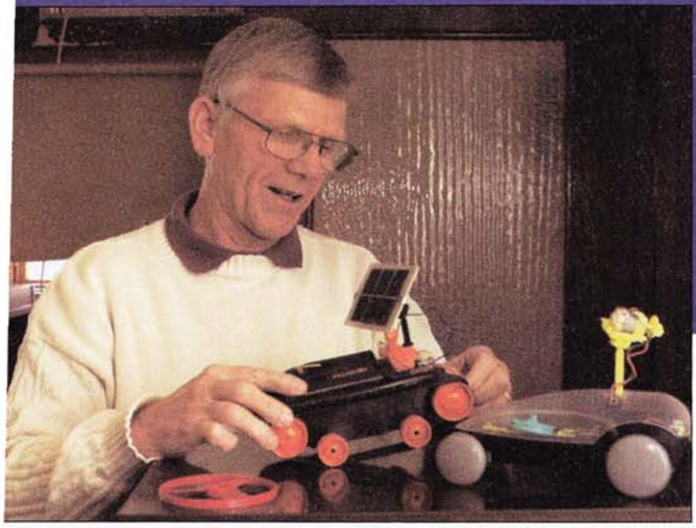
CHAPTER 26

Properties of Light



Roy Unruh demonstrates the conversion of light energy to electric energy with model solar-powered vehicles.

Light is the only thing we can really see. But what *is* light? We know that, during the day, the primary source of light is the Sun and the secondary source is the brightness of the sky. Other common sources are flames, white-hot filaments in lightbulbs, and glowing gas in glass tubes. Light originates from the accelerated motion of electrons. It is an electromagnetic phenomenon and only a tiny part of a larger whole—a wide range of electromagnetic waves called the *electromagnetic spectrum.* We begin our study of light 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.

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

Insights

Electromagnetic Waves

FIGURE 26.1
Shake an electrically charged object to and fro, and you produce an electromagnetic wave.

If you shake the end of a stick back and forth in still water, you will produce waves on the surface of the water. Similarly, if you shake an electrically charged rod to and fro in empty space, you will produce electromagnetic waves in space. This is because the moving charge is actually an electric current. What surrounds an electric current? The answer is, a magnetic field. What surrounds a changing electric current? The answer is, a changing magnetic field. Recall, from the previous chapter, that a changing magnetic field generates an electric field—electromagnetic induction. If the magnetic field is oscillating, the electric field that it generates will be oscillating, too. And what does an oscillating electric field do? In accordance with Maxwell's counterpart to Faraday's law of electromagnetic induction, it induces an oscillating magnetic field. 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.

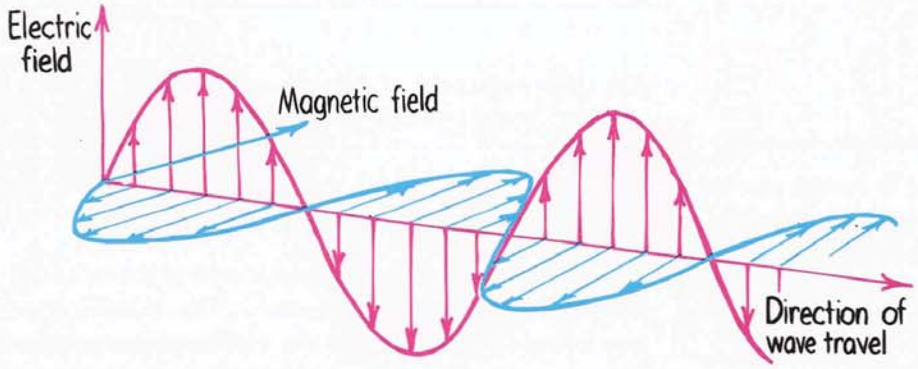


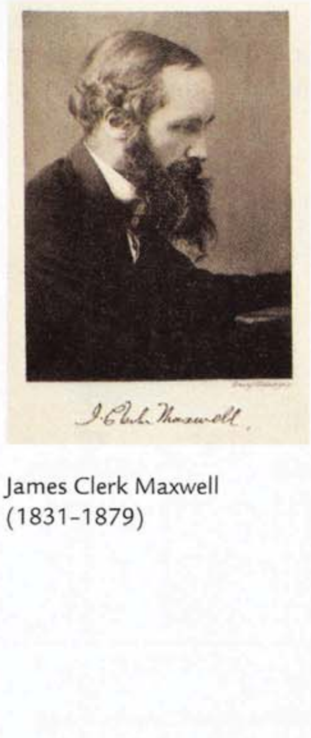
FIGURE 26.2
Interactive Figure
The electric and magnetic fields of an electromagnetic wave are perpendicular to each other and to the direction of motion of the wave.

Electromagnetic Wave Velocity

A spacecraft cruising through space may gain or lose speed, even if its engines are shut off, because gravity can accelerate it forward or backward. But an electromagnetic wave traveling through space never changes its speed. Not because gravity doesn't act on light, for it does. Gravity can change the frequency of light or deflect light, but it can't change the speed of light. What keeps light moving always at the same, unvarying speed in empty space? The answer has to do with 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. No energy would be transported from one place to another. So light cannot travel slower than it does.

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, James Clerk 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!



James Clerk Maxwell
(1831–1879)

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.

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

Light is energy carried in an electromagnetic wave emitted by vibrating electrons in atoms.

Insights

CHECK YOURSELF

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

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. Then come ultrahigh frequencies (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.

In empty space, there is light but no sound. In air, light travels a million times faster than sound.

Insights

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

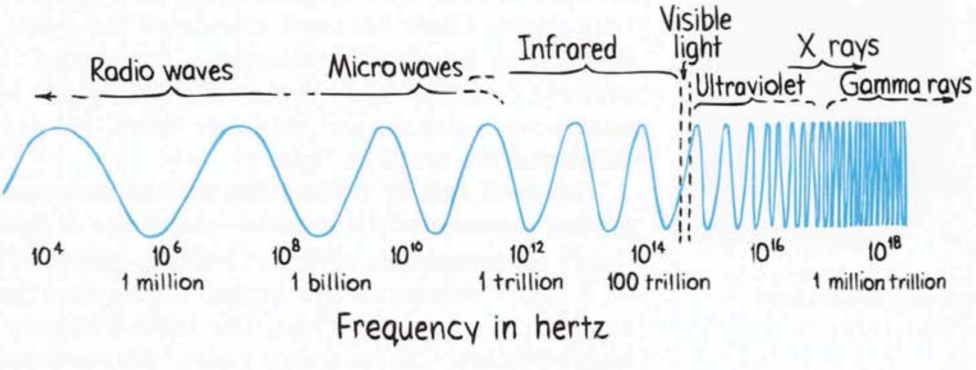

FIGURE 26.3

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.

CHECK YOUR ANSWER

The underlying principle that makes light and all other electromagnetic waves travel at one fixed speed is the conservation of energy.

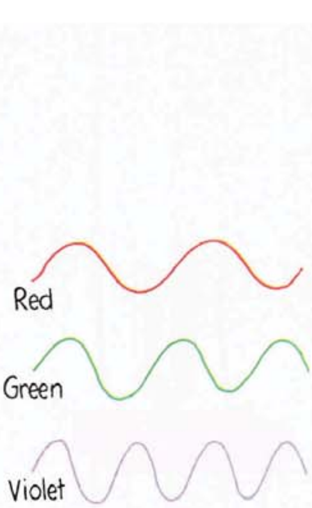

FIGURE 26.4
Interactive Figure

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

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 kilometers per second, an electric charge oscillating once per second (1 hertz) will produce a wave with a wavelength of 300,000 kilometers. This is because only one wavelength is generated in 1 second. If the frequency of oscillation were 10 hertz, then 10 wavelengths would be formed in 1 second, and the corresponding wavelength would be 30,000 kilometers. A frequency of 10,000 hertz would produce a wavelength of 30 kilometers. 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 waves, which engulf us every moment. Free electrons in every piece of metal on the Earth's surface continually dance to the rhythms of these waves. They jiggle in unison with the electrons being driven up and down along radio- and television-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 in which occasional concentrates are suspended.

Before the advent of microwave ovens, there were infrared ones—simply called "ovens."

Insights

CHECK YOURSELF

Is it correct to say that a radio wave can be considered a low-frequency light wave? Can a radio wave also be considered to be a sound wave?

Transparent Materials

The Physics Place
Light and Transparent Materials

Light is an energy-carrying electromagnetic wave that emanates from vibrating electrons in atoms. When light is transmitted through matter, some of the electrons in the matter are forced into vibration. In this way, vibrations in the

CHECK YOUR ANSWERS

Both a radio wave and a light wave are electromagnetic waves, which originate in the vibrations of 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 not electromagnetic. A sound wave is fundamentally different from an electromagnetic wave. So a radio wave is definitely not a sound wave.

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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.

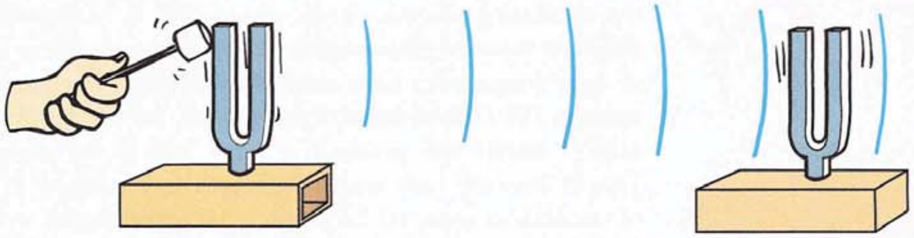

FIGURE 26.5
Just as a sound wave can force a sound receiver into vibration, a light wave can force electrons in materials into vibration.

emitter are transmitted to vibrations in the receiver. This is similar to the way sound is transmitted (Figure 26.5).

Thus 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, some 100 trillion times per second (10^{14} hertz). 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.

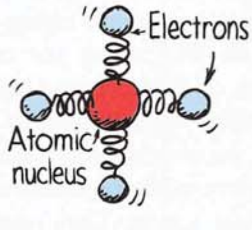

FIGURE 26.6
The electrons of atoms in glass have certain natural frequencies of vibration and can be modeled as particles connected to the atomic nucleus by springs.

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.

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 any glass atom receives 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 about 1 million vibrations, and it collides with neighboring atoms and gives up its energy as heat. Thus, glass is not transparent to ultraviolet light.

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

Insights

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 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

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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.

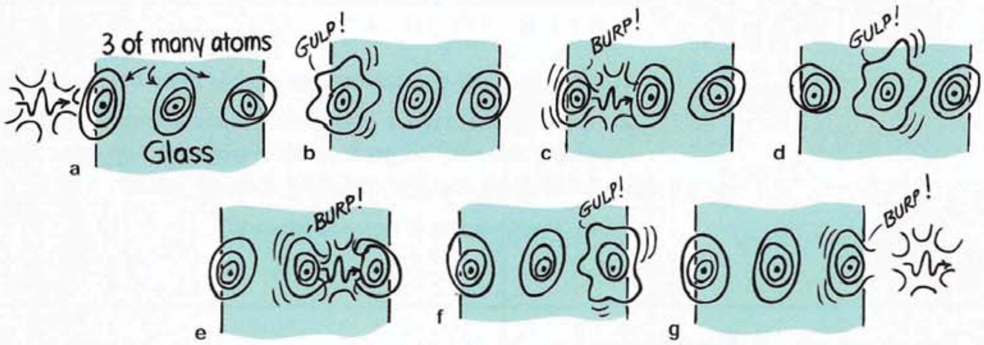


FIGURE 26.7
A wave of visible light incident upon a pane of glass sets up in atoms vibrations that produce a chain of absorptions and reemissions, which pass the light energy through the material and out the other side. Because of the time delay between absorptions and reemissions, the light travels through the glass more slowly than through empty space.

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.

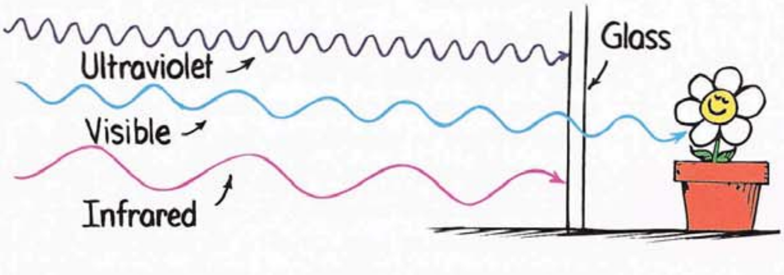
It is this time delay that results in a lower average speed of light through a transparent material (Figure 26.7). Light travels at different average speeds through different materials. We say *average speeds* because the speed of light in a vacuum, whether in interstellar space or in the space between molecules in a piece of glass, is a constant 300,000 kilometers per second. 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*.

Infrared waves, with frequencies lower than those of visible light, vibrate not only the electrons, but entire atoms or molecules in the structure of the glass. 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.

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

Insights

FIGURE 26.8
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 YOURSELF

1. Why is glass transparent to visible light but opaque to ultraviolet and infrared?
2. Pretend that, while you walk across a 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?

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. They become slightly warmer.

Longer-wavelength ultraviolet, called UV-A, is close to visible light and isn't harmful. Short-wavelength 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.

Insights

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 "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

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 26.9
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.

protection against ultraviolet. 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.

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 cannot 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 26.10). There is usually a dark part on the

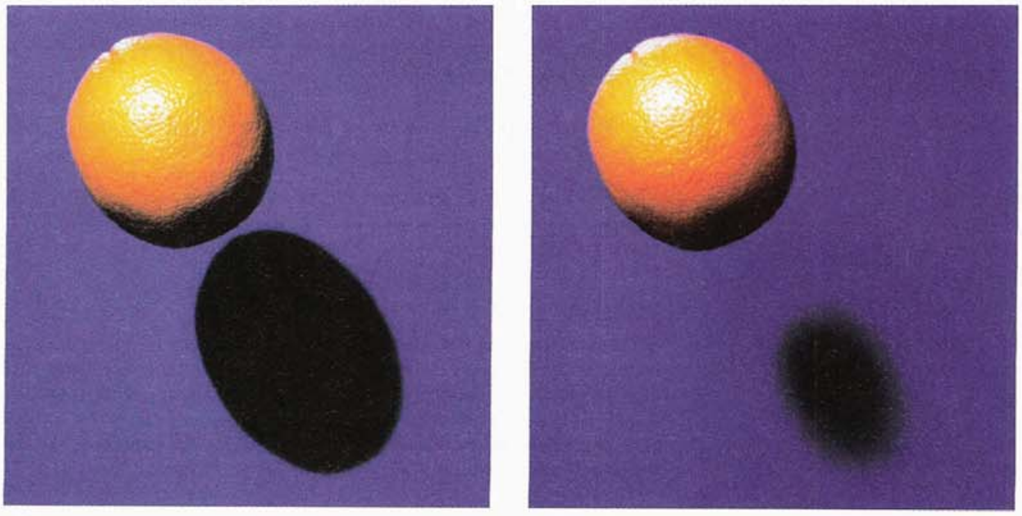

FIGURE 26.10
A small light source produces a sharper shadow than a larger source.

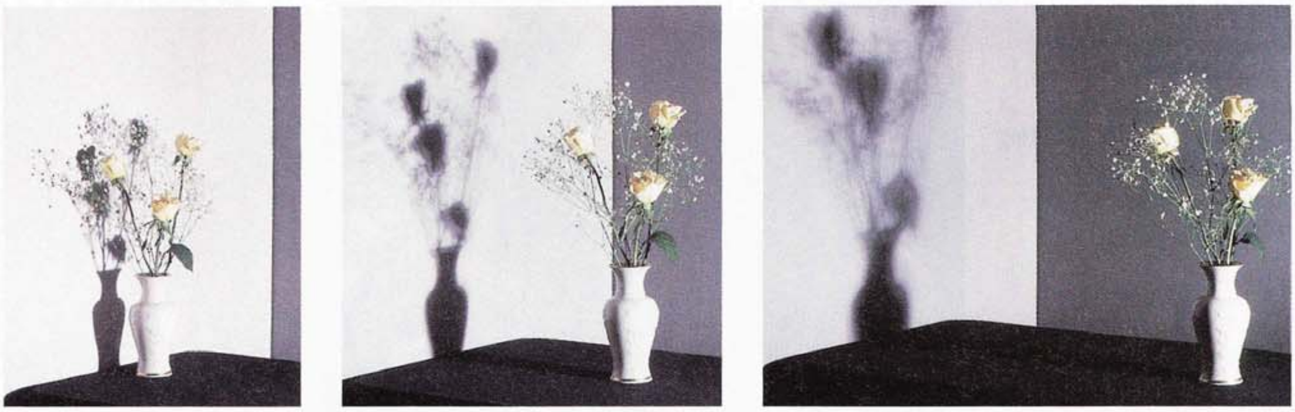

FIGURE 26.11
An object held close to a wall casts a sharp shadow because light coming from slightly different directions does not spread much behind the object. As the object is moved farther away from the wall, penumbras are formed and the umbra becomes smaller. When the object is farther away, the 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.

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 26.11). A penumbra also occurs where light from a broad source is only partially blocked.

Both the 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 26.12). A dramatic example of the umbra and penumbra occurs when the shadow of the Moon falls on the 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 26.13). If you stand in the umbra part of the shadow, you experience darkness 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.[6] In a **lunar eclipse,** the Moon passes into the shadow of the Earth.

CHECK YOURSELF

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?

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[6] 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.

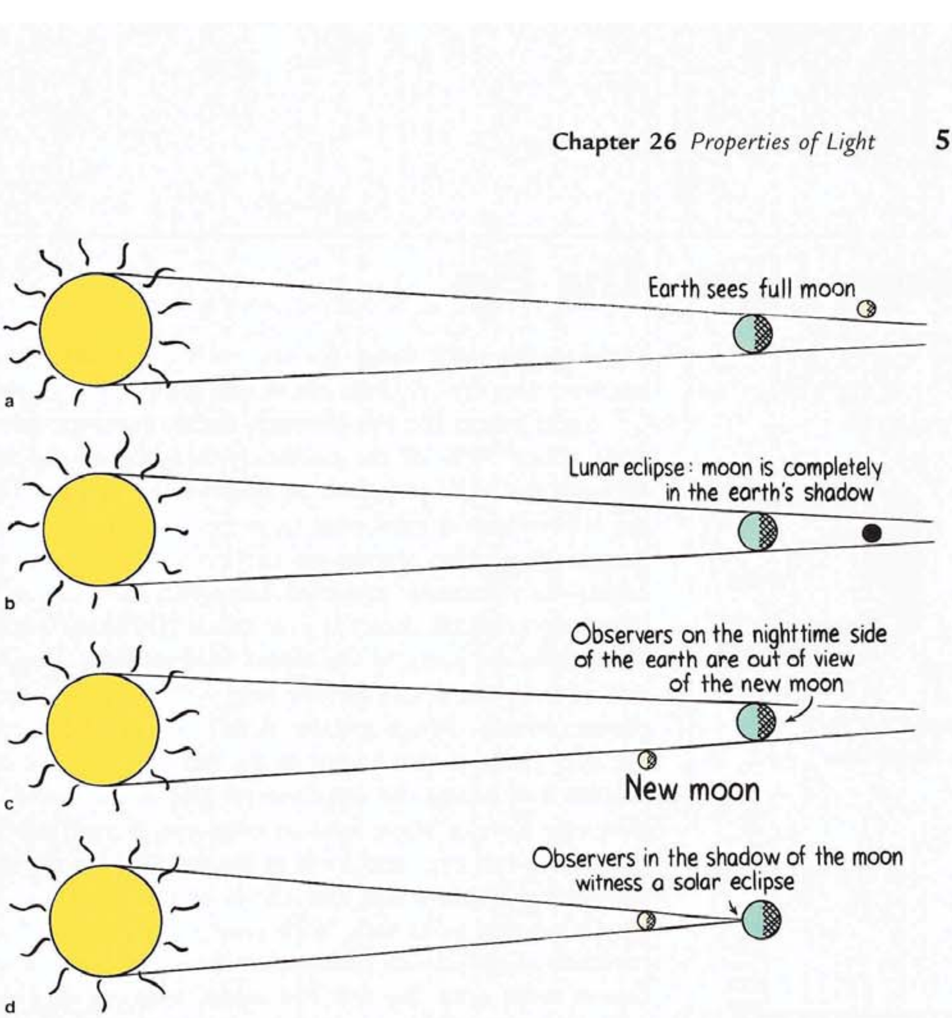

FIGURE 26.12 Interactive Figure
(a) A full Moon is seen when the Earth is between the Sun and the Moon. (b) When this alignment is perfect, the Moon is in Earth's shadow, and a lunar eclipse is produced. (c) A new Moon occurs when the Moon is between the Sun and Earth. (d) When this alignment is perfect, the Moon's shadow falls on part of the Earth to produce a solar eclipse.

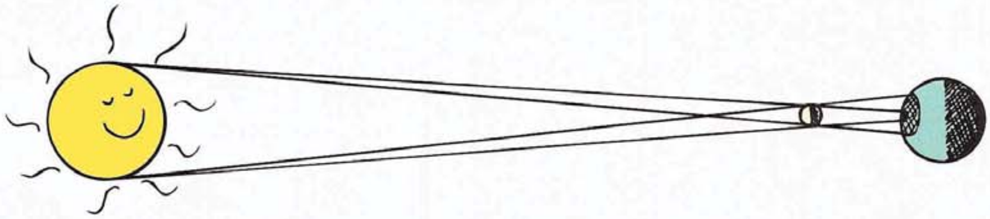

FIGURE 26.13
Interactive Figure
Details of a solar eclipse. A total eclipse is seen by observers in the umbra, and a partial eclipse is seen by observers in the penumbra. Most Earth observers see no eclipse at all.

CHECK YOUR ANSWERS

1. Only a solar eclipse is harmful when viewed directly 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 enough, 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 the Earth's surface, only a relatively few people are in the shadow of the Moon in a solar eclipse. But the shadow of the Earth completely covers the Moon during a total lunar eclipse, so everybody who views the nighttime sky can see the shadow of the Earth on the Moon.

Seeing Light—The Eye

Light is the only thing we see with the most remarkable optical instrument known—the eye. A diagram of the human eye is shown in Figure 26.14.

Light enters the eye through the transparent cover called the *cornea,* which does about 70% of the necessary bending of the light before the light passes through the pupil (which is an aperture in the iris). The light then passes through the lens, which is used only to provide the extra bending power needed to focus images of nearby objects on the layer at the back of the eye. This layer—the *retina*—is extremely sensitive: Until very recently, it was more sensitive to light than any artificial detector ever made. Different parts of the retina receive light from different parts of the visual field outside. The retina is not uniform. There is a spot in the center of our field of view called the *fovea,* the region of most distinct vision. Much greater detail can be seen here 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 26.15 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 centimeters 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 26.15 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!

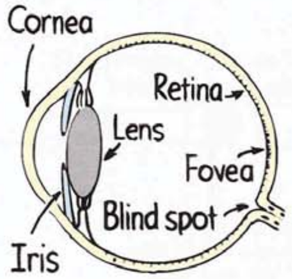

FIGURE 26.14
The human eye.

The giant squid has the largest eyes in the world.

Insights

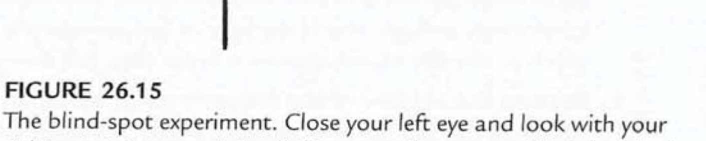

FIGURE 26.15
The blind-spot experiment. Close your left eye and look with your right eye at the round dot. Adjust your distance and find the blind spot that erases the X. Switch eyes and look at the X and the dot disappears. Does your brain fill in crossed lines where the dot was?

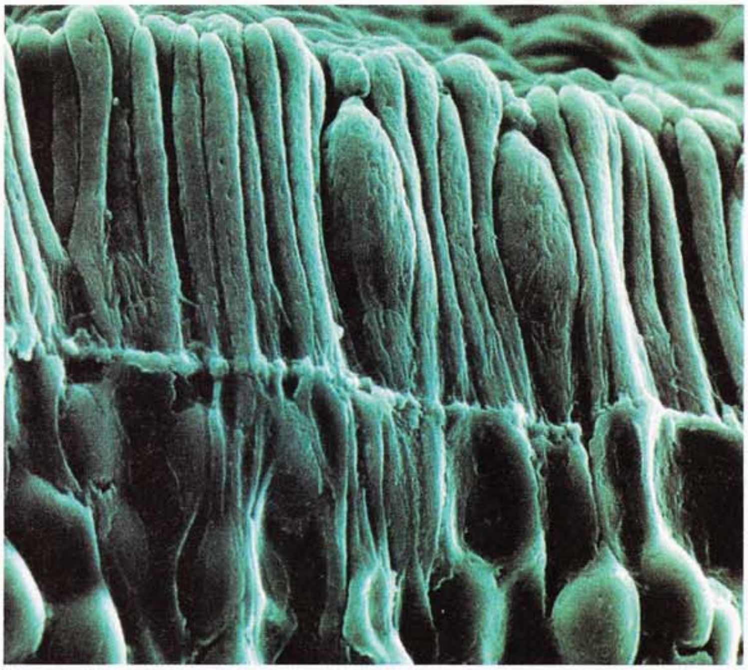

FIGURE 26.16
Magnified view of the rods and cones in the human eye.

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 26.16). As the names imply, some of the antennae are rod-shaped and some cone-shaped. 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 rods predominate toward the periphery of the retina, while the three types of cones are denser toward the fovea. 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. Color vision is possible because of the cones. Hence 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.

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 fact 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 26.17). Try it and see!

FIGURE 26.17
On the periphery of your vision, you can see an object and its color only if it is moving.

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. The cones can see a deep red where the rods see no light at all. Red light may as well be black as far as the rods are concerned. 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 interesting. 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 carry the magazine into the light. You should see a remarkable shift between the brightest and dimmest colors.[7]

The rods and cones in the retina are not connected directly to the optic nerve, but, interestingly enough, 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.

FIGURE 26.18
The size of your pupils depends on your mood.

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 relative size of this enlargement or contraction is also 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.*)

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

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

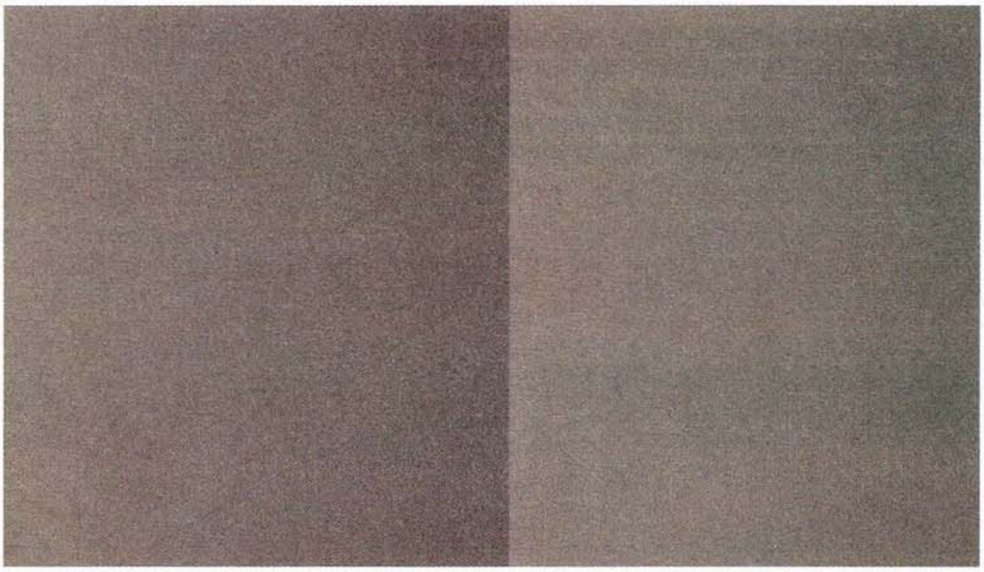


FIGURE 26.19
Both rectangles are equally bright. Cover the boundary between them with your pencil and see.

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 26.19 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.

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?

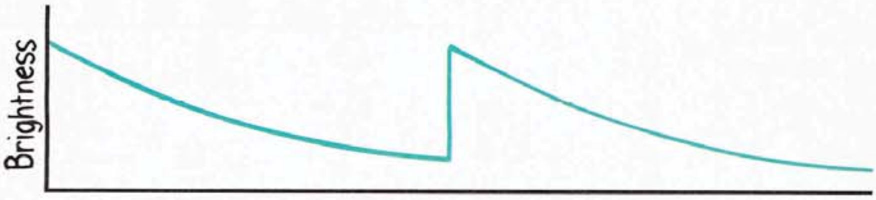
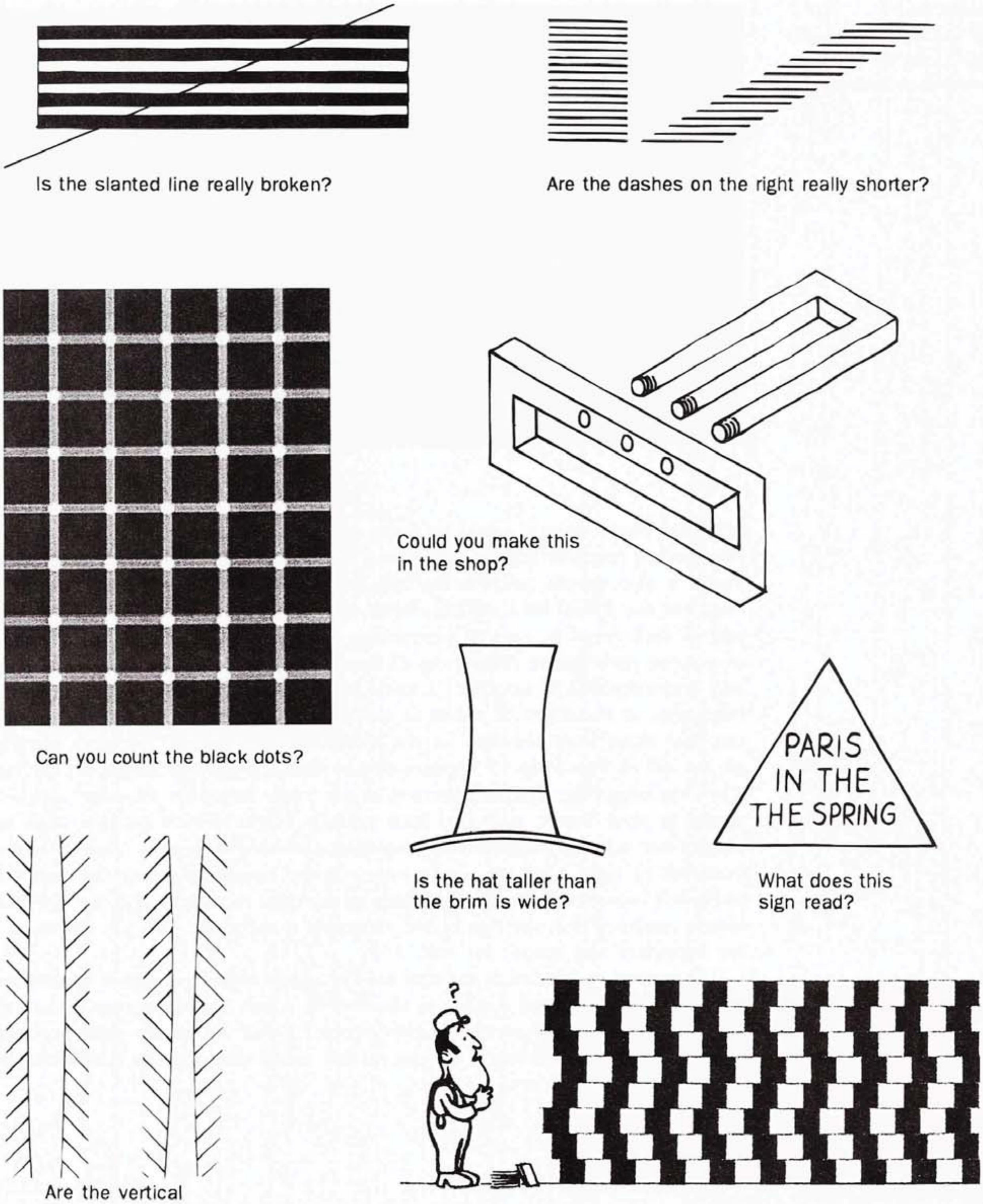


FIGURE 26.20
Graph of brightness levels for the rectangles in Figure 26.19.



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 26.21
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 the Earth.

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

Suggested Reading

Falk, D. S., D. R. Brill, and D. Stork. *Seeing the Light: Optics in Nature.* New York: Harper & Row, 1986.

For more on illusions, see www.michaelbach.de/ot

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?

Electromagnetic Wave Velocity

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?

Shadows

24. Distinguish between an *umbra* and a *penumbra.*
25. Do the 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 tree, it will slow down inside the tree 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 the Earth can witness a solar eclipse when it occurs, whereas all the people on the nighttime side of the Earth can witness a lunar eclipse when it occurs. Why is this so?

33. Lunar eclipses are always eclipses of a full Moon. That is, the Moon is always seen full just before and after the 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?

34. Do planets cast shadows? What is your evidence?

35. In 2004, the planet Venus passed between the 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 the Earth experiences a lunar eclipse? At the time the 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. From your experimentation with Figure 26.15, is your blind spot located noseward from your fovea or to the outside of it?

41. Why should you be skeptical when your sweetheart holds you and looks at you with constricted pupils and says, "I love you"?

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 five times as far from the Sun as the 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 about 1675, the Danish astronomer Olaus Roemer, measuring the times when one of Jupiter's moons appeared from behind Jupiter in its successive trips around that planet, and noticing the delays in these appearances as the Earth got farther from Jupiter, concluded that light took an extra 22 min to travel 300,000,000 km across the diameter of the Earth's orbit around the Sun. What approximate value for the speed of light did Roemer deduce? How much does it differ from our modern value? (Roemer's measurement, although not accurate by modern standards, was the first demonstration that light travels at a finite, not an infinite, speed.)

2. In one of Michelson's experiments, a beam from a revolving mirror traveled 15 km to a stationary mirror. How long a time interval elapsed before the beam returned to the revolving mirror?

3. The Sun is 1.50×10^{11} meters from the Earth. How long does it take for the Sun's light to reach the 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 seventeenth century (Problem 1).
4. How long does it take for a pulse of laser light to reach the Moon and to bounce back to the Earth?
5. The nearest star beyond the Sun is Alpha Centauri, 4.2×10^{16} meters away. If we were to receive a radio message from this star today, how long ago would it have been sent?
6. The wavelength of yellow sodium light in air is 589 nm. What is its frequency?
7. Blue-green light has a frequency of about 6×10^{14} Hz. Use the relationship $c = f\lambda$ to find the wavelength of this light in air. How does this wavelength compare with the size of an atom, which is about 10^{-10} m?
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?
9. A certain radar installation that is used to track airplanes transmits electromagnetic radiation of wavelength 3 cm. (a) What is the frequency of this radiation, measured in billions of hertz (GHz)? (b) What is the time required for a pulse of radar waves to reach an airplane 5 km away and return?
10. 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 26.13) 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 three times the diameter of the ball.