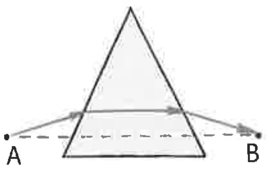


FIGURE 28.16
A prism.

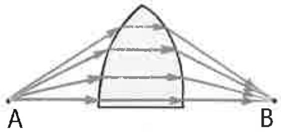


FIGURE 28.17
A curved prism.

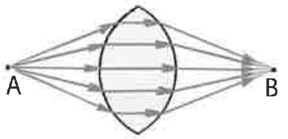


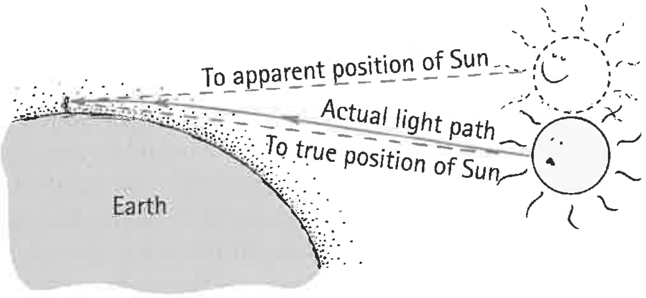
FIGURE 28.18
A converging lens.

should take a path closer to the upper vertex of the prism and seek the minimum thickness of glass. But if it did, the extra distance through the air would result in an overall longer time of travel. The quickest path followed is the path of least time.

It is interesting to note that a properly curved prism will provide many paths of equal time from a point A on one side to a point B on the opposite side (Figure 28.17). The curve decreases the thickness of the glass correctly to compensate for the extra distances light travels to points higher on the surface. For appropriate positions of A and B and for the appropriate curve on the surfaces of this modified prism, all light paths are of exactly equal time. In this case, all the light from A that is incident on the glass surface is focused on point B. We see that this shape is simply the upper half of a converging lens (Figure 28.18, and treated in more detail later in this chapter).

Whenever we watch a sunset, we see the Sun for several minutes after it has sunk below the horizon. Earth's atmosphere is thin at the top and dense at the bottom. Since light travels faster in thin air than it does in dense air, light from the Sun can reach us more quickly if, instead of traveling in a straight line, it avoids the denser air by taking a higher and longer path to penetrate the atmosphere at a steeper tilt (Figure 28.19).

FIGURE 28.19
Because of atmospheric refraction, when the Sun is near the horizon, it appears to be higher in the sky.



Since the density of the atmosphere changes gradually, the light path bends gradually to produce a curved path. Interestingly, this path of least time provides us with a slightly longer period of daylight than if the light traveled without bending. Furthermore, when the Sun (or Moon) is near the horizon, the rays from the lower edge are bent more than the rays from the upper edge. This produces a shortening of the vertical diameter, causing the Sun to appear pumpkin shaped (Figure 28.20).

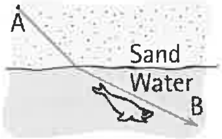
FIGURE 28.20
The Sun's shape is distorted by differential refraction.

CHECK POINT

Suppose the lifeguard in the preceding example were a seal instead of a human being. How would its path of least time from A to B differ?

Check Your Answer

The seal can swim faster than it can run, and its path would bend as shown; likewise with light emerging from the bottom of a piece of glass into air.



MIRAGE

We are all familiar with the mirage we sometimes see while driving on a hot road. The distant road appears to be wet, but when we get there, the road is dry. Why is this so? The air is very hot just above the road surface and cooler above. Light travels faster through the thinner hot air than through the denser cool air above. So light, instead of coming to us from the sky in straight lines, also has least-time paths by which it curves down into the hotter region near the road for a while before reaching our eyes (Figure 28.21). Where we are seeing "wetness," we are really seeing the sky. A mirage is not, as many people mistakenly believe, a "trick of the mind." A mirage is formed by real light and can be photographed, as shown in Figure 28.22.

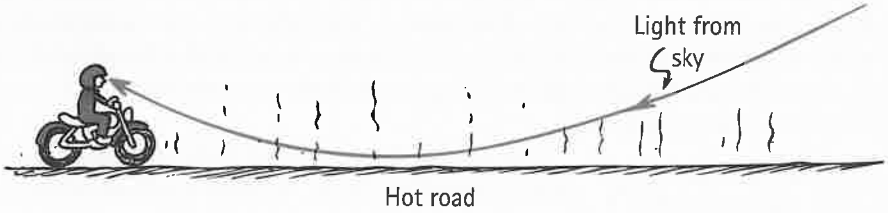


FIGURE 28.21

Light from the sky picks up speed in the air near the ground because that air is warmer and less dense than the air above. When the light grazes the surface and bends upward, the observer sees a mirage.

When we look at an object over a hot stove or over hot pavement, we see a wavy, shimmering effect. This is due to the various least-time paths of light as it passes through varying temperatures and therefore varying densities of air. The twinkling of stars results from similar phenomena in the sky, where light passes through unstable layers in the atmosphere.

In the foregoing examples, how does light seemingly "know" what conditions exist and what compensations a least-time path requires? When approaching window glass, a prism, or a lens at an angle, how does light know to travel a bit farther in air to save time in taking a shorter path through the glass? How does light from the Sun know to travel above the atmosphere an extra distance before taking a shortcut through the denser air to save time? How does sky light above know that it can reach us in minimum time if it dips toward a hot road before tilting upward to our eyes? The principle of least time appears to be noncausal, that light has a mind of its own and can "sense" all the possible paths, calculate the times for each, and choose the one that requires the least time. Is this the case? As intriguing as all this may seem, there is a simpler explanation that doesn't assign foresight to light—that refraction is simply a consequence of light having different average speeds in different media.

FIGURE 28.22

A mirage. The apparent wetness of the road is not reflection of the sky by water but, rather, refraction of sky light through the warmer and less-dense air near the road surface.

CHECK POINT

If the speed of light were the same in air of various temperatures and densities, would there still be slightly longer daytimes, twinkling stars at night, mirages, and slightly squashed Suns at sunset?

Check Your Answer

No, for no refraction would occur.

Cause of Refraction

Refraction occurs when the average speed of light *changes* in going from one transparent medium to another. We can understand this by considering the action of a pair of toy cart wheels connected to an axle as the wheels roll gently

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Model of Refraction

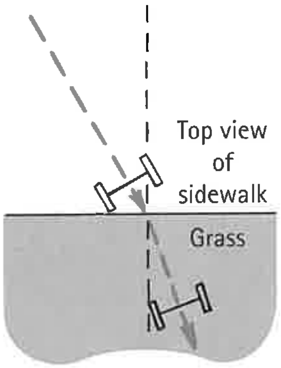


FIGURE 28.23
The direction of the rolling wheels changes when one wheel slows down before the other one does.

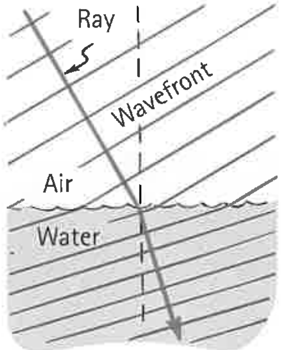
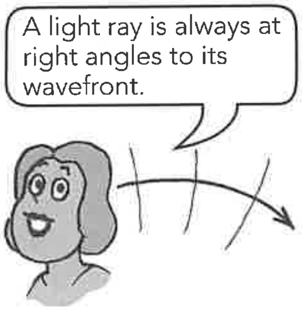


FIGURE 28.24
The direction of the light waves changes when one part of each wave slows down before the other part.

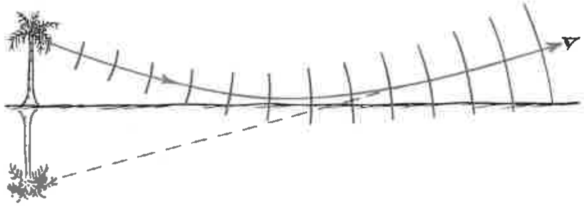
downhill from a smooth sidewalk onto a grass lawn. If the wheels meet the grass at an angle, as Figure 28.23 shows, they are deflected from their straight-line course. Note that the left wheel slows first when it interacts with the grass on the lawn. The higher-speed right wheel on the sidewalk then pivots about the slower-moving left wheel. The direction of the rolling wheels is bent toward the normal (the black dashed line perpendicular to the grass-sidewalk border in Figure 28.23).

A light wave bends in a similar way, as shown in Figure 28.24. Note the direction of light, indicated by the blue arrow (the light ray), and also note the *wavefronts* (red) drawn at right angles to the ray. In the figure the wave meets the water surface at an angle. This means that the left portion of the wave slows down in the water while the remainder in the air travels at speed c. The light ray remains perpendicular to the wavefront and therefore bends at the surface. It bends like the wheels bend when they roll from the sidewalk into the grass. In both cases, the bending is a consequence of a change in speed.[4]



The changeable speed of light provides a wave explanation for mirages. Sample wavefronts coming from the top of a tree on a hot day are shown in Figure 28.25. If the temperature of the air were uniform, the average speed of light would be the same in all parts of the air; light traveling toward the ground would meet the ground. But the air is warmer and less dense near the ground, and the wavefronts gain speed as they travel downward, making them bend upward. So, when the observer looks downward, he sees the top of the tree—this is a mirage.

FIGURE 28.25
A wave explanation of a mirage. Wavefronts of light travel faster in the hot air near the ground and bend upward.



Refraction accounts for many illusions. A common one is the apparent bending of a stick that is partially in water. The submerged part seems closer to the surface than it really is. Likewise when you view a fish in the water. The fish appears nearer to the surface and closer than it really is (Figure 28.27). If we look straight down into water, an object submerged 4 m beneath the surface will appear to be only 3 m deep. Because of refraction, submerged objects appear to be magnified.

We see that we can interpret the bending of light at the surface of the water in at least two ways. We can say that the light that leaves the fish and reaches the observer's eye does so in the least time by taking a shorter path upward toward the surface of the water and a correspondingly longer path through the air. In this view, least time dictates the path taken. Or we can say that the waves of light directed upward at an angle toward the surface are bent off-kilter as they speed up when emerging into the air reaching the observer's eye. In this view, the change in speed from water to air dictates

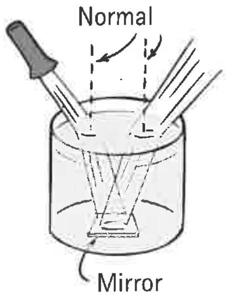


FIGURE 28.26
When light slows down in going from one medium to another, such as going from air to water, it refracts toward the normal. When it speeds up in traveling from one medium to another, such as going from water to air, it refracts away from the normal.

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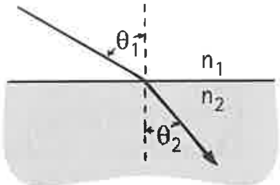
[4] The quantitative law of refraction, called *Snell's law,* is credited to W. Snell, a 17th-century Dutch astronomer and mathematician: $n_1 \sin\theta_1 = n_2 \sin\theta_2$, where n_1 and n_2 are the indices of refraction of the media on either side of the surface and θ_1 and θ_2 are the respective angles of incidence and refraction. If three of these values are known, the fourth can be calculated from this relationship.



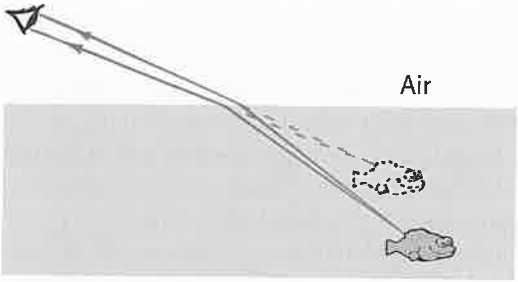


FIGURE 28.27

Because of refraction, a submerged object seems to be nearer to the surface than it actually is.

the path taken, and this path turns out to be a least-time path. Whichever view we choose, the results are the same.

CHECK POINT

If the speed of light were the same in all media, would refraction still occur when light passes from one medium to another?

Check Your Answer

No.

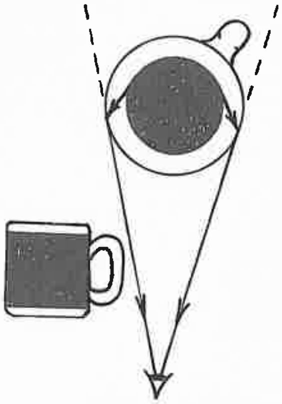


FIGURE 28.28

Because of refraction, the full root-beer mug appears to hold more root beer than it actually does.

DISPERSION

We know that the average speed of light is less than *c* in a transparent medium; how much less depends on the nature of the medium and on the frequency of light. The speed of light in a transparent medium depends on its frequency. Recall, from Chapter 26 that light whose frequencies match the natural or resonant frequencies of the electron oscillators in the atoms and molecules of the transparent medium is absorbed, and light with frequencies near the resonant frequencies is not absorbed, but interacts more often than light of lower frequencies in the absorption/reemission sequence. Since the natural or resonant frequency of most transparent materials is in the ultraviolet part of the spectrum, higher-frequency light travels more slowly than lower-frequency light. Violet light travels about 1% slower in ordinary glass than red light. Light waves with colors between red and violet travel at their own intermediate speeds.

Because different frequencies of light travel at different speeds in transparent materials, they refract by different amounts. When white light is refracted twice, as in a prism, the separation of the different colors of light is quite noticeable. This separation of light into colors arranged according to frequency is called *dispersion* (Figure 28.29). It is what enabled Isaac Newton to form a spectrum when he held a glass prism in sunlight.

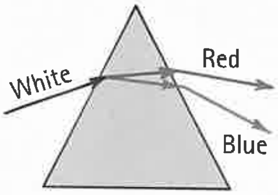


FIGURE 28.29

Dispersion by a prism makes the components of white light visible.

Rainbows

A most spectacular illustration of dispersion is a rainbow. For a rainbow to be seen, the Sun must be shining in one part of the sky and water drops in a cloud or in falling rain must be present in the opposite part of the sky. When we turn our backs toward the Sun, we see the spectrum of colors in a bow. Seen from an airplane near midday, the bow forms a complete circle. All rainbows would be completely round if the ground were not in the way.

The beautiful colors of rainbows are dispersed from the sunlight by millions of tiny spherical water droplets that act like prisms. We can better understand this by considering an individual raindrop, as shown in Figure 28.30. Follow the ray of sunlight as it enters the drop near its top surface. Some of the light here is reflected

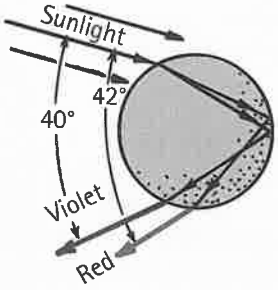


FIGURE 28.30

Dispersion of sunlight by a single raindrop.

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Video
The Rainbow

(not shown), and the remainder is refracted into the water. At this first refraction, the light is dispersed into its spectrum colors, violet being deviated the most and red the least. Reaching the opposite side of the drop, each color is partly refracted out into the air (not shown) and partly reflected back into the water. Arriving at the lower surface of the drop, each color is again reflected (not shown) and refracted into the air. This second refraction is similar to that of a prism, where refraction at the second surface increases the dispersion already produced at the first surface.

Two refractions and a reflection can actually result in the angle between the incoming and outgoing rays being anything between 0 and about 42° (0° corresponding to a full 180° reversal of the light). There is a strong concentration of light intensity, however, near the maximum angle of 42°. That is what is shown in Figure 28.30.

Although each drop disperses a full spectrum of colors, an observer is in a position to see the concentrated light of only a single color from any one drop (Figure 28.31). If violet light from a single drop reaches the eye of an observer, red light from the same drop is incident elsewhere below the eyes. To see red light, one must look to a drop higher in the sky. The color red will be seen when the angle between a beam of sunlight and the light sent back by a drop is 42°. The color violet is seen when the angle between the sunbeams and deflected light is 40°.

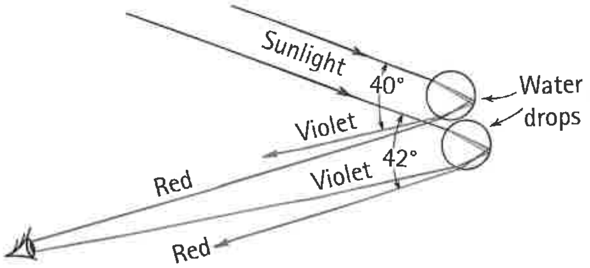

FIGURE 28.31
Sunlight incident on two sample raindrops, as shown, emerges from them as dispersed light. The observer sees the red light from the upper drop and the violet light from the lower drop. Millions of drops produce the whole spectrum of visible light.

Why does the light dispersed by the raindrops form a bow? The answer to this involves a little geometric reasoning. First of all, a rainbow is not the flat two-dimensional arc it appears to be. It appears flat for the same reason a spherical burst of fireworks high in the sky appears as a disc—because of a lack of distance cues. The rainbow you see is actually a three-dimensional cone with the tip (apex) at your eye (Figure 28.32). Consider a glass cone, the shape of those paper cones you sometimes see at drinking fountains. If you held the tip of such a glass cone against your eye, what would you see? You'd see the glass as a circle. Likewise with a rainbow.

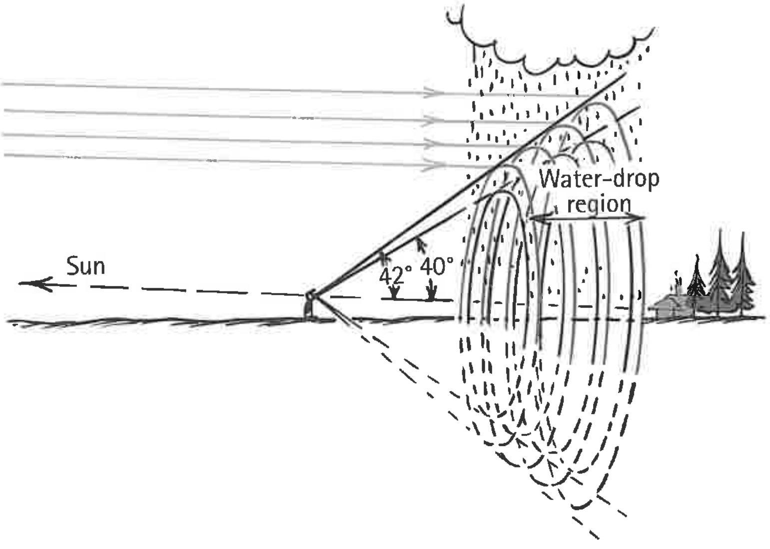

FIGURE 28.32
When your eye is located between the Sun (not shown off to the left) and a water drop region, the rainbow you see is the edge of a three-dimensional cone that extends through the water drop region. (Innumerable layers of drops form innumerable two-dimensional arcs like the four suggested here.)

All the drops that disperse the rainbow's light toward *you* lie in the shape of a cone—a cone of different layers with drops that disperse red to your eye on the outside, orange beneath the red, yellow beneath the orange, and so on, all the way to violet on the inner conical surface. The thicker the region containing water drops, the thicker the conical edge you look through, and the more vivid the rainbow.

To further understand this, consider only the deflection of red light. You see red when the angle between the incident rays of sunlight and dispersed rays is 42°. Of course, beams are dispersed 42° from drops all over the sky in all directions—up, down, and sideways. But the only red light *you* see is from drops that lie on a cone with a side-to-axis angle of 42°. Your eye is at the apex of this cone, as shown in Figure 28.33. To see violet, you look 40° from the conical axis (so the thickness of glass in the cone of the previous paragraph is tapered—very thin at the tip and thicker with increased distance from the tip). Your cone of vision that intersects the cloud of drops that creates your rainbow is different from that of a person next to you. So when a friend says, "look at the pretty rainbow," you can reply, "Okay, move aside so I can see it too." Everybody sees his or her own personal rainbow.

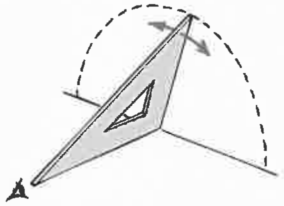

FIGURE 28.33

Only raindrops along the dashed line disperse red light to the observer at a 42° angle; hence, the light forms a bow.

Another fact about rainbows: A rainbow always faces you squarely, because of the lack of distance cues mentioned earlier. When you move, your rainbow moves with you. So you can never approach the side of a rainbow, or see it nearly end-on as in the exaggerated view of Figure 28.32. You *can't* get to its end. Hence the expression "looking for the pot of gold at the end of the rainbow" means pursuing something you can never reach.

Often a larger, secondary bow with colors reversed can be seen arching at a greater angle around the primary bow. We won't treat this secondary bow except to say that it is formed by similar circumstances and is a result of double reflection within the raindrops (Figure 28.34). Because of this extra reflection (and extra refraction loss), the secondary bow is much dimmer, and its colors are reversed.

FIGURE 28.34

Two refractions and a reflection in water droplets produce light at all angles up to about 42°, with the intensity concentrated where we see the rainbow at 40° to 42°. No light emerges from the water droplet at angles greater than 42° unless it undergoes two or more reflections inside the drop. So the sky is brighter inside the rainbow than outside it. Notice the weak secondary rainbow to the right of the primary.

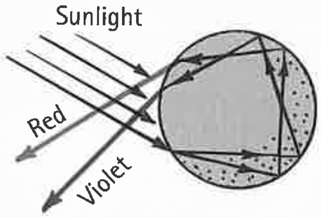

FIGURE 28.35

Double reflection in a drop produces a secondary bow.

CHECK POINT

1. If you point to a wall with your arm extended to make about a 42° angle to the normal to the wall, then rotate your arm in a full circle while keeping the same angle, what shape does your arm describe? What shape on the wall does your finger sweep out?
2. If light traveled at the same speed in raindrops as it does in air, would we still have rainbows?

Check Your Answers

1. Your arm describes a cone, and your finger sweeps out a circle. Likewise with rainbows.
2. No.

Total Internal Reflection

Some Saturday night when you're taking your bath, fill the tub extra deep and bring a waterproof flashlight into the tub with you. Switch off the bathroom light. Shine the submerged light straight up and then slowly tip it away from the surface. Note how the intensity of the emerging beam diminishes and how more light is reflected from the surface of the water to the bottom of the tub. At a certain angle, called the *critical angle,* you'll notice that the beam no longer emerges into the air above the surface. The intensity of the emerging beam reduces to zero where it tends to graze the surface. The **critical angle** is the minimum angle of incidence inside a medium at which a light ray is totally reflected. When the flashlight is tipped beyond the critical angle (48° from the normal for water), you'll notice that all the light is reflected back into the tub. This is **total internal reflection.** The light striking the air–water surface obeys the law of reflection: The angle of incidence is equal to the angle of reflection. The only light emerging from the surface of the water is that which is diffusely reflected from the bottom of the bathtub. This procedure is shown in Figure 28.36. The proportion of light refracted and light internally reflected is indicated by the relative lengths of the arrows.

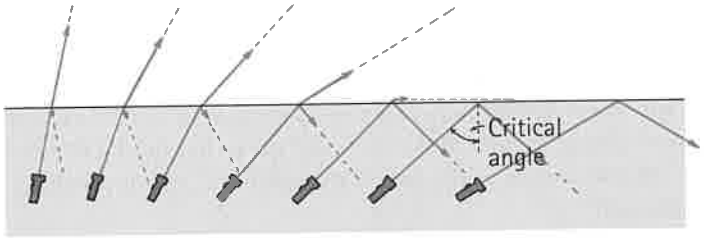

FIGURE 28.36

INTERACTIVE FIGURE

Light emitted in the water is partly refracted and partly reflected at the surface. The blue dashes show the direction of light and the length of the arrows indicates the proportions refracted and reflected. Beyond the critical angle, the beam is totally internally reflected.

Total internal reflection occurs in materials in which the speed of light is less than the speed of light outside. The speed of light is less in water than in air, so all light rays in water that reach the surface at more than an incident angle of 48° are reflected back into the water. So your pet goldfish in its aquarium looks up to see a reflected view of the sides and bottom of the aquarium. Directly above, it sees a compressed view of the outside world (Figure 28.37). The outside 180° view from horizon to opposite horizon is seen through an angle of 96°—twice the critical angle. A lens that similarly compresses a wide view, called a *fisheye lens,* is used for special-effect photography.

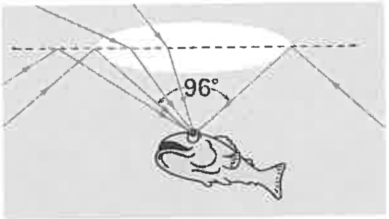

FIGURE 28.37

An observer underwater sees a circle of light at the still surface. Beyond a cone of 96° (twice the critical angle), an observer sees a reflection of the water interior or bottom.

Total internal reflection occurs in glass surrounded by air, because the speed of light in glass is less than in air. The critical angle for glass is about 43°, depending on the type of glass. So light in the glass that is incident at angles greater than 43° to the surface is totally internally reflected. No light escapes beyond this angle; instead, all of it is reflected back into the glass—even if the outside surface is marred by dirt or dust. Hence the usefulness of glass prisms (Figure 28.38). A little light is lost by reflection before it enters the prism, but once the light is inside, reflection from the 45° slanted face is total—100%. In contrast, silvered or aluminized mirrors reflect only about 90% of incident light. Hence the use of prisms instead of mirrors in many optical instruments.

Would you like to become rich? Be the first to invent a surface that will reflect 100% of external light incident upon it.

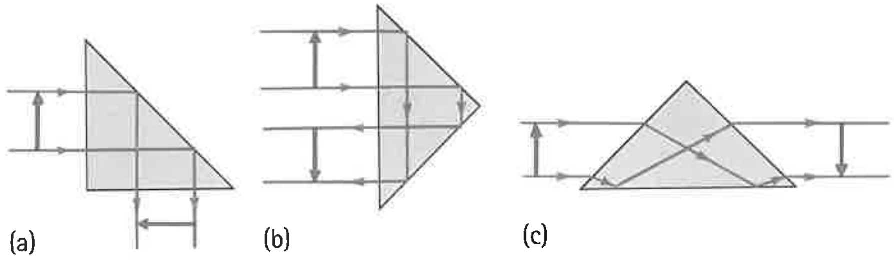

FIGURE 28.38

Total internal reflection in a prism. The prism changes the direction of the light beam (a) by 90°, (b) by 180°, and (c) not at all. Note that, in each case, the orientation of the image is different from the orientation of the object.

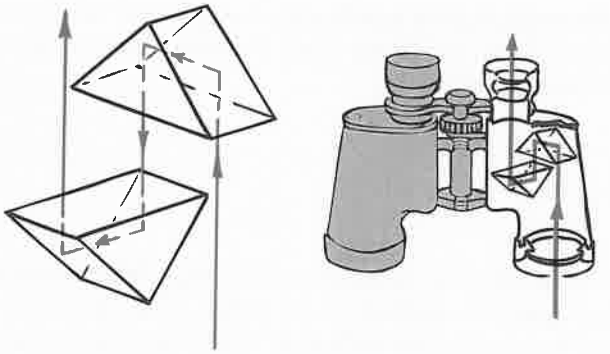

FIGURE 28.39

Total internal reflection in a pair of prisms, common in binoculars.

A pair of prisms, each reflecting light through 180°, is shown in Figure 28.39. Binoculars use pairs of prisms to lengthen the light path between lenses and thus eliminate the need for long barrels. So a compact set of binoculars is as effective as a longer telescope. Another advantage of prisms is that whereas the image in a straight telescope is upside down, reflection by the prisms in binoculars reinverts the image, so things are seen right-side up.

The critical angle for a diamond is about 24.5°, smaller than for any other common substance. The critical angle varies slightly for different colors, because the speed of light varies slightly for different colors. Once light enters a diamond gemstone, most is incident on the sloped backsides at angles greater than 24.5° and is totally internally reflected (Figure 28.40). Because of the great slowdown in speed as light enters a diamond, refraction is pronounced, and because of the frequency-dependence of the speed, there is great dispersion. Further dispersion occurs as the light exits through the many facets at its face. Hence we see unexpected flashes of a wide array of colors. Interestingly, when these flashes are narrow enough to be seen by only one eye at a time, the diamond "sparkles."

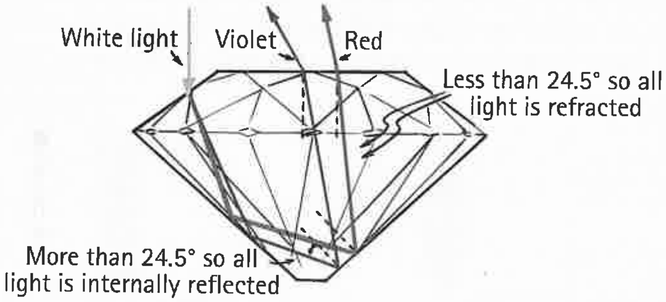

FIGURE 28.40

Paths of light in a diamond. Rays that strike the inner surface at angles greater than the critical angle are internally reflected and exit via refraction at the top surface.

Total internal reflection also underlies the operation of optical fibers, or light pipes (Figure 28.41). An optical fiber "pipes" light from one place to another by a series of total internal reflections, much as a bullet ricochets down a steel pipe. Light rays bounce along the inner walls, following the twists and turns of the fiber. Bundles of optical fibers are used to see what is going on in inaccessible places, such as the interior of a motor or a patient's stomach. They can be made small enough to snake through blood vessels or through narrow canals in the body, such as the urethra. Light shines down some of the fibers to illuminate the scene and is reflected back along others.

Fiber-optic cables are also important in communications because they offer a practical alternative to copper wires and cables. Thin glass fibers now replace thick, bulky, expensive copper cables to carry thousands of simultaneous telephone messages among the major switching centers and across the ocean floor. Control signals are fed in aircraft from the pilot to the control surfaces by means of fiber optics. Signals are carried in the modulations of laser

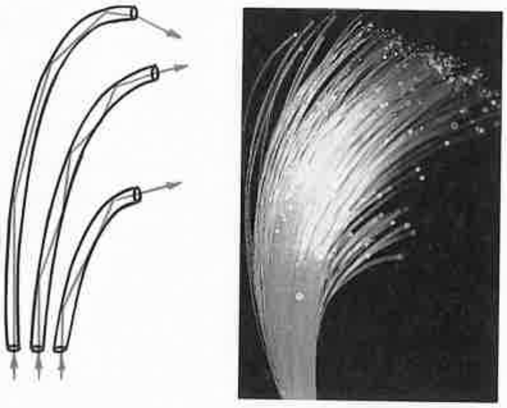

FIGURE 28.41

The light is "piped" from below by a succession of total internal reflections until it emerges at the top ends.

light. Unlike electricity, light is indifferent to temperature and fluctuations in surrounding magnetic fields, and so the signal is clearer. Also, it is much less likely to be tapped by eavesdroppers.

Lenses

Learning about lenses is a hands-on activity. Not fiddling with lenses while learning about them is like taking swimming lessons away from water.

A very practical case of refraction occurs in lenses. We can understand a lens by analyzing equal-time paths as we did earlier, or we can assume that it consists of a set of several matched prisms and blocks of glass arranged in the order shown in Figure 28.42. The prisms and blocks refract incoming parallel light rays so they converge to (or diverge from) a point. The arrangement shown in Figure 28.42a converges the light, and we call such a lens a **converging lens.** Note that it is thicker in the middle and thinner at the edges.

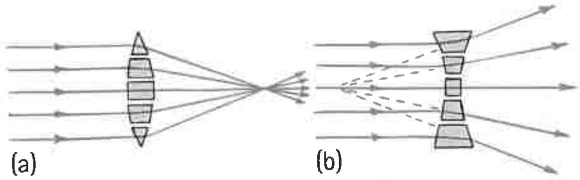

FIGURE 28.42

A lens may be thought of as a set of blocks and prisms. (a) A converging lens. (b) A diverging lens.

The arrangement in (b) is different. The middle is thinner than the edges, and it diverges the light; such a lens is called a **diverging lens.** Note that the prisms diverge the incident rays in a way that makes them appear to come from a single point in front of the lens. In both lenses, the greatest deviation of rays occurs at the outermost prisms, for they have the greatest angle between the two refracting surfaces. No deviation occurs exactly in the middle, for in that region the glass faces are parallel to each other. Real lenses are not made of prisms, of course, as is indicated in Figure 28.42; they are made of a solid piece of glass with surfaces that are ground usually to a spherical curve. In Figure 28.43, we see how smooth lenses refract waves.

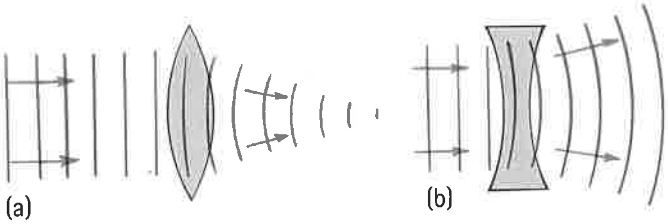

FIGURE 28.43

Wavefronts travel more slowly in glass than in air. (a) The waves are retarded more through the center of the lens, and convergence results. (b) The waves are retarded more at the edges, and divergence results.

Some key features in lens description are shown for a converging lens in Figure 28.44. The *principal axis* of a lens is the line joining the centers of curvatures of its surfaces. The *focal point* is the point to which a beam of parallel light, parallel to the principal axis, converges. Incident parallel beams that are not parallel to the principal axis focus at points above or below the focal point. All such possible points make up a *focal plane.* Because a lens has two surfaces, it has two focal points and two focal planes. When the lens of a camera is set for distant objects, the photosensitive surface is in the focal plane behind the lens in the

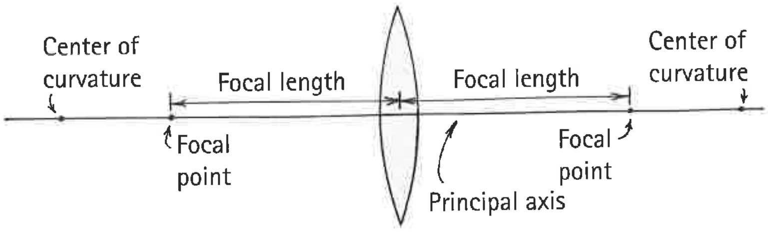

FIGURE 28.44

Key features of a converging lens.

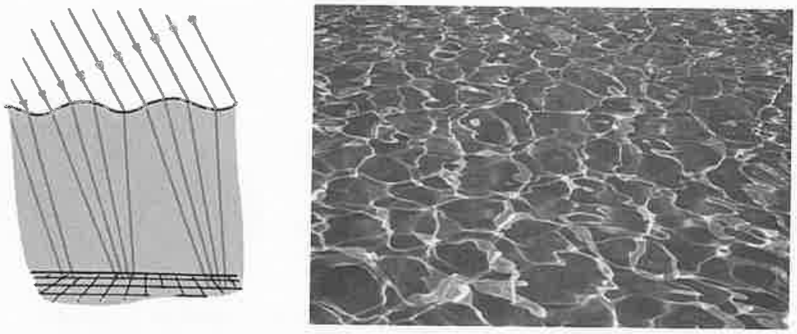

FIGURE 28.45

The moving patterns of bright and dark areas at the bottom of the pool result from the uneven surface of the water, which behaves like a blanket of undulating lenses. Just as we see the pool bottom shimmering, a fish looking upward at the Sun would see it shimmering too. Because of similar irregularities in the atmosphere, we see the stars twinkle.

camera. The *focal length* of the lens is the distance between the center of the lens and either focal point.

IMAGE FORMATION BY A LENS

At this moment, light is reflecting from your face onto this page. Light that reflects from your forehead, for example, strikes every part of the page. Likewise for the light that reflects from your chin. Every part of the page is illuminated with reflected light from your forehead, your nose, your chin, and every other part of your face. You don't see an image of your face on the page because there is too much overlapping of light. But put a barrier with a pinhole in it between your face and the page, and the light that reaches the page from your forehead does not overlap the light from your chin. Likewise for the rest of your face. Without this overlapping, an image of your face is formed on the page. It will be very dim, because very little light reflected from your face gets through the pinhole. To see the image, you'd have to shield the page from other light sources. The same is true of the vase and flowers in Figure 28.46b.[5]

If you wear glasses and have ever misplaced them, or if you find it difficult to read small print, try squinting, or, even better, try holding a pinhole (in a piece of paper or whatever) in front of your eye, close to the page. You'll see the print clearly, and, because you're close to it, it is magnified. Try it and see!

The first cameras had no lenses and admitted light through a small pinhole. You can see why the image is upside down by the sample rays in Figure 28.46b and c. Long exposure times were required because of the small amount of light admitted by

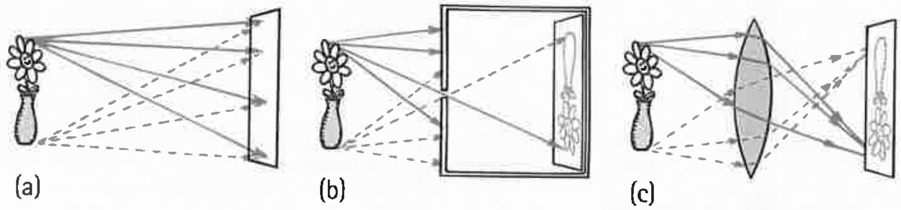

FIGURE 28.46

INTERACTIVE FIGURE

Image formation. (a) No image appears on the wall because rays from all parts of the object overlap all parts of the wall. (b) A single small opening in a barrier prevents overlapping rays from reaching the wall; a dim upside-down image is formed. (c) A lens converges the rays upon the wall without overlapping; more light makes a brighter image.

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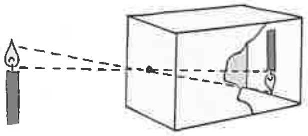
[5] A quantitative way of relating object distances with image distances is given by the thin-lens equation

$$\frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f} \quad \text{or} \quad d_i = \frac{d_o f}{d_o - f}$$

where d_o is the distance of the object from the lens, d_i is the distance from the lens to the image, and f is the focal length of the lens.

Practicing Physics

Make a pinhole camera. Cut out one end of a small cardboard box, and cover the end with semitransparent tracing or tissue paper. Make a clean-cut pinhole at the other end. (If the cardboard is thick, you can make the pinhole through a piece of tinfoil placed over a larger opening in the cardboard.) Aim the camera at a bright object in a darkened room, and you will see an upside-down image on the tracing paper. The tinier the pinhole, the dimmer and sharper the image. If, in a dark room, you replace the tracing paper with unexposed photographic film, cover the back so that it is light-tight and cover the pinhole with a removable flap. You're ready to take a picture. Exposure times differ depending principally on the kind of film and the amount of light. Try different exposure times, starting with about 3 seconds. Also try boxes of various lengths.

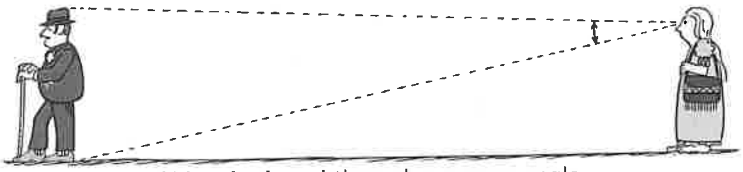


Rather than viewing a candle, as the sketch suggests, point your box skyward toward the Sun. The solar image on the tracing paper is clear and bright. Pinhole images of the Sun are also evident on the ground beneath a tree on a sunny day. When openings between leaves in the tree are small compared with the height of the tree, the openings behave as pinholes and cast circles of light, many overlapping, on the ground. Recall the opening photos of Chapter 1 that show what occurs at the time of a partial solar eclipse.

the pinhole. A somewhat larger hole would admit more light, but overlapping rays would produce a blurry image. Too large a hole would allow too much overlapping and no image would be discernible. That's where a converging lens comes in (Figure 28.46c). The lens converges light onto the screen without the unwanted overlapping of rays. Whereas the first pinhole cameras were useful only for still objects because of the long exposure time required, moving objects can be photographed with the lens camera because of the short exposure time—which is why photographs taken with lens cameras came to be called *snapshots.*

Can you see why the image in Figure 28.46b is upside down? And is it true that, when your photographs are processed and printed, they're all upside down?

The simplest use of a converging lens is a magnifying glass. To understand how it works, think about how you examine objects near and far. With unaided vision, a far-away object is seen through a relatively narrow angle of view and a close object is seen through a wider angle of view (Figure 28.47). To see the details of a small object, you want to get as close to it as possible for the widest angle view. But your eye can't focus when too close. That's where the magnifying glass comes in. When you are close to the object, the magnifying glass gives you a clear image that would be blurry otherwise.



Object is viewed through a narrow angle

Object is viewed through a wide angle

FIGURE 28.47
Viewing.

When we use a magnifying glass, we hold it close to the object we wish to examine. This is because a converging lens provides an enlarged, right-side-up image only when the object is inside the focal point (Figure 28.48). If a screen is placed at the image distance, no image appears on it because no light is directed to the image position. The rays that reach our eye, however, behave *as if* they came from the image position; we call the result a **virtual image.**

When the object is far away enough to be outside the focal point of a converging lens, a **real image** is formed instead of a virtual image. Figure 28.49 shows a case in which a converging lens forms a real image on a screen. A real image is upside down. A similar arrangement is used for projecting slides and motion pictures on a screen and for projecting a real image on the photosensitive area of a camera. Real images with a single lens are always upside down.

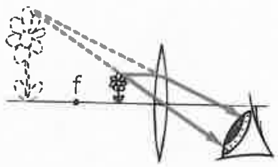


FIGURE 28.48

When an object is near a converging lens (inside its focal point *f*), the lens acts as a magnifying glass to produce a virtual image. The image appears larger and farther from the lens than the object.

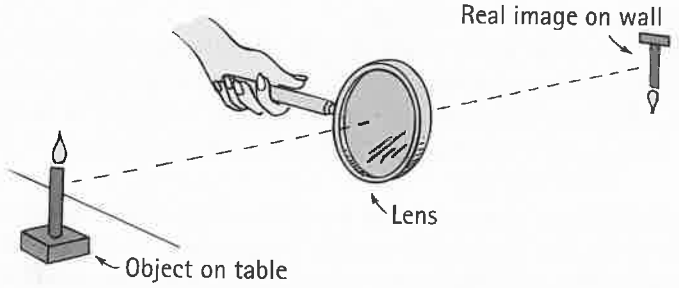


FIGURE 28.49

When an object is far from a converging lens (beyond its focal point), a real upside-down image is formed.

A diverging lens used alone produces a reduced virtual image. It makes no difference how far or how near the object is. When a diverging lens is used alone, the image is always virtual, right-side up, and smaller than the object. A diverging lens is often used as a "finder" on a camera. When you look at the object to be photographed through such a lens, you see a virtual image that approximates the same proportions as the photograph.

FIGURE 28.50

A diverging lens forms a virtual, right-side-up image of Jamie and his cat.

CHECK POINT

1. Why is the greater part of the photograph in Figure 28.50 out of focus?
2. When the lens of a projector for PowerPoint presentations is half covered, what happens to the image on the screen?

Check Your Answers

1. Both Jamie and his cat and the virtual image of Jamie and his cat are "objects" for the lens of the camera that took this photograph. Because the objects are at different distances from the lens, their respective images are at different distances with respect to the film in the camera. So only one can be brought into focus. The same is true of your eyes. You cannot focus on near and far objects at the same time.
2. The image for a half-covered lens is dimmer because it is formed with half as much light. Importantly, this does not mean half the *image* is formed. The full image, though dimmer, is still there. (More rays, rather than the few we've chosen in Figure 28.46 to show image location, would show this.)

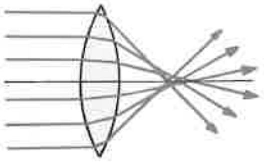


FIGURE 28.51
Spherical aberration.

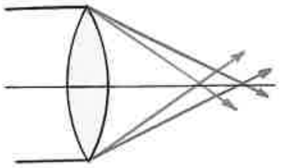


FIGURE 28.52
Chromatic aberration.

Lens Defects

No lens provides a perfect image. A distortion in an image is called an **aberration.** By combining lenses in certain ways, aberrations can be minimized. For this reason, most optical instruments use compound lenses, each consisting of several simple lenses, instead of single lenses.

Spherical aberration results from light that passes through the edges of a lens focusing at a slightly different place from where light passing near the center of the lens focuses (Figure 28.51). This can be remedied by covering the edges of a lens, as with a diaphragm in a camera. Spherical aberration is corrected in good optical instruments by a combination of lenses.

Chromatic aberration is the result of light of different colors having different speeds and hence different refractions in the lens (Figure 28.52). In a simple lens (as in a prism), different colors of light do not come to focus in the same place. *Achromatic lenses,* which combine simple lenses of different kinds of glass, correct this defect.

The pupil of the eye changes in size to regulate the amount of light that enters. Vision is sharpest when the pupil is smallest because light then passes through only the central part of the eye's lens, where spherical and chromatic aberrations are minimal. Also, the eye then acts more like a pinhole camera, so minimum focusing is required for a sharp image. You see better in bright light because in such light your pupils are smaller.

Astigmatism of the eye is a defect that results when the cornea is curved more in one direction than the other, somewhat like the side of a barrel. Because of this defect, the eye does not form sharp images. The remedy is eyeglasses with cylindrical lenses that have more curvature in one direction than in another.

Today, an option for those with poor sight is wearing eyeglasses. The advent of eyeglasses probably occurred in China and in Italy in the late 1200s. (Curiously enough, the telescope wasn't invented until some 300 years later. If, in the meantime, anybody viewed objects through a pair of lenses separated along their axes, such as lenses fixed at the ends of a tube, there is no record of it.) An alternative to wearing eyeglasses is contact lenses. A further alternative is lasik (acronym for laser-assisted in-situ keratomileusis), where pulses of laser light reshape the cornea and produce normal vision. Another procedure, PRK (photorefractive keratectomy), corrects all three common defects in vision. IntraLase, implantable contact lenses, and newer procedures continue. It's safe to say that quite soon, the wearing of eyeglasses and contact lenses may be a thing of the past. We really do live in a rapidly changing world. And that can be nice.

fyi

- Now there are inexpensive eyeglasses with water-filled lenses. Adding or removing water between two polycarbonate membranes can correct both nearsighted and farsighted vision. A small pump regulates the amount of water between the membranes. Water can produce a convex lens for farsighted vision, or less water can produce a concave lens for nearsighted vision. Once each lens is optimized, the user locks the water setting in place. The pump and tube assembly is removed and left intact for later adjustments. Check the web for *Self-Adjusting Eyeglasses for the World's Poor.*

CHECK POINT

1. If light traveled at the same speed in glass and in air, would glass lenses alter the direction of light rays?
2. Why is there chromatic aberration in light that passes through a lens but none in light that reflects from a mirror?

Check Your Answers

1. No.
2. Different frequencies travel at different speeds in a transparent medium and therefore refract at different angles, which produces chromatic aberration. The angles at which light reflects, however, has nothing to do with its frequency. One color reflects the same as any other color. In telescopes, therefore, mirrors are preferable to lenses because there is no chromatic aberration.

SUMMARY OF TERMS

Reflection The return of light rays from a surface.

Fermat's principle of least time Light takes the path that requires the least time when it goes from one place to another.

Law of reflection The angle of reflection equals the angle of incidence.

Refraction The bending of an oblique ray of light when it passes from one transparent medium to another.

Critical angle The minimum angle of incidence inside a medium at which a light ray is totally reflected.

Total internal reflection The total reflection of light traveling within a denser medium when it strikes the boundary with a less dense medium at an angle greater than the critical angle.

Converging lens A lens that is thicker in the middle than at the edges and that refracts parallel rays to a focus.

Diverging lens A lens that is thinner in the middle than at the edges, causing parallel rays to diverge as if from a point.

Virtual image An image formed by light rays that do not converge at the location of the image.

Real image An image formed by light rays that converge at the location of the image. A real image, unlike a virtual image, can be displayed on a screen.

Aberration Distortion in an image produced by a lens, which to some degree is present in all optical systems.

REVIEW QUESTIONS

Reflection

1. How does incident light that falls on an object affect the motion of electrons in the atoms of the object?
2. What do the electrons affected by illumination do when they are made to vibrate with greater energy?

Principle of Least Time

3. What is Fermat's principle of least time?

Law of Reflection

4. Cite the law of reflection.
5. Relative to the distance of an object in front of a plane mirror, how far behind the mirror is the image?
6. What fraction of the light shining straight at a piece of clear glass is reflected from the first surface?
7. Can a surface be polished for some waves and not for others? Cite an example.

Refraction

8. How does the angle at which a ray of light strikes a pane of window glass compare with the angle at which it passes out the other side?
9. How does the angle at which a ray of light strikes a prism compare with the angle at which it passes out the other side?
10. In which medium does light travel faster, in thin air or in dense air? What does this difference in speed have to do with the length of a day?
11. Is a mirage the result of reflection or refraction?

Cause of Refraction

12. When the wheel of a cart rolls from a smooth sidewalk onto a plot of grass, the interaction of the wheel with blades of grass slows the wheel. What slows light when it passes from air into glass or water?
13. Does the refraction of light make a swimming pool seem deeper or shallower?
14. Which travels more slowly in glass, red light or violet light?

Rainbows

15. Does a single raindrop illuminated by sunlight deflect light of a single color or does it disperse a spectrum of colors?
16. Does a viewer see a single color or a spectrum of colors coming from a single faraway drop?
17. Why is a secondary rainbow dimmer than a primary bow?

Total Internal Reflection

18. What is meant by *critical angle?*
19. At what angle inside glass is light totally internally reflected? At what angle inside a diamond is light totally internally reflected?
20. Light normally travels in straight lines, but it "bends" in an optical fiber. Explain.

Lenses

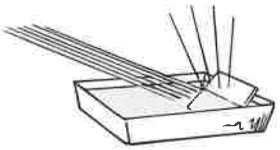
21. Distinguish between a *converging lens* and a *diverging lens.*
22. What is the *focal length* of a lens?
23. Distinguish between a *virtual image* and a *real image.*
24. What kind of lens can be used to produce a real image? A virtual image?

Lens Defects

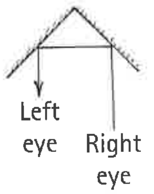
25. Why is vision sharpest when the pupils of the eye are very small?
26. What is astigmatism, and how can it be corrected?

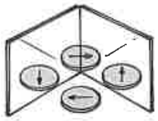
PROJECTS

1. Text Grandma and convince her that in order to see her full-length image in a mirror, the mirror need be only half her height. Discuss also the intriguing role of distance in a mirror being half size. Perhaps rough sketches to accompany your explanations will help.
2. You can produce a spectrum by placing a tray of water in bright sunlight. Lean a pocket mirror against the inside edge of the tray and adjust it until a spectrum appears on the wall or ceiling. Aha! You've produced a spectrum without a prism.

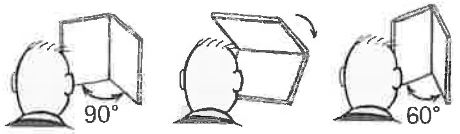


3. Set up two pocket mirrors at right angles and place a coin between them. You'll see four coins. Change the angle of the mirrors and see how many images of the coin you can see. With the mirrors at right angles, look at your face. Then wink. Do you see anything unusual? Hold a printed page up to the double mirrors and contrast its appearance with the reflection from a single mirror.





4. Look at yourself in a pair of mirrors at right angles to each other. You see yourself as others see you. Rotate the mirrors, still at right angles to each other. Does your image rotate also? Now place the mirrors 60° apart so you again see your face. Again rotate the mirrors and see if your image rotates also. Amazing?

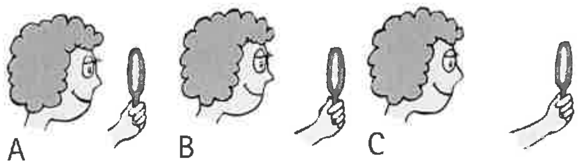


5. Determine the magnifying power of a lens by focusing on the lines of a ruled piece of paper. Count the spaces between the lines that fit into one magnified space and you have the magnifying power of the lens. You can do the same with binoculars and a distant brick wall. Hold the binoculars so that only one eye looks at the bricks through the eyepiece while the other eye looks directly at the bricks. The number of bricks seen with the unaided eye that will fit into one magnified brick gives the magnification of the instrument.

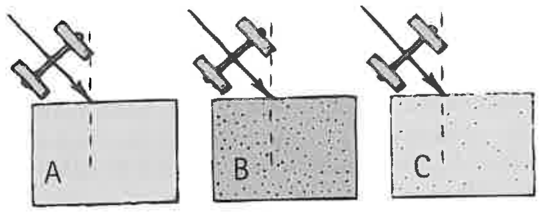
6. Poke a hole in a piece of paper, hold it in sunlight so that the solar image is the same size as a coin on the ground, and then determine how many coins would fit between the ground and the pinhole. That's the same number of solar diameters that would fit in the distance from Earth to the Sun. (Do you remember this from Chapter 1?)

RANKING

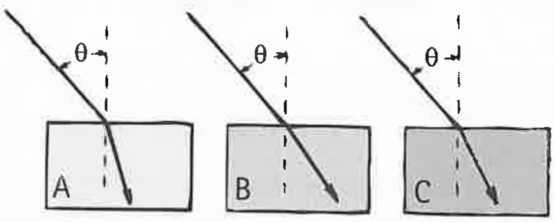
1. She looks at her face in the handheld mirror. Rank the amount of her face she sees in the three locations, from greatest to least (or is it the same in all positions?): A, B, C.



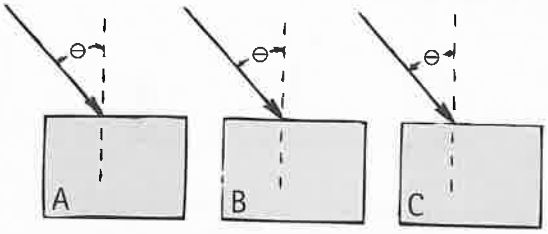
2. Wheels from a toy cart are rolled from a concrete sidewalk onto the following surfaces: A, a paved driveway; B, a grass lawn; C, close-cropped grass on a golf-course putting green. Due to slowing, each set of wheels bends at the boundary and is deflected from its initial straight-line course. Rank the surfaces according to the amount each set of wheels bends at the boundary, from greatest amount of bending to least.



3. Identical rays of light enter three transparent blocks composed of different materials. Light slows down upon entering the blocks. Rank the blocks according to the speed light travels in each, from highest speed to lowest speed.

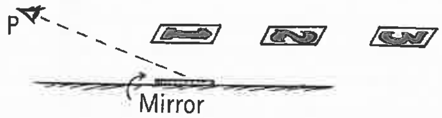


4. Identical rays of light in air are refracted upon entering three transparent materials: A, water, where the speed of light is $0.75c$; B, ethyl alcohol (speed $0.7c$); C, crown glass (speed $0.6c$). Rank the materials according to how much the light ray bends toward the normal, from most bending to least bending.



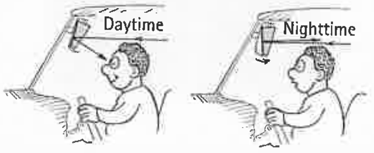
EXERCISES

1. This chapter opened with a photo of physics instructor Peter Hopkinson seeming to hover above the table. He isn't. Explain how he creates this illusion.
2. In the opening photo of the duck standing on the rock, why are the duck's feet not shown in the reflected view?
3. In the other opening photo of physics teacher Fred Myers taking a photo of his daughter McKenzie, how many mirrors were involved? Explain.
4. Fermat's principle is of least time rather than of least distance. Would least distance apply as well for reflection? For refraction? Why are your answers different?
5. Her eye at point P looks into the mirror. Which of the numbered cards can she see reflected in the mirror?



6. Cowboy Joe wishes to shoot his assailant by ricocheting a bullet off a mirrored metal plate. To do so, should he simply aim at the mirrored image of his assailant? Explain.
7. Why is the lettering on the front of some vehicles "backward"?

8. Trucks often have signs on their back ends that say, "If you can't see my mirrors, I can't see you." Explain the physics here.
9. When you look at yourself in the mirror and wave your right hand, your beautiful image waves the left hand. Then why don't the feet of your image wiggle when you shake your head?
10. Car mirrors are uncoated on the front surface and silvered on the back surface. When the mirror is properly adjusted, light from behind reflects from the silvered surface into the driver's eyes. Good. But this is not so good at nighttime with the glare of headlights behind. This problem is solved by the wedge shape of the mirror (see sketch). When the mirror is tilted slightly upward to the "nighttime" position, glare is directed upward toward the ceiling, away from the driver's eyes. Yet the driver can still see cars behind in the mirror. Explain.



11. To reduce glare from the surroundings, the windows of some department stores, rather than being vertical, slant inward at the bottom. How does this reduce glare?
12. A person in a dark room looking through a window can clearly see a person outside in the daylight, whereas the person outside cannot see the person inside. Explain.
13. What is the advantage of having matte (nonglossy) pages in this book rather than pages with a glossier surface?
14. Which kind of road surface is easier to see when driving at night—a pebbled, uneven surface or a mirror-smooth surface? And why is it difficult to see the roadway in front of you when driving on a rainy night?
15. What must be the minimum length of a plane mirror in order for you to see a full image of yourself?
16. What effect does your distance from the plane mirror have in your answer to the preceding exercise? (Try it and see!)
17. On a steamy mirror, wipe away just enough to see your full face. How tall will the wiped area be compared with the vertical dimension of your face?
18. Hold a pocket mirror almost at arm's length from your face and note how much of your face you can see. To see more of your face, should you hold the mirror closer or farther away, or would you have to have a larger mirror? (Try it and see!)

19. The diagram shows a person and her twin at equal distances on opposite sides of a thin wall. Suppose a window is to be cut in the wall so each twin can see a complete view of the other. Show the size and location of the smallest window that can be cut in the wall to do the job. (*Hint:* Draw rays from the top of each twin's head to the other twin's eyes. Do the same from the feet of each to the eyes of the other.)

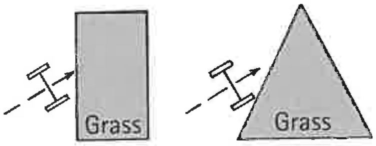
20. Why does reflected light from the Sun or Moon appear as a column in the body of water as shown? How would the reflected light appear if the water surface were perfectly smooth?

21. You can tell whether a person is nearsighted or farsighted by looking at the size of their eyes through their glasses. When a person's eyes seem magnified, is the person nearsighted or farsighted?

22. What is wrong with the cartoon of the man looking at himself in the mirror? (Have a friend face a mirror as shown, and you'll see.)

23. Your friend says that the wavelength of light waves is less in water than in air and cites Figure 28.24 as evidence. Do you agree or disagree, and why?

24. A pair of toy cart wheels is rolled obliquely from a smooth surface onto two plots of grass, a rectangular plot and a triangular plot, as shown. The ground is on a slight incline so that, after slowing down in the grass, the wheels will speed up again when emerging on the smooth surface. Finish each sketch by showing some positions of the wheels inside the plots and on the other sides, thereby indicating the direction of travel.

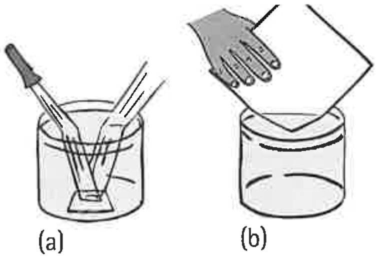


25. A pulse of red light and a pulse of blue light enter a glass block at the same time normal to its surface. Strictly speaking, after passing through the block, which pulse exits first?

26. During a lunar eclipse, the Moon is not completely dark but is usually a deep red in color. Explain this in terms of the refraction of all the sunsets and sunrises around the world.

27. If you place a glass test tube in water, you can see the tube. If you place it in clear soybean oil, you may not be able to see it. What does this indicate about the speed of light in the oil and in the water relative to its speed in glass?

28. A beam of light bends as shown in (a), while the edges of the immersed square bend as shown in (b). Do these pictures contradict each other? Explain.


(a) (b)

29. If, while standing on a bank, you wish to spear a fish beneath the water surface in front of you, should you aim above, below, or directly at the observed fish to make a direct hit? If, instead, you zap the fish with a laser, should you aim above, below, or directly at the observed fish? Defend your answers.

30. If the fish in the previous exercise were small and blue and your laser light were red, what corrections should you make? Explain.

31. When a fish in a pond looks upward at an angle of 45°, does it see the sky above the water's surface or a reflection from the water–air boundary of the bottom of the pond? Defend your answer.

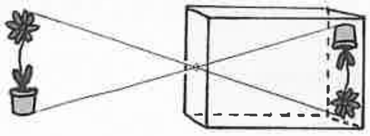
32. Upward rays of light in water toward the water–air boundary at angles greater than 48° to the normal are totally reflected. No rays beyond 48° refract outside. How about the reverse? Is there an angle at which light rays in air meeting the air–water boundary will totally reflect? Or will some light be refracted at all angles?

33. If you were to send a beam of laser light to a space station above the atmosphere and just above the horizon, would you aim the laser above, below, or at the visible space station? Defend your answer.

34. What exactly are you seeing when you observe a "water-on-the-road" mirage?

35. What accounts for the large shadows cast by the ends of the thin legs of the water strider?

36. When you stand with your back to the Sun, you see a rainbow as a circular arc. Could you move off to one side and then see the rainbow as the segment of an ellipse rather than the segment of a circle (as Figure 28.32 suggests)? Defend your answer.
37. Two observers standing apart from one another do not see the "same" rainbow. Explain.
38. A rainbow viewed from an airplane may form a complete circle. Where will the shadow of the airplane appear? Explain.
39. How is a rainbow similar to the halo sometimes seen around the Moon on a frosty night? If you're stumped, check the web and see how rainbows and halos differ.
40. Transparent plastic swimming-pool covers called *solar heat sheets* have thousands of small air-filled bubbles that resemble lenses. The bubbles in these sheets are advertised to focus heat from the Sun into the water, thereby raising its temperature. Do you think these bubbles direct more solar energy into the water? Defend your answer.
41. Would the average intensity of sunlight measured by a light meter at the bottom of the pool in Figure 28.45 be different if the water were still?
42. When your eye is submerged in water, is the bending of light rays from water to your eyes more, less, or the same as in air?
43. Why will goggles allow a swimmer under water to focus more clearly on what he or she is looking at?
44. If a fish wore goggles above the water surface, why would vision be better for the fish if the goggles were filled with water? Explain.
45. Does a diamond under water sparkle more or less than in air? Defend your answer.
46. Cover the top half of a camera lens. What effect does this have on the pictures taken?
47. What will happen to the image projected onto a screen by a lens when you cover one-third of the lens with a red filter, one-third with a green filter, and one-third with a blue filter? (Try it and see!)
48. How could a converging lens be made for sound waves? (Such a lens, a spherical bag of gas, is a feature of San Francisco's Exploratorium.)
49. Would refracting telescopes and microscopes magnify if light had the same speed in glass as in air? Defend your answer.
50. There is less difference between the speed of light in glass and the speed of light in water than there is between the speed of light in glass and the speed of light in air. Does this mean that a magnifying glass will magnify more or magnify less when it is used under water rather than in air?
51. Waves don't overlap in the image of a pinhole camera. Does this feature contribute to sharpness or to a blurry image?
52. Why does the sharpness of the image in a pinhole camera not depend on the position of the viewing screen?



53. Whereas pinholes provide sharp images, lenses with large apertures are advantageous for spy cameras in high-flying aircraft. Why?
54. If you point the pinhole camera of Exercise 52 at the Sun, a clear and bright solar image will be seen on the viewing screen. How does this relate to the circular spots of light that surround Lillian beneath the sunlit tree shown in the photo?

55. In terms of focal length, how far behind the camera lens is photosensitive surface located when very distant objects are being photographed?
56. Why do you put slides into an old-fashioned slide projector upside down?
57. The image produced by a converging lens is upside down. Our eyes have converging lenses. Does this mean the images we see are upside down on our retinas? Explain.
58. The images produced by a converging camera lens are upside down. Does this mean the photographs taken with cameras are upside down?
59. Maps of the Moon are upside down. Why?
60. Why do older people who do not wear glasses read books farther away from their eyes than younger people do?

PROBLEMS

1. Suppose you walk toward a mirror at 2 m/s. How fast do you and your image approach each other? (The answer is *not* 2 m/s.)
2. Show with a simple diagram that when a mirror with a fixed beam incident upon it is rotated through a certain angle, the reflected beam is rotated through an angle twice as large. (This doubling of displacement makes irregularities in ordinary window glass more evident.)
3. A butterfly at eye level is 20 cm in front of a plane mirror. You are behind the butterfly, 50 cm from the mirror.

What is the distance between your eye and the image of the butterfly in the mirror?

4. When light strikes glass perpendicularly, about 4% is reflected at each surface. Show that 92% of light is transmitted through a pane of window glass.
5. No glass is perfectly transparent. Mainly because of reflections, about 92% of light passes through an average sheet of clear windowpane. The 8% loss is not noticed through a single sheet, but through several sheets, the loss is apparent. How much light is transmitted by a double-paned window (one with two sheets of glass)?
6. • The diameter of the Sun makes an angle of 0.53° from Earth. How many minutes does it take the Sun to move 1 solar diameter in an overhead sky? (Remember that it takes 24 hours, or 1440 minutes, for the Sun to move through 360°.) How does your answer compare with the time it takes the Sun to disappear, once its lower edge meets the horizon at sunset? (Does refraction affect your answer?)

CHAPTER 28 ONLINE RESOURCES

PhysicsPlace.com™

Interactive Figures

- 28.6, 28.14, 28.36, 28.46

Videos

- Image Formation in a Mirror
- Model of Refraction
- The Rainbow

Quizzes

Flashcards

Links