21 Musical Sounds

1 Gracie Hewitt produces soothing tones with her clarinet. 2 Norm Whitlatch shows the first five harmonics, in blue, from a Fourier analysis of sound from a guitar pitch pipe, which is displayed on the upper green oscilloscope trace. 3 Michelle Anna Wong and Miriam Dijamco delight audiences when they draw bows across the strings of their violins.

What does physics have to do with music? PLENTY! Since ancient times, scientists have seen a close connection between music and mathematics. One such mathematician and physicist was Jean Baptiste Joseph Fourier, who was born in France in 1768. He was the son of a tailor and was orphaned at age 10. Fourier showed signs of great brightness, but since not being of "good birth," he was ineligible for a commission he sought in the scientific corps of the army. Instead, he accepted a military lectureship and became a teacher of mathematics.

In his home district, Fourier took a prominent part in promoting the French Revolution. At age 30 he went with Napoleon Bonaparte on his Egyptian expedition and was made governor of Lower Egypt. Cut off from France by the English fleet, he organized the workshops on which the French army relied on for their munitions of war. At that time he also contributed several mathematical papers to the institute that Napoleon founded, the Cairo Institute. After British victories, Fourier made his way back to France, where he conducted experiments on the propagation of heat. He discovered that sums of mathematical trigonometric functions greatly simplified the study of heat propagation.

Fourier discovered a mathematical regularity to the component parts of any type of periodic wave motion. He found that even the most complex periodic waves can be disassembled into simple sine waves that add together. What he discovered in 1822 is today called Fourier analysis. In this chapter let's see how this applies to musical sounds.

Noise and Music

Most of the sounds we hear are noises. The impact of a falling object, the slamming of a door, the roaring of a motorcycle, and most of the sounds from traffic in city streets are noises. Noise corresponds to an irregular vibration of the eardrum produced by some irregular vibration in our surroundings, a jumble of wavelengths and amplitudes. *White noise* is a mixture of a variety of frequencies of sound, just as white light is a mixture of all the frequencies of light. We describe the sound of surf, rustling leaves, or bubbling water in a brook as white noise.

Music is the art of sound and has a different character. Musical sounds have periodic tones—or musical *notes*. Although noise doesn't have these characteristics, the line that separates music and noise can be thin and subjective. To some contemporary composers, it is nonexistent. Some people consider contemporary music and music from other cultures to be noise. Differentiating these types of music from noise becomes a problem of aesthetics. However, differentiating traditional music—that is, Western classical music and most types of popular music—from noise presents no problem. A person with total hearing loss could distinguish between these by using an oscilloscope, as Norm Whitlatch shows in the opening photo. When an electrical signal from a microphone is fed into an oscilloscope, patterns of air-pressure variations with time are nicely displayed that make it easy to distinguish between noise and traditional music (Figure 21.1).

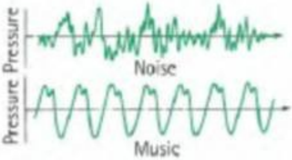


FIGURE 21.1
Graphical representations of noise and music.

Musicians usually speak of musical tones in terms of three principal characteristics: pitch, loudness, and quality.

CHECK POINT

A thud makes noise. Can a series of thuds be musical?

Check Your Answer

Yes, especially when they are periodic—think of a drum solo.

Pitch

Music is organized on many different levels. Most noticeable are musical notes. You may remember these in your earlier school years as "do, re, mi, fa, sol, la, ti, and do." Each note has its own **pitch.** We can describe pitch by frequency. Rapid vibrations of the sound source (high frequency) produce sound of a high pitch, whereas slow vibrations (low frequency) produce a low pitch. We often speak of the pitch of a sound in terms of its position on the musical scale. Musicians give different pitches different letter names: A, B, C, D, E, F, G. When A, called concert A, is struck on a piano, a hammer strikes two or three strings, each of which vibrates 440 times in 1 second. The pitch of concert A corresponds to 440 hertz.[1] Notes A

[1]Interestingly, concert A varies from as low as 436 Hz to as high as 448 Hz in frequency.

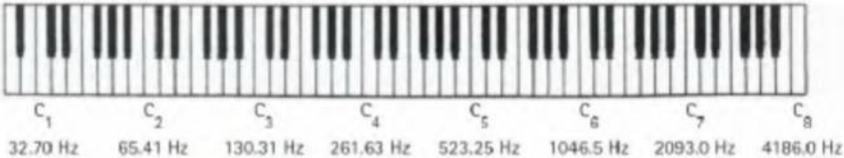


FIGURE 21.2

Piano keyboard. Low C (C_1) is 32.70 Hz and successive overtones of C keep doubling in frequency. The 261.63-Hz C is called middle C.

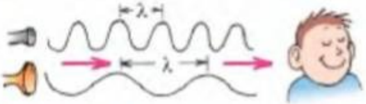


FIGURE 21.3

Both sound waves travel at the same speed. The one with the shorter wavelength λ reaches the listener's ear more frequently. It therefore has a higher frequency and is heard as a higher pitch.

through G are all notes within one octave. Multiply the frequency on any note by 2, and you have the same note at a higher pitch in the next octave. A piano keyboard covers a little more than seven octaves (Figure 21.2).

Different musical notes are obtained by changing the frequency of the vibrating sound source. This is usually done by altering the size, the tightness, or the mass of the vibrating object. A guitarist or violinist, for example, adjusts the tightness, or tension, of the strings when tuning them. Then different notes can be played by altering the length of each string by "stopping" it with the fingers. In wind instruments, the length of the vibrating air column can be altered (trombone and trumpet) or holes in the side of the tube can be opened and closed in various combinations (saxophone, clarinet, flute) to change the pitch of the note produced.

High-pitched sounds used in music are most often less than 4000 Hz, but the average human ear can hear sounds with frequencies up to 18,000 Hz. Some people and most dogs can hear tones of higher pitch than this. In general, the upper limit of hearing in people gets lower as they grow older. A high-pitched sound is often inaudible to an older person and yet may be clearly heard by a younger one. This is due to aging of the sensitive hairs on the organ of Corti in the ear. The sense of hearing, especially of higher frequencies, decreases as we grow older.

CHECK POINT

The sound emitted by bats is extremely intense. Why cannot humans hear them?

Check Your Answer

The pitch of sound emitted by bats is higher than humans can hear. Otherwise the sound of bats would drive people batty!

Sound Intensity and Loudness

The **intensity** of sound depends on the amplitude of pressure variations within the sound wave. (And, as with all waves, intensity is directly proportional to the square of the wave amplitude.) Intensity is measured in units of watts/square meter. The human ear responds to intensities covering the enormous range from 10^{-12} W/m^2 (the threshold of hearing) to more than 1 W/m^2 (the threshold of pain). Because the range is so great, intensities are scaled by factors of 10, with the barely audible 10^{-12} W/m^2 as a reference intensity—called 0 *bel* (a unit named after Alexander Graham Bell). A sound 10 times more intense has an intensity of 1 bel (10^{-11} W/m^2) or 10 *decibels*. Table 21.1 lists typical sounds and their intensities. A sound of 10 decibels is 10 times as intense as 0 decibels, the threshold of hearing. Accordingly, 20 decibels is 100, or 10^2, times the intensity of the threshold of hearing, 30 decibels is 10^3 times the threshold of hearing, and 40 decibels is 10^4 times. So 60 decibels represents sound intensity a million times (10^6) greater than 0 decibels. Can you see that 80 decibels represents sound 10^2 times as intense as 60 decibels?[2]

Physiological hearing damage begins at exposure to 85 decibels, the degree of damage depending on the length of exposure and on frequency characteristics. Damage from loud sounds can be temporary or permanent, depending on whether the nerve ending on the organ of Corti, the receptor organ in the inner ear, is impaired or destroyed. A single burst of sound can produce vibrations in the organ intense enough to tear it apart. Less intense, but severe, noise can interfere with cellular processes in the organ and cause its eventual breakdown. Unfortunately, the cells of the organ do not regenerate.

Sound intensity is a purely objective and physical attribute of a sound wave, and it can be measured by various acoustical instruments (and the oscilloscope in Figure 21.4). **Loudness,** on the other hand, is a physiological sensation. The ear senses some frequencies much better than others. A 3500-Hz sound at 80 decibels, for example, sounds about twice as loud to most people as a 125-Hz sound at 80 decibels; humans are more sensitive to the 3500-Hz range of frequencies. The loudest sounds we can tolerate have intensities a trillion times greater than the faintest sounds. The difference in perceived loudness, however, is much less than this amount.

Ear plugs typically reduce noise by about 30 dB.

FIGURE 21.4

James displays a sound signal on an oscilloscope.

TABLE 21.1

Common Sources and Sound Intensities

Source of Sound	Intensity (W/m^2)	Sound Level (dB)
Jet airplane 30 m away	10^2	140
Air-raid siren, nearby	1	120
Disco music, amplified	10^{-1}	110
Riveter	10^{-3}	90
Busy street traffic	10^{-5}	70
Conversation in home	10^{-6}	60
Quiet radio in home	10^{-8}	40
Whisper	10^{-10}	20
Rustle of leaves	10^{-11}	10
Threshold of hearing	10^{-12}	0

fyi

- The Blue Whale emits the loudest sounds, greater than 180 db in water, but pitched too low for humans to detect without sensitive equipment.

CHECK POINT

Is hearing permanently impaired when attending concerts, clubs, or functions that feature very loud music?

Check Your Answer

Yes, depending on how loud, how long, how near, and how often. Some music groups have emphasized loudness over quality. Tragically, as hearing becomes more and more impaired, members of the group (and their fans) require louder and louder sounds for stimulation. Hearing loss caused by sounds is particularly common in the frequency range of 2000–5000 Hz. Recall that human hearing is normally most sensitive around 3000 Hz. (Looking for a career? Consider becoming an audiologist—you'll be busy!)

[2]The decibel scale is called a logarithmic scale. The decibel rating is proportional to the logarithm of the intensity.

Quality

We have no trouble distinguishing between the tone from a piano and a tone of the same pitch from a clarinet. Each of these tones has a characteristic sound that differs in **quality,** the "color" of a tone—*timbre*. Timbre describes all of the aspects of a musical sound other than pitch, loudness, or length of tone. Timbre is described subjectively as heavy, light, murky, thin, smooth, or transparently clear. Sound from a viola, for example, has a noticeably "deeper" sound, while the violin has a noticeably "brighter" sound.

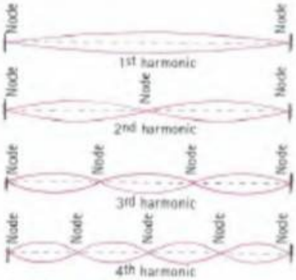


FIGURE 21.5

Modes of vibration of a guitar string.

Most musical sounds are composed of a superposition of many tones differing in frequency. The various tones are called **partial tones,** or simply *partials*. The lowest frequency, called the **fundamental frequency,** determines the pitch of the note. A partial tone whose frequency is a whole-number multiple of the fundamental frequency is called a **harmonic.** Different harmonics have different pitches. A tone that has twice the frequency of the fundamental is the second harmonic; a tone with 3 times the fundamental frequency is the third harmonic; and so on (Figure 21.5).[5] It is the variety of partial tones that gives a musical note its characteristic quality. So we see that musical instruments have characteristic timbres, each with their own "color."

Thus, if we strike middle C on the piano, we produce a fundamental tone with a pitch of about 262 Hz and also a blending of partial tones of two, three, four, five, and so on, times the frequency of middle C. The number and relative loudness of the partial tones determine the quality of sound associated with the piano. Sound from practically every musical instrument consists of a fundamental and partials. Pure tones, those having only one frequency, can be produced electronically. Electronic synthesizers produce pure tones, and mixtures of these tones, to give a vast variety of musical sounds.

FIGURE 21.6

A composite vibration of the fundamental mode and the third harmonic.

FIGURE 21.7

Sounds from the piano and clarinet differ in quality.

The quality of a tone is determined by the presence and relative intensity of the various partials. The sound produced by a certain tone from the piano and a clarinet of the same pitch have different qualities that the ear can recognize because their partials are different. A pair of tones of the same pitch with different qualities have either different partials or a difference in the relative intensity of the partials.

CHECK POINT

The pitch and loudness of two people's voices may be the same, but we easily distinguish between them. Why?

Check Your Answer

The voice of each person has a characteristic mixture of partial tones. We say each person's voice has its own timbre—its own special "color."

[5]In the terminology often used in music, the second harmonic is called the *first overtone*, the third harmonic is called the *second overtone*, and so on. Not all partial tones present in a complex tone are integer multiples of the fundamental. Unlike the harmonics of woodwinds and brasses, stringed instruments, such as pianos, produce "stretched" partial tones that are nearly, but not quite, harmonics. This is an important factor in tuning pianos, and it occurs because the stiffness of the strings adds a little bit of restoring force to the tension.

Musical Instruments

Conventional musical instruments can be grouped into one of three classes: those in which the sound is produced by vibrating strings, those in which the sound is produced by vibrating air columns, and those in which the sound is produced by *percussion*—as with the vibrating of a two-dimensional surface.

In a stringed instrument, the vibration of the strings is transferred to a sounding board and then to the air, but with low efficiency. To compensate for this, we find relatively large string sections in orchestras. A smaller number of the high-efficiency wind instruments sufficiently balances a much larger number of violins.

In a wind instrument, the sound is a vibration of an air column in the instrument. There are various ways to set air columns into vibration. In brass instruments, such as trumpets, French horns, and trombones, air is blown into the instrument's mouthpiece at or near one end of the tube and exits at the other end. Vibrations of the player's lips interact with standing waves that are set up by acoustic energy reflected within the instrument by the flared bell at the end of the instrument. Sound from wind instruments depends mostly on the size and shape of the tube that the air moves through. The lengths of the vibrating air columns are manipulated by pushing valves that add or subtract extra segments[4] or by extending the length of the tube, as in a slide trombone. In woodwinds, such as clarinets, oboes, and saxophones, a stream of air produced by the musician sets a reed vibrating, whereas in fifes, flutes, and piccolos, the musician blows air against the edge of a hole to produce a fluttering stream that sets the air column into vibration.

In percussion instruments such as drums and cymbals, a two-dimensional membrane or elastic surface is struck to produce sound. The fundamental tone produced depends on the geometry, the elasticity, and, in some cases, the tension of the surface. Changes in pitch result from changing the tension in the vibrating surface; depressing the edge of a drum membrane with the hand is one way of accomplishing this. A variety of modes of vibration can be set up by striking the surface in different places. In the kettledrum, for example, the shape of the kettle changes the frequency of the drum. As in all musical sounds, the quality depends on the number and relative loudness of the partial tones.

Electronic musical instruments differ markedly from conventional musical instruments. Instead of strings that must be bowed, plucked, or struck, or reeds over which air must be blown, or diaphragms that must be tapped to produce sounds, some electronic instruments use electrons to generate the signals that produce musical sounds. Others start with sound from an acoustical instrument and then modify it. Electronic music demands of the composer and player an expertise beyond the knowledge of musicology. It brings a powerful new tool to the hands of the musician.

CHECK POINT

Sound from a guitar comes from vibrating strings. What vibrates to produce sound from a bugle?

Check Your Answer

In a bugle the players lips vibrate against each other and against the rim of the mouthpiece. More than depending on brass metal, brass instruments depend on the vibrating reeds or lips at the mouthpiece.

[4]A bugle has neither valves nor variable length. A bugler must be adept in creating various overtones to get various notes.

Fourier Analysis

Did you ever look closely at the grooves in an old phonograph record, the kind that provided music for Grandma and Grandpa? Variations in the width of the grooves, seen in Figure 21.8, cause the phonograph needle (stylus) to vibrate as it rides in the moving groove. These mechanical vibrations, in turn, are transformed into electrical vibrations to produce sound. Isn't it remarkable that all the distinct vibrations made by the various pieces of an orchestra are captured and then converted to a single sound signal?

Parrots, like humans, use their tongues to craft and shape sound. Tiny changes in the position of a parrot's tongue produce big differences in the sound first produced in the parrot's syrinx, a voice-box organ nestled between the trachea and the lungs.

FIGURE 21.8
A microscopic view of the grooves in a phonograph record.

The sound of an oboe displayed on the screen of an oscilloscope looks like Figure 21.9a. This wave corresponds to the vibrations in the oboe. It also corresponds to the amplified signal that activates the speaker of the sound system and to the amplitude of air vibrating against the eardrum. Figure 21.9b shows the wave appearance of a clarinet. When oboe and clarinet are sounded together, the principle of superposition is evident as their individual waves combine to produce the waveform shown in Figure 21.9c.

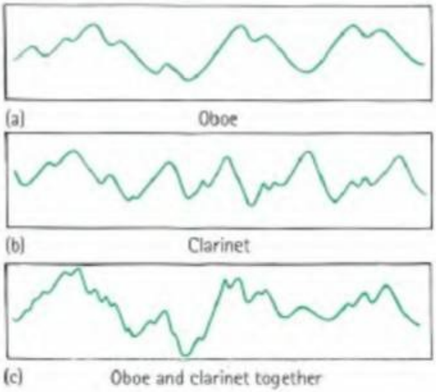


FIGURE 21.9
Waveforms of (a) an oboe, (b) a clarinet, and (c) the oboe and clarinet sounded together.

The shape of the wave in Figure 21.9c is the net result of shapes a and b superposing (interfering). If we know a and b, it is a simple thing to create c. But it is a far different problem to discern in c the shapes of a and b that make it up. Looking only at shape c, we cannot unscramble the oboe from the clarinet. But if we listen to a recording of the music, our ears will at once distinguish what instruments are being played, what notes they are playing, and what their relative loudness is. Our ears break the overall signal into its component parts automatically.

As mentioned at the beginning of this chapter, the French mathematician Joseph Fourier discovered a mathematical regularity to the component parts of periodic wave motion. He found that even the most complex periodic wave motion can be disassembled into simple sine waves that add together. Recall that a sine wave is the simplest of waves, having a single frequency (Figure 21.10). Fourier found that all periodic waves may be broken down into constituent sine waves of different amplitudes and frequencies. The mathematical operation for performing this is called **Fourier analysis.** We will not explain the mathematics here but simply point out that, by such analysis, one can find the pure sine waves that add to compose the tone of, say, a violin. When these pure tones are sounded together, as by striking a number of tuning forks or by selecting the proper keys on an electric organ, they combine to give the tone of the violin. The lowest-frequency sine wave is the fundamental and determines the pitch of the note. The higher-frequency sine waves are the partials that give the characteristic quality. Thus, the waveform of any musical sound is no more than a sum of simple sine waves.

FIGURE 21.10
A sine wave.

Since the waveform of music is a multitude of various sine waves, to duplicate sound accurately by any of the means by which sound is recorded, we should process as large a range of frequencies as possible. The notes of a piano keyboard range from 27 Hz to 4200 Hz, but, to duplicate the music of a piano composition accurately, the sound system must have a range of frequencies up to 20,000 Hz. The greater the range of the frequencies of an electrical sound system, the closer the musical output approximates the original sound, and hence the wide range of frequencies in the best of sound systems.

FIGURE 21.11
Does each listener hear the same music?

Our ear performs a sort of Fourier analysis automatically. It sorts out the complex jumble of air pulsations that reach it and transforms them into pure tones composed of sine waves. We recombine various groupings of these pure tones when we listen. What combinations of tones we have learned to focus our attention on determines what we hear when we listen to a concert. We can direct our attention to the sounds of the various instruments and discern the faintest tones from the loudest; we can delight in the intricate interplay of instruments and still detect the extraneous noises of others around us. This is a most incredible feat.

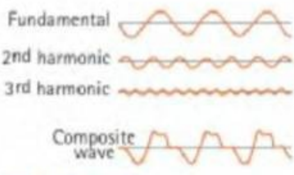


FIGURE 21.12
The fundamental and its harmonics combine to produce a composite wave.

Digital Versatile Discs (DVDs)

The phonograph records of old utilized a conventional stylus that vibrated in the squiggly groove of a disc more than twice the diameter of today's CDs (compact discs) and DVDs (first called digital video discs, and now digital versatile discs). The output of phonograph records was signals like those shown in Figure 21.9. This type of continuous waveform is called an *analog* signal. The analog signal can be changed to a *digital* signal by measuring the numerical value of its amplitude during each split second (Figure 21.13). This numerical value is expressed in the number system that is convenient for computers, called *binary*. In the binary code, any number can be expressed as a succession of 1s and 0s; for example, the number 1 is 1, 2 is 10, 3 is 11, 4 is 100, 5 is 101, 17 is 10001, and so forth. So the shape of the analog waveform is expressed as a series of "on" and "off" pulses that corresponds to a series of 1s and 0s in binary code.

Who better appreciates music—one knowledgeable about it, or the casual listener?

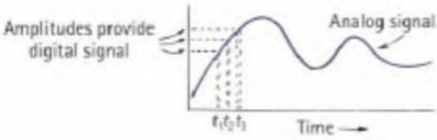


FIGURE 21.13
The amplitude of the analog waveform is measured at successive split seconds to provide digital information that is recorded in binary form on the reflective surface of the CD.

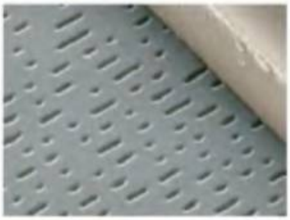


FIGURE 21.14

A microscopic view of the pits on a laser disc.

Microscopic pits about one-thirtieth the diameter of a strand of human hair are imbedded in the CD or DVD (Figure 21.14). The pits are of two types, short and long, with short corresponding to 0 and long to 1. A laser beam reads these pits. When the beam falls on a short pit on the reflective surface, it is reflected directly into the player's optical system and registers a 0. When the beam is incident upon a passing longer pit, the optical sensor registers a 1. Hence the beam reads the 1 and 0 digits of the binary code.

On a CD, the rate at which these tiny pits are sampled is 44,100 times per second. If you could gather all these pits together without overlapping they would be the size of the period at the end of this sentence. Billions of bits of information are encoded on the reflective surface, which is covered with a protective layer of clear lacquer.

Single-layer digital versatile discs (DVDs) have about 6 times the information-carrying or information-storage capacity of CDs, 4.37 GB versus 700 MB. DVD discs have smaller pits, which, in effect, make the length of the spiral track more than twice as long as that of a CD. The smaller pits of the DVD are read with laser light of shorter wavelength and also by way of a more powerful focusing lens. Whereas the pits on a CD lie on a single reflecting surface, a DVD can have multiple layers, storing even more information on a disk. By precision focusing, laser light reads the pits in the desired layer.

Now we have the 25-GB Blu-ray™ DVD player. The even shorter-wavelength blue light reads even more pits stored on a disc. More information (up to 50 GB) means higher resolution, so this feature is responsible for the incredibly sharp pictures on high-definition Blu-ray™ DVDs.

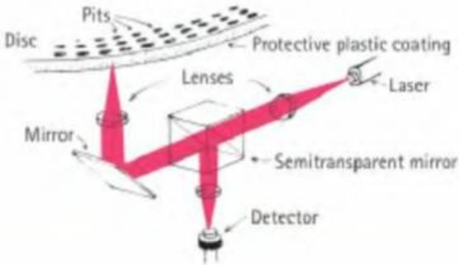


FIGURE 21.15

A tightly focused laser beam reads digital information represented by a series of pits on the laser disc.

SUMMARY OF TERMS

Pitch The "highness" or "lowness" of a tone, as on a musical scale, which is principally governed by frequency. A high-frequency vibrating source produces a sound of high pitch; a low-frequency vibrating source produces a sound of low pitch.

Intensity The power per square meter carried by a sound wave, often measured in decibels.

Loudness The physiological sensation directly related to sound intensity or volume.

Quality The characteristic timbre of a musical sound, which is governed by the number and relative intensities of partial tones.

Partial tone Single-frequency component sound wave of a complex tone. When the frequency of a partial tone is an integer multiple of the lowest frequency, it is referred to as a *harmonic*.

Fundamental frequency The lowest frequency of vibration, or first harmonic, in a musical tone.

Harmonic A partial tone whose frequency is an integer multiple of the fundamental frequency. The second harmonic has twice the frequency of the fundamental, the third harmonic 3 times the frequency, and so on in sequence.

Fourier analysis A mathematical method that disassembles any periodic waveform into a combination of simple sine waves.

REVIEW QUESTIONS

Noise and Music

1. Distinguish between noise and music.
2. What are the three principal characteristics of musical tones?

Pitch

3. How does a high-pitch musical note compare with a low one in terms of frequency?
4. How does the highest pitch one can hear vary with age?

Sound Intensity and Loudness

5. What is a decibel, and how many decibels correspond to the lowest-intensity sound we can hear?
6. Is the sound of 30 dB 30 times greater than the threshold of hearing, or 10^3 (a thousand) times greater?
7. Distinguish between sound intensity and loudness.
8. How do the loudest sounds we can tolerate compare with the faintest sounds?

Quality

9. What is it that determines the pitch of a note?
10. If the fundamental frequency of a note is 200 Hz, what is the frequency of the second harmonic? The third harmonic?
11. What exactly determines the musical quality of a note?
12. Why do the same notes plucked on a banjo and on a guitar have distinctly different sounds?

Musical Instruments

13. What are the three principal classes of musical instruments?
14. Why do orchestras generally have a greater number of stringed instruments than wind instruments?

Fourier Analysis

15. What did Fourier discover about complex periodic wave patterns?
16. A high-fidelity sound system may have a frequency range that extends up to or beyond 20,000 Hz. What is the purpose of this extended range?

Digital Versatile Discs (DVDs)

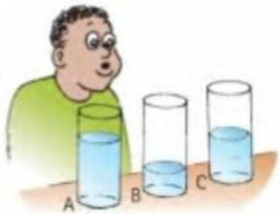
17. How was the sound signal captured on phonograph records of the 20th century? How is the sound signal captured on a CD?
18. Why does the use of blue light allow more information on a DVD?

PROJECTS

1. Test to see which ear has the better hearing by covering one ear and finding how far away your open ear can hear the ticking of a clock; repeat for the other ear. Notice also how the sensitivity of your hearing improves when you cup your ears with your hands.
2. Make the lowest-pitched sound you are capable of; then keep doubling the pitch to see how many octaves your voice can span. If you are a singer, what is your range?
3. On a sheet of graph paper, construct one full cycle (one period of the fundamental) of the composite wave of Figure 21.12 by superposing various vertical displacements of the fundamental and first two partial tones. Your instructor can show you how this is done. Then find the composite waves of partial tones of your own choosing.

RANKING

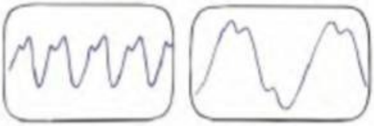
1. Consider three notes: A, 220 Hz; B, 440 Hz; and C, 660 Hz. Rank them from highest to lowest for
   a. pitch.
   b. frequency.
   c. wavelength.
2. You blow across the mouths of identical bottles A, B, and C, each containing a different amount of water, as shown. From highest to lowest, rank the pitch of sound for each.



EXERCISES

1. Your friend says that frequency is a quantitative measure of pitch. Do you agree or disagree?
2. As the pitch of sound increases, what happens to the frequency?
3. Your classmate says that timbre refers to the quality of a steady musical sound composed of a mixture of harmonics of different intensities. Do you agree or disagree?
4. The yellow-green light emitted by streetlights matches the yellow-green color to which the human eye is most sensitive. Consequently, such a 100-W streetlight emits light that is better seen at night. Similarly, the monitored sound intensities of TV commercials are louder than the sound of regular programming, yet don't exceed the regulated intensities. At what frequencies do advertisers concentrate the commercial's sound?
5. Why should guitars be played offstage before they are brought onstage for a concert? (*Hint:* Think thermally.)
6. A guitar and a flute are in tune with each other. Explain how a change in temperature could alter this situation.
7. If sound becomes louder, which wave characteristic is likely increasing—frequency, wavelength, amplitude, or speed?
8. Explain how you can lower the pitch of a note on a guitar by altering the string's (a) length, (b) tension, or (c) thickness or mass.
9. Does the pitch of a note depend on sound frequency, loudness, quality, or on all of these?
10. When a guitar string is struck, a standing wave is produced that causes the sounding board to oscillate with a large sustained amplitude, pushing back and forth against the surrounding air to generate sound. How does the frequency of the resulting sound compare with the frequency of the standing wave in the string?
11. The strings on a harp are of different lengths and produce different notes. How are different notes produced on a guitar, where all strings have the same length?
12. If a vibrating string is made shorter (as by holding a finger on it), how does this affect the frequency of vibration and pitch?
13. A nylon guitar string vibrates in a standing-wave pattern, as shown below. What is the wavelength of the wave?

14. Why do tuning forks with long tines vibrate at a lower frequency than short-tined forks? (*Hint:* This question could have been asked back in Chapter 8.)
15. Why is the thickness greater for the bass strings of a guitar than for the treble strings?
16. Will the thicker or thinner of two guitar strings of the same tension and length vibrate at the higher frequency?
17. Why does a vibrating guitar string not sound as loud when it is mounted on a work bench as it does when mounted on the guitar?
18. Would a plucked guitar string vibrate for a longer time or a shorter time if the instrument had no sounding board? Why?
19. If you very lightly touch a guitar string at its midpoint, you can hear a tone that is one octave above the fundamental for that string. (An octave is a factor of 2 in frequency.) Explain.
20. If a guitar string vibrates in two segments, where can a tiny piece of folded paper be supported without flying off? How many pieces of folded paper could similarly be supported if the waveform were of three segments?
21. Your classmate says that a harmonic series of frequencies includes the fundamental frequency and integral multiples of the fundamental frequency. Do you agree or disagree?
22. Why do the same notes on a trumpet and on a saxophone sound different when both are played with the same pitch and loudness?
23. The amplitude of a transverse wave in a stretched string is the maximum displacement of the string from its equilibrium position. What does the amplitude of a longitudinal sound wave in air correspond to?
24. Which of the two musical notes displayed one at a time on an oscilloscope screen has the higher pitch?



25. In the oscilloscopes shown above, which screen displays the louder sound (assuming detection by equivalent microphones)?
26. Tom Senior makes music by setting small columns of air into vibration by blowing across the ends of drinking straws of various lengths. Which straws, the short ones or the long ones, produce lower pitch? What would you expect of the pitch produced by the much larger musical instrument behind Tom that uses resonant air columns excited by striking the ends of the tubes with paddles?

27. Which is a more objective measurement—sound intensity or loudness? Defend your answer.
28. One person has a threshold of hearing of 5 dB, and another of 10 dB. Which person has the more acute hearing?
29. How is an electronic organ able to imitate the sounds of various musical instruments?
30. After inhaling helium gas, a person talks with a high-pitched voice. One of the reasons for this is the higher speed of sound in helium than in air. Why does sound travel faster in helium?
31. Why does your voice sound fuller in the shower?
32. The frequency range for a telephone is between 500 Hz and 4000 Hz. Why does a telephone not do a very good job of transmitting music?
33. How many octaves does normal human hearing span? How many octaves are on a common piano keyboard? (If you're not sure, look and see.)

34. The note middle C on a piano has a fundamental frequency of about 262 Hz. What is the frequency of the second harmonic of this note?

35. If the fundamental frequency of a guitar string is 220 Hz, what is the frequency of the second harmonic? Of the third harmonic?

36. If the fundamental frequency of a violin string is 440 Hz, what is the frequency of the second harmonic? Of the third harmonic?

37. How many nodes, not including the endpoints, are in a standing wave three wavelengths long? How many nodes are in a standing wave four wavelengths long?

38. How can you tune the note A_3 on a piano to its proper frequency of 220 Hz with the aid of a tuning fork whose frequency is 440 Hz?

39. At an outdoor concert, the pitch of musical tones is *not* affected on a windy day. Explain.

40. A trumpet has keys and valves that permit the trumpeter to change the length of the vibrating air column and the position of the nodes. A bugle has no such keys and valves, yet it can sound various notes. How do you think the bugler achieves different notes?

41. The human ear is sometimes called a Fourier analyzer. What does this mean, and why is it an appropriate description?

42. The width of a laser beam is significant in reading CDs and DVDs. The thinner the beam, the closer the series of pits can be. Why will blue laser light allow closer pits than red laser light?

43. Do all the people in a group hear the same music when they listen attentively as in Figure 21.11? Do all see the same sight when viewing a painting? Do all taste the same flavor when sipping the same wine? Do all perceive the same aroma when smelling the same perfume? Do all feel the same texture when touching the same fabric? Do all come to the same conclusion when listening to a logical presentation of ideas?

44. Why is it a safe prediction that you, presently reading this, will have a significantly greater loss of hearing in your later years than your grandparents experienced?

45. Make up a multiple-choice question that distinguishes between any of the terms listed in the Summary of Terms.

PROBLEMS

1. The highest frequency humans can hear is about 20,000 Hz. What is the wavelength of sound in air at this frequency? What is the wavelength of the lowest sounds we can hear, about 20 Hz?

2. A violin string playing the note "A" oscillates at 440 Hz. What is the period of the string's oscillation?

3. The string of a cello playing the note C oscillates at 264 Hz. What is the period of the string's oscillation?

4. How much more intense than the threshold of hearing is a sound of 10 dB? 30 dB? 60 dB?

5. How much more intense is sound at 40 dB than sound at 0 dB?

6. How much more intense is a sound of 40 dB than a sound of 30 dB?

7. A certain note has a frequency of 1000 Hz. What is the frequency of a note one octave above it? Two octaves above it? One octave below it? Two octaves below it?

• **8.** Starting with a fundamental tone, how many harmonics are between the first and second octaves? Between the second and third octaves? (See Figure 21.5 to get started.)

CHAPTER 21 ONLINE RESOURCES

PhysicsPlace.com

Quizzes

Links

Flashcards

PART FOUR MULTIPLE-CHOICE PRACTICE EXAM

Choose the BEST answer to the following:

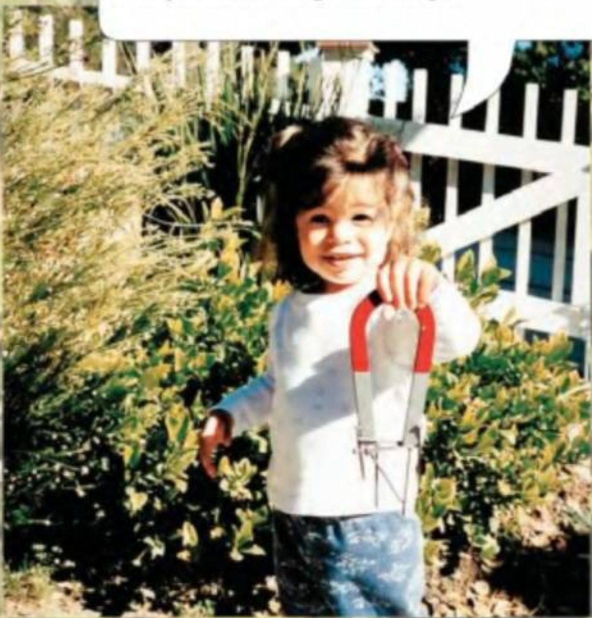
1. You swing to and fro on a playground swing. If you stand rather than sit, the time for a to-and-fro swing is
(a) lengthened. (c) unchanged.
(b) shortened.
2. The time it takes for a pendulum swinging to and fro refers to its
(a) frequency. (c) wavelength.
(b) period. (d) amplitude.
3. The period of a 10-Hz wave is
(a) 1/10 s. (c) 10 s.
(b) 1.0 s. (d) None of these.
4. A wave transfers
(a) amplitude. (c) frequency.
(b) wavelength. (d) energy.
5. Find the speed of a wave by multiplying its frequency by its
(a) period. (c) amplitude.
(b) wavelength. (d) None of these.
6. The vibrations in a transverse wave move in a direction
(a) along the wave. (c) Both of these.
(b) perpendicular to the wave. (d) Neither of these.
7. The vibrations in a longitudinal wave move in a direction
(a) along and parallel to the wave.
(b) perpendicular to the wave.
(c) Both of these.
(d) Neither of these.
8. Interference is characteristic of
(a) sound waves. (c) water waves.
(b) light waves. (d) All of these.
9. Standing waves are the result of
(a) interference.
(b) waves overlapping in phase and out of phase.
(c) waves reflecting upon themselves.
(d) All of these.
10. The Doppler effect occurs when a source of sound moves
(a) toward you. (c) Both of these.
(b) away from you. (d) None of these.
11. Compared with the sound you hear from the siren of a stationary fire engine, its sound when it approaches you has an increased
(a) speed. (c) Both of these.
(b) frequency. (d) Neither of these.
12. Bow waves are produced by waves of water
(a) overlapping one another.
(b) constructively interfering.
(c) moving slower than the source producing them.
(d) All of these.
13. Shock waves are produced by waves of sound
(a) overlapping one another.
(b) constructively interfering.
(c) moving slower than the source producing them.
(d) All of these.
14. During the time an aircraft produces a sonic boom, the aircraft is
(a) breaking the sound barrier.
(b) pulling out of a subsonic dive.
(c) flying faster than sound.
(d) All of these.
15. The sound waves that most humans cannot hear are
(a) infrasonic. (c) Both of these.
(b) ultrasonic. (d) Neither of these.
16. Sound travels in air by a series of
(a) compressions. (c) Both of these.
(b) rarefactions. (d) Neither of these.
17. The compressions and rarefactions in sound normally travel
(a) in the same direction.
(b) in opposite directions.
(c) at right angles to each other.
(d) None of these.
18. Sound travels in
(a) solids. (c) gases.
(b) liquids. (d) All of these.
19. The speed of sound is slightly greater on a
(a) cold day.
(b) hot day.
(c) day with steady temperature.
(d) None of these.
20. Sound will travel fastest in
(a) a steel beam. (c) ocean water.
(b) a wooden plank. (d) air in a balloon.
21. The loudness of a sound is most closely related to its
(a) frequency. (c) wavelength.
(b) period. (d) amplitude.
22. Your friend states that under all conditions, any radio wave travels faster than any sound wave. You
(a) agree with your friend.
(b) disagree with your friend.
23. When you tap a piece of wood it will produce a characteristic sound related to its
(a) wavelength. (c) period.
(b) amplitude. (d) natural frequency.
24. When an object is set vibrating by a wave that has a matching frequency, what occurs is
(a) forced vibration. (c) refraction.
(b) resonance. (d) amplitude reduction.
25. Noise-canceling devices make use of sound
(a) destruction. (c) resonance.
(b) interference. (d) amplification.
26. The phenomenon of beats is the result of sound
(a) destruction. (c) resonance.
(b) interference. (d) amplification.
27. A 1134-Hz tuning fork is sounded at the same time a piano note is struck. You hear 3 beats per second. The frequency of the piano string is
(a) 1131 Hz.
(b) 1134 Hz.
(c) 1137 Hz.
(d) More information is needed.
28. The pitch of a sound is mostly related to its
(a) intensity. (c) amplitude.
(b) frequency. (d) speed.
29. Compared with a sound of 60 decibels, a sound of 80 decibels has an intensity
(a) 10 times greater.
(b) 100 times greater.
(c) 1000 times greater.
(d) more than 1000 time greater.
30. Compared with a fundamental tone, the frequency of its second harmonic is
(a) half as much. (c) the same.
(b) twice as much. (d) 4 times as much.

After you have made thoughtful choices, and discussed them with your friends, find the answers on page 681.

Part Five

Electricity and Magnetism

How intriguing that this magnet outpulls the whole world when it lifts these nails. The pull between the nails and the Earth I call a **gravitational force,** and the pull between the nails and the magnet I call a **magnetic force.** I can name these forces, but I don't yet understand them. My learning begins by realizing there's a big difference in knowing the names of things and really understanding those things.



22 Electrostatics

1 Jim Stith, former president of the American Association of Physics Teachers, demonstrates a Whimshurst generator that produces miniature lighting strokes. 2 Nature produces larger and more energetic ones. 3 Lillian, with her hand on a charged Van de Graaff generator, is charged to a high voltage as evidenced by the electrostatic repulsion of strands of her hair.

It's reasonable to say that if Benjamin Franklin had not been born, the birth of the American Revolution would have turned out differently. This is because Franklin, in addition to his contributions to the Declaration of Independence, influenced the French to position a fleet of warships near the American coast to prevent the British from reinforcing General Cornwallis, whom George Washington defeated in a defining battle of the war. Franklin's clout in Europe stemmed from the high level of respect he earned as America's leading diplomat and scientist. Wherever he went in France, admiring crowds formed.

Franklin was a man for all seasons. His accomplishments as printer, publisher, balladeer, inventor, philosopher, politician, soldier, firefighter, ambassador, cartoonist, and antislavery agitator were all parts of his commitment to public service. A very important part of his legacy has to do with his scientific accomplishments.

Although he is popularly remembered for his invention of the lightning rod, he also invented the glass harmonica, the Franklin stove, bifocal glasses, and the flexible urinary catheter. He never patented his inventions, stating in his autobiography, ". . . as we enjoy great advantages from the inventions of others, we should be glad of an opportunity to serve others by any invention of ours; and this we should do freely and generously." He is especially remembered for his investigations of electricity.

At a time when electricity was thought of as two types of fluid, called vitreous and resinous, Franklin proposed that electric current was of one electrical fluid under different pressures. He was the first to label these pressures as positive and negative, respectively, and he was the first to discover the principle of conservation of charge. The story of his lightning rod began with a publication in 1750. He proposed an experiment to prove that lightning is electricity by flying a kite in a storm, at a stage before it became a lightning storm. Legend has it that with a kite he successfully extracted sparks from a cloud. What he did not do was fly his kite in the midst of a lightning storm, which others unfortunately did and were electrocuted. Instead, the collection of electrical charge on Franklin's kite string proved to him that lightning was electrical.

His lightning rod came about by his experiments showing that metals with a sharp point could collect or discharge electricity silently, preventing charge buildup on buildings when charged clouds were overhead. On the roof of his home he installed rods of iron, with sharp tips, with a wire running from the foot of the rods to the ground below. His hypothesis was that the rods would draw 'electrical fire' silently from the clouds before it struck as lightning. Satisfied that lightning was prevented, he encouraged the installation of lightning rods on the Academy of Philadelphia (later the University of Pennsylvania) and the Pennsylvania State House (later Independence Hall) in 1752.

In recognition of his achievements with electricity, Franklin received the British Royal Society's Copley Medal in 1753, and in 1756 he became one of the few Americans to be elected as a Fellow of the Royal Society. With this reputation he was in a position to affect the outcome of the forthcoming War of Independence in America.

Benjamin Franklin truly reshaped the world.

Electricity

Electricity is the name given to a wide range of electrical phenomena that, in one form or another, underlie just about everything around us. It's in the lightning from the sky, it's in the spark when we strike a match, and it's what holds atoms together to form molecules. The control of electricity is evident in technological devices of many kinds, from lamps to computers. In this chapter, we will investigate electricity at rest, static electricity, or simply **electrostatics.**

PhysicsPlace.com
Tutorial
Electrostatics

Electrostatics involves electric charges, the forces between them, the aura that surrounds them, and their behavior in materials. In Chapter 23, we'll investigate the motion of electric charges, or *electric currents*. We'll also study the voltages that produce currents and how they can be controlled. In Chapter 24, we'll study the relationship of electric currents to magnetism, and, in Chapter 25, we'll learn how magnetism and electricity can be controlled to operate electrical devices and how electricity and magnetism connect to become light.

An understanding of electricity requires a step-by-step approach, for one concept is the foundation on which the next concept is based. So please put in extra attention in studying this material. It can be difficult, confusing, and frustrating if you're hasty; but, with careful effort, it can be comprehensible and rewarding. Onward!

Electrical Forces

What if there were a universal force that, like gravity, varies inversely as the square of the distance but is billions upon billions of times stronger? If there were such a force and if it were attractive like gravity, the universe would be pulled together into a tight ball, with all matter pulled as close together as it could get. But suppose this force were a repelling force, with every bit of matter repelling every other bit. What then? Then the universe would blow itself apart in short order. Suppose, however, that the universe consisted of two kinds of particles—positives and negatives, say. Suppose that positives repelled positives but attracted negatives and that negatives repelled negatives but attracted positives. In other words, like kinds repel and unlike kinds attract (Figure 22.1). Suppose that there were equal numbers of each so that this strong force were perfectly balanced! What would the universe

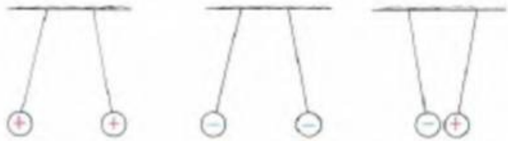


FIGURE 22.1

INTERACTIVE FIGURE

Like charges repel. Unlike charges attract.

be like? The answer is simple: It would be like the one we are living in. For there are such particles, and there is such a force. We call it the *electric force.*

Inside every piece of matter are atoms. And what is inside every atom? Positive and negative charges held together by the enormous attraction of electric force. By forming compact and evenly mixed clusters of positives and negatives, the huge electric forces have balanced themselves out almost perfectly. When two or more atoms join to form a molecule, the molecule also contains balanced positives and negatives. And when trillions of molecules combine to form a speck of matter, the electrical forces balance again. Between two pieces of ordinary matter, there is scarcely any electrical attraction or repulsion at all, because each piece contains equal numbers of positives and negatives. Between Earth and the Moon, for example, there is no electrical force. The much weaker gravitational force, which only attracts, remains as the predominant force between these bodies.

Electric Charges

The terms *positive* and *negative* refer to electric *charge,* the fundamental quantity that underlies all electrical phenomena. The positively charged particles in ordinary matter are protons, and the negatively charged particles are electrons. Protons and electrons, with neutral particles called neutrons, make up the atom. When two atoms get close together, the balance of attractive and repelling forces is not perfect, because electrons whiz around within the volume of each atom. The atoms may then attract each other and form a molecule. In fact, all the chemical bonding forces that hold atoms together to form molecules are electrical in nature. Anyone planning to study chemistry should first know something about electrical attraction and repulsion and, before studying electrical phenomena, should know something about atoms. Recall from Chapter 11 some important facts about atoms:

Which charges are called positive and which are called negative is the result of a choice made by Benjamin Franklin. It could have been the other way around.

1. Every atom is composed of a positively charged *nucleus* surrounded by negatively charged electrons.
2. The electrons of all atoms are identical. Each has the same quantity of negative charge and the same mass.
3. Protons and neutrons compose the nucleus. (The common form of the hydrogen atom, which has no neutron, is the only exception.) Protons are about 1800 times more massive than electrons, but they carry an amount of positive charge equal to the negative charge of electrons. Neutrons have slightly more mass than protons and have no net charge.
4. Atoms usually have as many electrons as protons, so the atom has zero *net* charge.

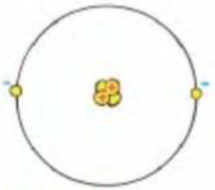


FIGURE 22.2

INTERACTIVE FIGURE

Model of a helium atom. The atomic nucleus is composed of two protons and two neutrons. The positively charged protons attract two negative electrons.

Why don't protons pull the oppositely charged electrons into the nucleus? You might think that electrons behave the same way as planets that orbit the Sun. But not so, for this planetary explanation is invalid for electrons. When the nucleus was discovered in 1911, scientists knew that electrons couldn't orbit placidly around the nucleus in the way Earth orbits the Sun. In only about a hundred-millionth of a second, according to classical physics, the electron would spiral into the nucleus, emitting electromagnetic radiation as it did so. So a new theory was needed, the theory called quantum mechanics. In describing electron motion, we still use old terminology, *orbit* and *orbital*, although the preferred word is *shell*, which suggests that the electrons are spread out over a spherical region. Today, the explanation for the atom's stability has to do with the wave nature of electrons. An electron behaves like a wave and requires a certain amount of space related to its wavelength. When we treat quantum mechanics in Chapter 32, we'll see that atomic size is determined by the minimum amount of 'elbow room' that an electron requires.

Why don't the protons in the nucleus mutually repel and fly apart? What holds the nucleus together? The answer is that, in addition to electrical forces in the nucleus, even stronger nonelectrical nuclear forces hold the protons together and overcome the electrical repulsion. In Chapter 33 we will learn about nuclear forces, and how neutrons put a needed distance between the protons.

CHECK POINT

1. Beneath the complexities of electrical phenomena, there lies a fundamental rule from which nearly all other effects stem. What is this fundamental rule?
2. How does the charge of an electron differ from the charge of a proton?

Check Your Answers

1. Like charges repel; opposite charges attract.
2. The charge of an electron is equal in magnitude, but opposite in sign, to the charge of a proton.

Conservation of Charge

A basic rule of physics is that, whenever something is charged, no electrons are created or destroyed. Electrons are simply transferred from one material to another. Charge is *conserved*. In every event, whether large scale or at the atomic and nuclear level, the principle of **conservation of charge** has always been found to apply. No case of the creation or destruction of net electric charge has ever been found. The conservation of charge ranks with the conservation of energy and momentum as a significant fundamental principle in physics.

In a neutral atom, there are as many electrons as protons, so there is no net charge. The positive balances the negative exactly. If an electron is removed from an atom, then it is no longer neutral. The atom then has one more positive charge (proton) than negative charge (electron) and is said to be positively charged.[1] A charged atom is called an *ion*. A *positive ion* has a net positive charge. A *negative ion*, an atom with one or more extra electrons, is negatively charged.

So we see that an object having unequal numbers of electrons and protons is electrically charged. If it has more electrons than protons, it is negatively charged. If it has fewer electrons than protons, it is positively charged.

Interestingly, any electrically charged object has an excess or deficiency of some whole number of electrons—meaning the charge of the object is a whole-number multiple of the charge of an electron. Electrons cannot be divided into fractions of electrons. Charge is 'grainy,' or made of elementary units called *quanta*. We say that charge is *quantized*, with the smallest quantum of charge being that of the electron

FIGURE 22.3
Electrons are transferred from the fur to the rod. The rod is then negatively charged. Is the fur charged? How much compared to the rod? Positively or negatively?

Charge is like a baton in a relay race. It can be passed from one object to another but isn't lost.

[1]Each proton has a charge $+e$, equal to $+1.6 \times 10^{-19}$ coulomb. Each electron has a charge $-e$, equal to -1.6×10^{-19} coulomb. Why such different particles have the same magnitude of charge is an unanswered question in physics. The equality of the magnitudes has been tested to high accuracy.

Electronics Technology and Sparks

Electric charge can be dangerous. Two hundred years ago, young boys called powder monkeys ran barefooted below the decks of warships to bring sacks of black gunpowder to the cannons above. It was ship law that this task be done barefoot. Why? Because it was important that no static charge build up on the powder on their bodies as they ran to and fro. Bare feet scuffed the decks much less than shoes and assured no charge accumulation that might produce an igniting spark and an explosion.

Static charge is a danger in many industries today—not because of explosions, but because delicate electronic circuits may be destroyed by static charges. Some circuit components are sensitive enough to be 'fried' by sparks of static electricity. Electronics technicians frequently wear clothing of special fabrics with ground wires between their sleeves and their socks. Some wear special wristbands that are connected to a grounded surface so that static charges will not build up—when moving a chair, for example. The smaller the electronic circuit, the more hazardous are sparks that may short-circuit the circuit elements.

fyi

- Static electricity is a problem at gasoline pumps. Even the tiniest of sparks ignite gasoline vapors and cause fires—frequently lethal. A good rule is to touch metal and discharge static charge from your body before you fuel. Also, don't use a cell phone when fueling.

(or proton). In all matter, no smaller units of charge have ever been observed.[2] All charged objects to date have a charge that is a whole-number multiple of the charge of a single electron or proton.

CHECK POINT

If you scuff electrons onto your feet while walking across a rug, are you negatively or positively charged?

Check Your Answer

You have more electrons after you scuff your feet, so you are negatively charged (and the rug is positively charged).

Coulomb's Law

The electrical force, like gravitational force, decreases inversely as the square of the distance between charged bodies. This relationship, discovered by Charles Coulomb in the 18th century, is called **Coulomb's law.** It states that, for two charged objects that are much smaller than the distance between them, the force between the two objects varies directly as the product of their charges and inversely as the square of the separation distance. (Review the inverse-square law back in Figure 9.5.) The force acts along a straight line from one charged object to the other. Coulomb's law can be expressed as

Coulomb's law is like Newton's law of gravity. But, unlike gravity, electric forces can be attractive or repulsive.

$$F = k\frac{q_1 q_2}{d^2}$$

where d is the distance between the charged particles, q_1 represents the quantity of charge of one particle, q_2 represents the quantity of charge of the other particle, and k is the proportionality constant.

The unit of charge is the **coulomb,** abbreviated C. It turns out that a charge of 1 C is the charge associated with 6.25 billion billion electrons. This might seem like a great number of electrons, but it only represents the amount of charge that flows in a common 100-watt lightbulb in a little over a second.

[2]Within the atomic nucleus, however, elementary particles called *quarks* carry charges 1/3 and 2/3 the magnitude of the electron's charge. Each proton and each neutron is made up of three quarks. Since quarks always exist in such combinations and have never been found separated, the whole-number-multiple rule of electron charge holds for nuclear processes as well.

The proportionality constant k in Coulomb's law is similar to G in Newton's law of gravitation. Instead of being a very small number like G (6.67×10^{-11}), the electrical proportionality constant k is a very large number. It is approximately

$$9{,}000{,}000{,}000\ \mathrm{N \cdot m^2/C^2}$$

or, in scientific notation, $k = 9 \times 10^9\ \mathrm{N \cdot m^2/C^2}$. The unit $\mathrm{N \cdot m^2/C^2}$ is not central to our interest here; it simply converts the right-hand side of the equation for Coulomb's law to the unit of force, the newton (N). What is important is the large magnitude of k. If, for example, a pair of like charged particles of 1 C each were 1 m apart, the force of repulsion between them would be 9 billion N.[3] That would be more than 10 times the weight of a battleship! Obviously, such amounts of net charge do not exist in our everyday environment.

So Newton's law of gravitation for masses is similar to Coulomb's law for electrically charged bodies.[4] The most important difference between gravitational and electrical forces is that electrical forces may be either attractive or repulsive, whereas gravitational forces are only attractive. Coulomb's law underlies the bonding forces between molecules that are essential in the field of chemistry.

The greatest threat to civilization is an excess of certitude.

CHECK POINT

1. The proton that is the nucleus of the hydrogen atom attracts the electron that orbits it. Relative to this force, does the electron attract the proton with less force, with more force, or with the same amount of force?
2. If a proton at a particular distance from a charged particle is repelled with a given force, by how much will the force decrease when the proton is 3 times farther away from the particle? When it is 5 times farther away?
3. What is the sign of charge of the particle in this case?

Check Your Answers

1. The same amount of force, in accord with Newton's third law—basic mechanics! Recall that a force is an interaction between two things—in this case, between the proton and the electron. They pull on each other equally.
2. It decreases to 1/9 its original value; to 1/25 its original value.
3. Positive.

Conductors and Insulators

It is easy to establish an electric current in metals because one or more of the electrons in the outer shell of its atoms are not anchored to the nuclei of particular atoms but are free to wander in the material. Such a material is called a good

[3]Contrast this to the gravitational force of attraction between two 1-kg masses 1 m apart: 6.67×10^{-11} N. This is an extremely small force. For the force to be 1 N, the masses at 1 m apart would have to be nearly 123,000 kg each! Gravitational forces between ordinary objects are exceedingly small, while electrical forces between ordinary objects can be exceedingly huge. We don't sense them because the positives and negatives normally balance out. Even for highly charged objects, the imbalance of electrons to protons is normally less than one part in a trillion trillion.

[4]According to quantum theory, a force that varies inversely as the square of the distance involves the exchange of particles with no mass. Exchange of massless photons is responsible for the electrical force, and exchange of massless gravitons accounts for the gravitational force. Some scientists pursue an even deeper relationship between gravity and electricity. Albert Einstein spent the latter part of his life searching with little success for a "unified field theory." More recently, the electrical force has been unified with one of the two nuclear forces, the *weak force*, which plays a role in radioactive decay.

FIGURE 22.4

It is easier to establish an electric current through hundreds of kilometers of metal wire than through a few centimeters of insulating material.

conductor. Any metal is a good conductor of electric current for the same reason it is a good heat conductor—the electrons in the outer atomic shell of its atoms are "loose." The expensive metals such as silver, gold, and platinum are among the very best conductors, don't corrode, and are commonly used in small quantities for high-value products. Copper and aluminum are commonly used in wiring electrical systems because of their good performance and lower cost.

The electrons in other materials—rubber and glass, for example—are tightly bound and belong to particular atoms. They are not free to wander about among other atoms in the material. Consequently, it isn't easy to make them flow. These materials are poor conductors of electric current for the same reason they are generally poor heat conductors. Such a material is called a good **insulator.** Glass is an extremely good insulator and is used to keep electrical wires away from the metal towers that carry them. Many plastics are also good insulators, which is why wiring in your home is covered with a layer of plastic.

All substances can be arranged in order of their ability to conduct electric charge. Those at the top of such a list would be conductors and those at the bottom would be insulators. The ends of the list are very far apart. The conductivity of a metal, for example, can be more than a million trillion times greater than the conductivity of an insulator such as glass.

SEMICONDUCTORS

Some materials, such as germanium (Ge) and silicon (Si), are neither good conductors nor good insulators. These materials fall in the middle of the range of electrical resistivity, being fair insulators in their pure crystalline form and becoming excellent conductors when even 1 atom in 10 million is replaced with an impurity that adds or removes an electron from the crystal structure. A material that can be made to behave sometimes as an insulator and sometimes as a conductor is called a **semiconductor.** Thin layers of semiconducting materials sandwiched together make up *transistors*, which are used to control the flow of electrons in circuits, to detect and amplify radio signals, and to produce oscillations in transmitters; they also act as digital switches. These tiny solids were the first electrical components in which materials with different electrical characteristics were not interconnected by wires but were physically joined in one structure. They require very little power, and they last indefinitely in normal use.

A semiconductor will also conduct when light of the proper color shines on it. A pure selenium plate is normally a good insulator, and any electric charge built up on its surface will remain for extended periods in the dark. If the plate is exposed to light, however, the charge leaks away almost immediately. If a charged selenium plate is exposed to a pattern of light, such as the pattern of light and dark that makes up this page, the charge will leak away only from the areas exposed to light. If a black plastic powder were brushed across its surface, the powder would stick only to the charged areas where the plate had not been exposed to light. Now if a piece of paper with an electric charge on the back of it were put over the plate, the black plastic powder would be drawn to the paper to form the same pattern as, say, the one on this page. This is the nuts and bolts of photocopiers.

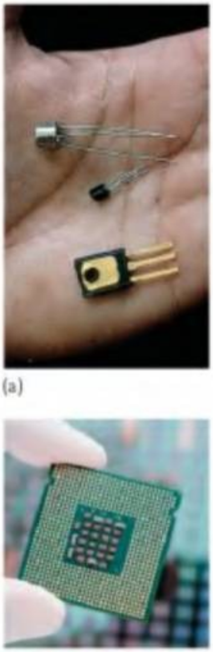
fyi

- The new memristor (short for memory resistor) utilizes a thin film of titanium oxide sandwiched between two platinum layers. It packs into chips 100 times more densely than transistors and remembers information without electric power. Will memristors soon appear in computers and wireless devices?

Superconductors

An ordinary conductor has only a small resistance to the flow of electric charge. An insulator has much greater resistance (we'll treat the topic of electric resistance in the following chapter). Remarkably, in certain materials at sufficiently low temperatures, electrical resistance disappears. The materials acquire zero resistance (infinite conductivity) to the flow of charge. Such a material is called a

superconductor. Once electric current is established in a superconductor, the electrons flow indefinitely. With no electrical resistance, current passes through a superconductor without losing energy; no heat loss occurs when charges flow. Superconductivity in metals near absolute zero was discovered in 1911. In 1987, superconductivity at a "high" temperature (above 100 K) was discovered in a nonmetallic compound. Superconductivity has since progressed with applications that include low-loss power-line transmission and high-speed, magnetically levitated vehicles intended to replace traditional rail trains.



(a)

(b)

FIGURE 22.5

(a) Three transistors.
(b) Many transistors in an integrated circuit.

Charging

We charge things by transferring electrons from one place to another. We can do this by physical *contact*, as occurs when substances are rubbed together or simply touched. Or we can redistribute the charge on an object simply by putting a charged object near it—this is called *induction*.

CHARGING BY FRICTION AND CONTACT

We are all familiar with the electrical effects produced by friction. We can stroke a cat's fur and hear the crackle of sparks that are produced, or comb our clean, dry hair in front of a mirror in a dark room and see as well as hear the sparks. We can scuff our shoes across a rug and feel a tingle as charge flows when we touch a doorknob. Talk to old-timers and they'll tell you about the surprising shock that was typical of sliding across a plastic seat cover while parked in an automobile (Figure 22.6). Charge is transferred in clothes in a clothes dryer. In all these cases, electrons are transferred by friction when one material rubs against another.

Electrons can transfer from one material to another by simply touching. For example, when a negatively charged rod is placed in contact with a neutral object, some electrons will move to the neutral object. This method of charging is simply

FIGURE 22.6

Charging by friction and then by contact.

called **charging by contact.** If the object is a good conductor, electrons will spread to all parts of its surface because the transferred electrons repel one another. If it is a poor conductor, it may be necessary to touch the rod at several places on the object in order to get a more-or-less uniform distribution of charge.

CHARGING BY INDUCTION

If you bring a charged object *near* a conducting surface, electrons are made to move in the surface material, even without physical contact. Consider the two insulated metal spheres, A and B, in Figure 22.7. (a) They touch each other, so in effect they form a single uncharged conductor. (b) When a negatively charged rod is brought near A, electrons in the metal, being free to move, are repelled as far as possible until their mutual repulsion is big enough to balance the influence of the rod: The charge is redistributed. (c) If A and B are separated while the rod is still present, (d) each will be equal and oppositely charged. This is **charging by induction.** The charged rod has never touched them, and the rod retains the same charge it had initially.

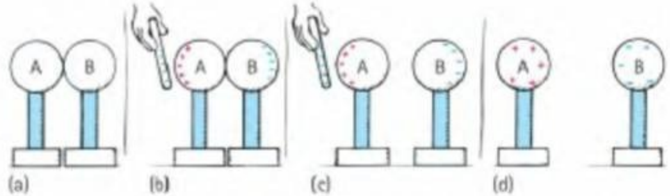


FIGURE 22.7
INTERACTIVE FIGURE
Charging by induction.

We can similarly charge a single sphere by induction if we touch it when different parts of it are differently charged. Consider the metal sphere that hangs from a nonconducting string, as shown in Figure 22.8. When we touch the metal surface with a finger, we are providing a path for charge to flow to or from a very large reservoir for electric charge—the ground. We say that we are *grounding* the sphere, a process that may leave it with a net charge. We will return to this idea of grounding in Chapter 23 when we discuss electric currents.

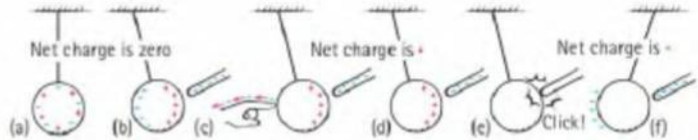


FIGURE 22.8
INTERACTIVE FIGURE
Stages of charge induction by grounding. (a) The net charge on the metal sphere is zero. (b) Charge redistribution is induced on the sphere by the presence of the charged rod. The net charge on the sphere is still zero. (c) Touching the negative side of the sphere removes electrons by contact. (d) This leaves the sphere positively charged. (e) The sphere is more strongly attracted to the negative rod, and, when it touches, charging by contact occurs. (f) The negative sphere is repelled by the still somewhat negatively charged rod.

FIGURE 22.9
The negative charge at the bottom of the cloud induces a positive charge at the surface of the ground below.

Charging by induction occurs during thunderstorms. The negatively charged bottoms of clouds induce a positive charge on the surface of the ground below. As mentioned at the beginning of this chapter, Benjamin Franklin was the first to demonstrate this when his famous kite-flying experiment proved that lightning is an electrical phenomenon.[5] Lightning is an electrical discharge between a cloud and the oppositely charged ground or between oppositely charged parts of clouds.

Franklin also found that charge flows readily to or from sharp metal points, and he fashioned the first lightning rod. The primary purpose of the lightning rod is to

FIGURE 22.10
Lightning rods are connected by heavy-duty wires so that very large currents can be conducted to the ground if lightning strikes. Most often, charge leaks off the pointed tips to prevent the occurrence of lightning.

[5]Benjamin Franklin invented many things that improved the quality of life. He was certainly a very busy man! Only a task as important as helping to form the United States' system of government prevented him from devoting even more of his time to his favorite activity—the scientific investigation of nature.

prevent a fire caused by lightning. If, for any reason, sufficient charge does not leak from the air to the rod and lightning strikes anyway, it may be attracted to the rod and take a direct path to the ground, thereby sparing the building.

fyi

- Lightning occurs mainly in warm climates. As warm water vapor rises in air it brushes against ice crystals high in the air above, producing a charge similar to what occurs when you scuff your feet on a carpet. The ice crystals gain a slight positive charge, and the updraft carries them to the top of the cloud. So the top of a cloud is usually positively charged, with the bottom negatively charged. Lightning is the bolt that arcs between these regions and between the cloud and the ground below.

CHECK POINT

1. Would the charges induced on the spheres A and B of Figure 22.7 necessarily be exactly equal and opposite?
2. Why does the negative rod in Figure 22.7 have the same charge before and after the spheres are charged, but not when charging takes place, as in Figure 22.8?

Check Your Answers

1. Yes, because each positive charge on sphere A results from an electron taken from A and moved to B. This is like removing bricks from the surface of a brick road and placing them all on the sidewalk. The number of bricks on the sidewalk exactly matches the number of holes in the road. Likewise, the number of extra electrons on B will exactly match the number of "holes" (positive charges) left in A. The positive charge is the result of an absent electron.
2. In the charging process of Figure 22.7, no contact was made between the negative rod and either of the spheres. In Figure 22.8, however, the rod touched the positively charged sphere. A transfer of charge by contact reduced the negative charge on the rod.

Charge Polarization

Charging by induction is not restricted to conductors. When a charged rod is brought near an insulator, there are no free electrons that can migrate throughout the insulating material. Instead, there is a rearrangement of charges within the atoms and molecules themselves (Figure 22.11). Although atoms don't move from their relatively fixed positions, their "centers of charge" are moved. One side of the atom or molecule is induced into becoming more negative (or positive) than the opposite side. The atom or molecule is said to be **electrically polarized.** If the charged rod is negative, say, then the positive part of the atom or molecule is tugged in a direction toward the rod, and the negative side of the atom or molecule is pushed in a direction away from the rod. The positive and negative parts of the atoms and molecules become aligned. They are electrically polarized.

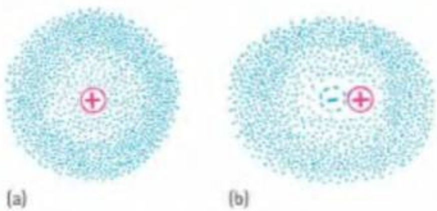


FIGURE 22.11

An electron buzzing around the atomic nucleus produces an electron cloud. (a) The center of the negative cloud normally coincides with the center of the positive nucleus in an atom. (b) When an external negative charge is brought nearby to the right, as on a charged balloon, the electron cloud is distorted so that the centers of negative and positive charge no longer coincide. The atom is now electrically polarized.

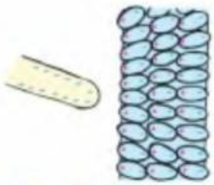


FIGURE 22.12

INTERACTIVE FIGURE

All the atoms or molecules near the surface become electrically polarized. Surface charges of equal magnitude and opposite sign are induced on opposite surfaces of the material.

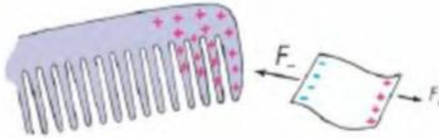


FIGURE 22.13

A charged comb attracts an uncharged piece of paper because the force of attraction for the closer charge is greater than the force of repulsion for the farther charge.

We can understand why electrically neutral bits of paper are attracted to a charged object—a comb passed through your hair, for example. When the charged comb is brought nearby, molecules in the paper are polarized. The sign of charge closest to the comb is opposite to the comb's charge. Charges of the same sign are slightly more distant. Closeness wins, and the bits of paper experience a net attraction. Sometimes they will cling to the comb and then suddenly fly off. This repulsion occurs because the paper bits acquire the same sign of charge as the charged comb when they come in contact. Rub an inflated balloon on your hair, and it becomes charged. Place the balloon against the wall, and it sticks. This is because the charge on the balloon induces an opposite surface charge on the wall. Again, closeness wins, for the charge on the balloon is slightly closer to the opposite induced charge than to the charge of same sign (Figure 22.14).

Many molecules—H_2O, for example—are electrically polarized in their normal states. The distribution of electric charge is not perfectly even. There is a little more negative charge on one side of the molecule than the other (Figure 22.15). Such molecules are said to be *electric dipoles*.

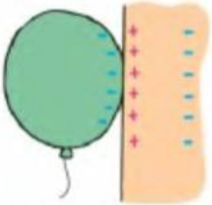


FIGURE 22.14

The negatively charged balloon polarizes atoms in the wooden wall and creates a positively charged surface, so the balloon sticks to the wall.

FIGURE 22.15

An H_2O molecule is an electric dipole.

CHECK POINT

1. A negatively charged rod is brought close to some small pieces of neutral paper. The positive sides of molecules in the paper are attracted to the rod and the negative sides of the molecules are repelled. Why don't these attractive and repulsive forces cancel out?
2. In a humorous vein, if you rub a balloon on your hair and put your head to the wall, will it stick to the wall like the balloon would?

Check Your Answers

1. The positive sides are simply closer to the rod. They therefore experience a greater electrical force than the father-away negative sides. Hence we say that closeness wins. Can you see that a positive rod would still produce attraction?
2. It would, if you were an airhead—that is, if the mass of your head were about that of the balloon, so that the force produced would be evident.

Electric Field

Electrical forces, like gravitational forces, act between things that are not in contact with each other. For both electricity and gravity, a *force field* exists that influences charged and massive bodies, respectively. Recall, from Chapter 9, that the properties of space surrounding any massive body are altered such that another massive body introduced to this region will experience a force. The force is gravitational, and the altered space surrounding a massive body is its *gravitational field*. We can think of any other massive body as interacting with the field and not directly with the massive body producing it. For example, when an apple falls from a tree, we say it is interacting with Earth, but we can also think of the apple as interacting with the gravitational field of Earth. The field plays an intermediate role in the force between bodies. It is common to think of distant rockets and the like as interacting with gravitational fields rather than with the masses of Earth and other bodies responsible for

Sharks and related species of fish are equipped with specialized receptors in their snouts that sense extremely weak electric fields generated by other creatures in seawater.

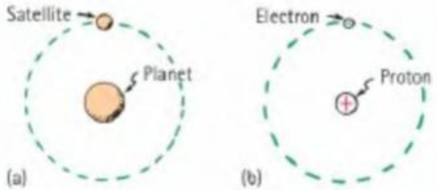


FIGURE 22.16

(a) A gravitational force holds the satellite in orbit about the planet, and (b) an electrical force holds the electron in orbit about the proton. In both cases, there is no contact between the bodies. We say that the orbiting bodies interact with the *force fields* of the planet and proton and are everywhere in contact with these fields. Thus, the force that one electrically charged body exerts on another can be described as the interaction between one body and the field set up by the other.

An electric field is nature's storehouse of electrical energy.

the fields. Just as the space around a planet (and around every other massive body) is filled with a gravitational field, the space around every electrically charged body is filled with an **electric field**—an energetic aura that extends through space.

An electric field has both magnitude (strength) and direction. The magnitude of the field at any point is simply the force per unit of charge. If a body with charge q experiences a force F at some point in space, then the electric field E at that point is

$$E = \frac{F}{q}$$

The electric field is depicted with vector arrows in Figure 22.17a. The direction of the field is shown by the vectors and is defined to be the direction in which a small positive test charge at rest would be pushed.[6] The direction of the force and that of the field at any point are the same. In the figure, we see that all the vectors therefore point to the center of the negatively charged ball. If the ball were positively charged, the vectors would point away from its center because a positive test charge in the vicinity would be repelled.

A more useful way to describe an electric field is with lines of force, as shown in Figure 22.17b. The lines of force shown in the figure represent a small number of the infinitely numerous possible lines that indicate the direction of the field. The figure is a two-dimensional representation of three dimensions. Where the lines are farther apart, the field is weaker. For an isolated charge, the lines extend to infinity; for two or more opposite charges, we represent the lines as emanating from a positive charge and terminating on a negative charge. Some electric-field configurations are shown in Figure 22.18, and photographs of field patterns are shown in Figure 22.19. The photographs show bits of thread that are suspended in an oil bath surrounding charged conductors. The ends of the thread bits are charged by induction and tend to line up end-to-end with the field lines, like iron filings in a magnetic field.

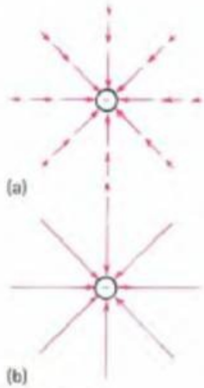


FIGURE 22.17

INTERACTIVE FIGURE

Electric-field representations about a negative charge. (a) A vector representation. (b) A lines-of-force representation.

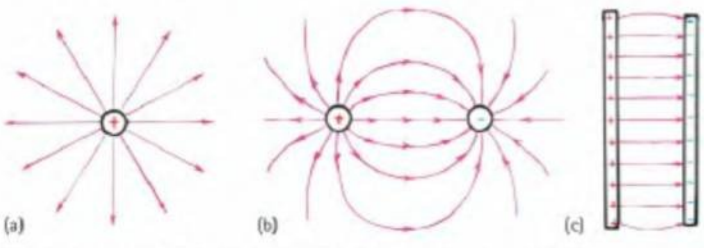


FIGURE 22.18

INTERACTIVE FIGURE

Some electric-field configurations. (a) Lines of force emanating from a single positively charged particle. (b) Lines of force for a pair of equal but oppositely charged particles. Note that the lines emanate from the positive particle and terminate on the negative particle. (c) Uniform lines of force between two oppositely charged parallel plates.

[6] The test charge is small so that it does not appreciably influence the sources of the field being measured. Recall, from our study of heat, the similar need for a thermometer of small mass when measuring the temperature of bodies of larger masses.

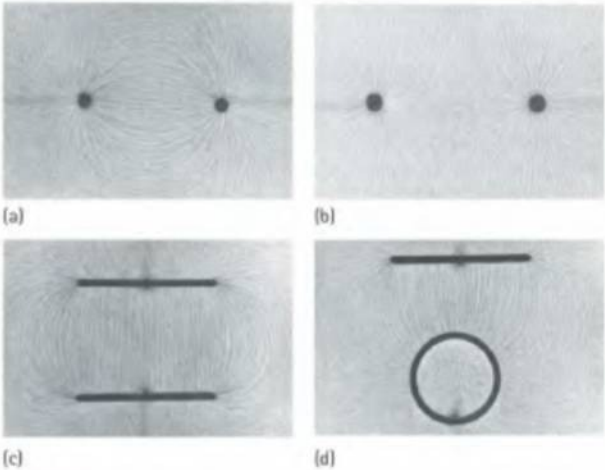


FIGURE 22.19
The electric field due to a pair of charged conductors is shown by bits of thread suspended in an oil bath surrounding the conductors. Note that the threads line up end-to-end along the direction of the electric field.
(a) Equal and oppositely charged conductors (like those in Figure 22.18b).
(b) Equal and identically charged conductors.
(c) Oppositely charged plates.
(d) Oppositely charged cylinder and plate.

A candy bar in Percy Spencer's pocket mysteriously melted while he was experimenting with electrical oscillations in a new vacuum tube in 1946. Intrigued, he placed some popcorn kernels near the tube and saw them pop. The birth of the microwave oven soon followed.

The electric-field concept helps us understand not only the forces between isolated stationary charged bodies but also what happens when charges move. When charges move, their motion is communicated to neighboring charged bodies in the form of a field disturbance. Such a disturbance emanates from an accelerating charged body at the speed of light. We will learn that the electric field is a storehouse of energy and that energy can be transported over long distances in an electric field. Energy that is traveling in an electric field may be directed through, and guided by, metal wires, or it may be teamed up with a magnetic field to move through empty space. We will return to this idea in the next chapter and later when we learn about electromagnetic radiation.

ELECTRIC SHIELDING

An important difference between electric fields and gravitational fields is that electric fields can be shielded by various materials, while gravitational fields cannot. The amount of shielding depends on the material used for shielding. For example, air

Microwave Oven

Imagine an enclosure with Ping-Pong balls among a few batons, all at rest. Now imagine the batons suddenly flipping to and fro like semirotating propellers, striking neighboring Ping-Pong balls. The balls are energized, moving in all directions. A microwave oven operates similarly. The batons are water molecules (or other polar molecules) made to flip to and fro in rhythm with the oscillating microwaves in the enclosure. The Ping-Pong balls are nonpolar molecules that make up the bulk of the food being cooked.

Each H_2O molecule is an electric dipole that aligns with an electric field, like a compass needle aligns with a magnetic field. When the electric field is made to oscillate, the H_2O molecules oscillate also. The H_2O molecules move quite energetically when the oscillation frequency matches their natural frequency—at resonance. Food is cooked by a sort of "kinetic friction" as flip-flopping H_2O molecules (or other polar molecules) impart thermal motion to surrounding molecules. The metal enclosure reflects microwaves to and fro throughout the oven for rapid cooking.

Dry paper, foam plates, or other materials recommended for use in microwave ovens contain no water or any other polar molecules, so microwaves pass through them with no effect. Likewise for ice, in which the H_2O molecules are locked in position and can't rotate to and fro. Metallic materials reflect microwaves, which is why metal pans do not work well in a microwave oven.

A note of caution is due when boiling water in a microwave oven. Water can sometimes heat faster than bubbles can form, and the water then heats beyond its boiling point—it becomes superheated. If the water is bumped or jarred just enough to cause the bubbles to form rapidly, they'll violently expel the hot water from its container. More than one person has had boiling water blast into his or her face.

makes the electric field between two charged objects slightly weaker than it would be in a vacuum, while oil placed between the objects can diminish the field to nearly a hundredth of its original strength. Metal can completely shield an electric field. Quite interestingly, when no current is flowing, the electric field inside metal is zero, regardless of the field strength outside.

Consider, for example, electrons on a spherical metal ball. Because of mutual repulsion, the electrons will spread out uniformly over the outer surface of the ball. It is not difficult to see that the electrical force exerted on a sample test charge placed at the exact center of the ball is zero, because opposing forces balance in every direction. Interestingly enough, complete cancellation occurs *anywhere* inside a conducting sphere. Understanding why this is true requires more thought and involves the inverse-square law and a bit of geometry. Consider the test charge at point P in Figure 22.20. The test charge is twice as far from the left side of the charged sphere as it is from the right side. If the electrical force between the test charge and the charges depended only on distance, then the test charge would be attracted only 1/4 as much to the left side as to the right side. (Remember the inverse-square law: Twice as far away means only 1/4 the effect, three times as far away means only 1/9 the effect, and so on.) But the force depends also on the amount of charge. In the figure, the cones extending from point P to areas A and B have the same apex angle, but one has twice the altitude of the other. This means that area A at the base of the longer cone is 4 times area B at the base of the shorter cone, which is true for any apex angle. Since 1/4 of 4 is equal to 1, a test charge at P is attracted equally to each side. Cancellation occurs. A similar argument applies if the cones emanating from point P are oriented in any direction. Complete cancellation occurs at all points within the sphere. (Recall this argument back in Chapter 9, Figure 9.25, for the cancellation of gravity inside a hollow planet. The metal ball behaves the same way, whether hollow or not, because all of its charge gathers on its outer surface.)

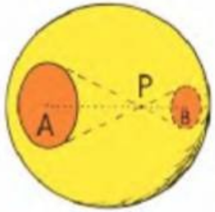


FIGURE 22.20

The test charge at P is attracted just as much to the greater amount of charge at farther region A as it is to the smaller amount of charge at closer region B. The net force on the test charge is zero—there, or anywhere inside the conductor. The electric field everywhere inside is also zero.

If the conductor is not spherical, then the charge distribution will not be uniform. The charge distribution over conductors of various shapes is shown in Figure 22.21. Most of the charge on a conducting cube, for example, is mutually repelled toward the corners. The remarkable thing is this: The exact charge distribution over the surface of a conductor is such that the electric field everywhere inside the conductor is zero. Look at it this way: If there were an electric field inside a conductor, then free electrons inside the conductor would be set in motion. How far would they move? Until equilibrium is established—which is to say, when the positions of all the electrons produce a zero field inside the conductor.

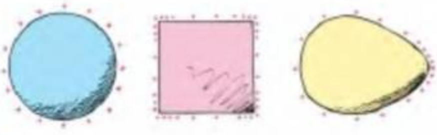


FIGURE 22.21

Electric charge distributes itself on the surface of all conductors in such a way that the electric field inside the conductors is zero.

FIGURE 22.22

Electrons from the lightning bolt mutually repel to the outer metal surface. Although the electric field the electrons set up may be great *outside* the car, the net electric field *inside* the car is zero.

We cannot shield ourselves from gravity, because gravity only attracts. There are no repelling parts of gravity to offset attracting parts. Shielding electric fields, however, is quite simple. Surround yourself, or whatever you wish to shield, with a conducting surface. Put this surface in an electric field of any field strength. The free charges in the conducting surface will arrange themselves on the surface of the conductor in such a way that all field contributions inside cancel one another.

That's why certain electronic components are encased in metal boxes and why certain cables have a metal covering—to shield them from outside electrical activity.

CHECK POINT

Small bits of aligned thread vividly show the electric fields in the four photos of Figure 22.19. But the threads are not aligned inside the cylinder in Figure 22.19d. Why?

Check Your Answer

The electric field is shielded inside the cylinder, shown as a circle in the two-dimensional photograph. Hence, the threads are without alignment. The electric field inside any conductor is zero—so long as no electric charge is flowing.

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Electric Potential

Electric Potential

When we studied energy in Chapter 7, we learned that an object has gravitational potential energy because of its location in a gravitational field. Similarly, a charged object has potential energy by virtue of its location in an electric field. Just as work is required to lift a massive object against the gravitational field of Earth, work is required to push a charged particle against the electric field of a charged body. This work changes the electric potential energy of the charged particle.[7] Consider the particle with the small positive charge located at some distance from a positively charged sphere in Figure 22.23b. If you push the particle closer to the sphere, you will expend energy to overcome electrical repulsion; that is, you will do work in pushing the charged particle against the electric field of the sphere. This work done in moving the particle to its new location increases its energy. We call the energy the particle possesses by virtue of its location **electric potential energy.** If the particle is released, it accelerates in a direction away from the sphere, and its electric potential energy changes to kinetic energy.

If we instead push a particle with twice the charge, we do twice as much work pushing it, so the doubly charged particle in the same location has twice as much electric potential energy as before. A particle with 3 times the charge has 3 times as much potential energy and so on. Rather than dealing with the potential energy of a charged particle, it is convenient, when working with charged particles in an electric field, to consider the electric potential energy *per unit of charge*. The unit of electric

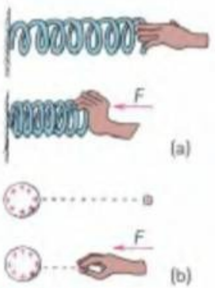

FIGURE 22.23
(a) The spring has more mechanical PE when compressed.
(b) The charged particle similarly has more electrical PE when pushed closer to the charged sphere. In both cases, the increased PE is the result of work input.

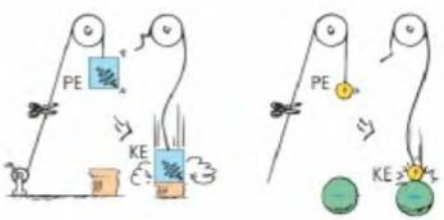

FIGURE 22.24
(a) The PE (gravitational potential energy) of a mass held in a gravitational field, when released, transforms to KE (kinetic energy).
(b) The PE of a charged particle held in an electric field, when released, becomes KE. Can you see that the KE acquired by each equals the decrease in PE?

[7]This work is positive if it increases the electric potential energy of the charged particle and negative if it decreases it.

charge is the coulomb, so we consider the electric potential energy *per coulomb* of charge. Then at any location the electric potential energy per coulomb will be the same—for however much charge. For example, an object with 10 coulombs of charge at a specific location has 10 times as much electric potential energy as an object with 1 coulomb of charge. But 10 times as much electric potential energy for 10 times as much charge gives the same value as the electric potential energy per 1 coulomb of charge. The concept of electric potential energy per unit charge has a special name, **electric potential:**

$$\text{Electric potential} = \frac{\text{electric potential energy}}{\text{charge}}$$

The unit of measurement for electric potential is the volt, so electric potential is often called *voltage*. A potential of 1 volt (V) equals 1 joule (J) of energy per 1 coulomb (C) of charge.

$$1\ \text{volt} = 1\frac{\text{joule}}{\text{coulomb}}$$

Thus, a 1.5-volt battery gives 1.5 joules of energy to every 1 coulomb of charge passing through the battery. Both the names *electric potential* and *voltage* are common, so either may be used. In this book, the names will be used interchangeably.

Electric potential (voltage) plays the same role for charge that pressure does for fluids. When a pressure difference exists between two ends of a pipe filled with fluid, the fluid flows from the high pressure end towards the lower pressure end. We will see in the next chapter that charges respond to differences in potential in a similar way.

If you rub a balloon on your hair, the balloon becomes negatively charged—perhaps to several thousand volts! That would be several thousand joules of energy, if the charge were 1 coulomb. However, 1 coulomb is a very large amount of charge. The charge on a balloon rubbed on hair is more typically much less than a millionth of a coulomb. Therefore, the amount of energy associated with the charged balloon is very, very small. A high voltage means a lot of energy only if a lot of charge is involved. There is an important difference between electric potential energy and electric potential.

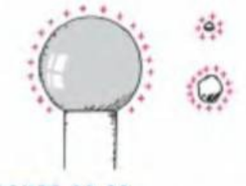

FIGURE 22.25

Of the two charged bodies near the charged dome, the one with the greater charge has the higher electrical PE in the field of the dome. But the *electric potential* of each is the same—likewise for any amount of charge in the same location. Can you see why?

So *electric potential* and *voltage* mean the same thing—electrical potential energy per unit charge—in units of volts.

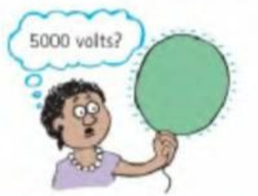

FIGURE 22.26

Although the electric potential (voltage) of the charged balloon is high, the electric potential energy is low because of the small amount of charge. Therefore, very little energy transfers when the balloon is discharged.

High voltage at low energy is similar to the harmless high-temperature sparks of a fireworks sparkler. Recall that temperature is average kinetic energy per molecule, which means total energy is large only for a large number of molecules. Similarly, high voltage means a large quantity of energy only for a large amount of charge.

CHECK POINT

If twice as many coulombs were in the test charge near the charged sphere in Figure 22.23b, how would the electric potential energy of the test charge relative to the sphere be affected? How would its electric potential be affected?

Check Your Answers

Twice as many coulombs means that the test charge has twice as much electric potential energy (because twice as much work put the charge at that location). But the electric potential would not be affected. Electric potential (measured in volts) is different from electric potential energy (measured in joules). Be sure you understand this before you study further.

Electric Energy Storage

Electric energy can be stored in a common device called a **capacitor.** The simplest capacitor is a pair of conducting plates separated by a small distance, but not touching each other. When the plates are connected to a charging device, such as the battery shown in Figure 22.27, electrons are transferred from one plate to the

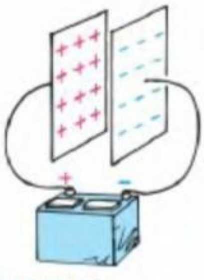

FIGURE 22.27
A capacitor consisting of two closely spaced parallel metal plates. When connected to a battery, the plates acquire equal and opposite charges. The voltage between the plates then matches the electric potential difference between the battery terminals.

other. This occurs as the positive battery terminal pulls electrons from the plate connected to it. These electrons, in effect, are pumped through the battery and through the negative terminal to the opposite plate. The capacitor plates then have equal and opposite charges—the positive plate connected to the positive battery terminal, and the negative plate connected to the negative terminal. The charging process is complete when the potential difference between the plates equals the potential difference between the battery terminals—the battery voltage. The greater the battery voltage, and the larger and closer the plates, the greater the charge that can be stored. In practice, the plates may be thin metallic foils separated by a thin sheet of paper. This "paper sandwich" is then rolled up to save space and inserted into a cylinder. Such a practical capacitor is shown with others in Figure 22.29.

Capacitors are found in nearly all electronic circuits. A capacitor stores energy in common photoflash units. The rapid release of this energy is evident in the short duration of the flash. Likewise for a defibrillator, where short bursts of energy are applied to a heart attack victim. Similarly, but on a grander scale, enormous amounts of energy are stored in banks of capacitors that power giant lasers in national laboratories.

The energy stored in a capacitor comes from the work required to charge it. Discharging a charged capacitor can be a shocking experience if you happen to be the conducting path. The energy transfer that occurs can be fatal where high voltages are present, such as the power supply in a TV set—even after the set has been turned off. This is the main reason for the warning signs on such devices. The energy is stored in the electric field between its plates. Between parallel plates, the electric field is uniform, as indicated in Figure 22.18c and Figure 22.19c. So the energy stored in a capacitor is the energy of its electric field. In Chapter 23, we'll consider the role of capacitors in electric circuits. Then in Chapters 25 and 26, we will see how energy from the Sun is radiated in the form of electric and magnetic fields. The fact that energy is contained in electric fields is truly far-reaching.

FIGURE 22.28
Mona El Tawil-Nassar adjusts demonstration capacitor plates.

CHECK POINT

What is the net charge of a charged capacitor?

Check Your Answer

Zero, because the charges on its two plates are equal in number and opposite in sign. Even when the capacitor is discharged—say, by providing a path for charge flow between the oppositely charged plates—the net charge of the capacitor remains zero, for then each plate has zero charge.

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Video
Van de Graaff Generator

VAN DE GRAAFF GENERATOR

A common laboratory device for producing high voltages and creating static electricity is the *Van de Graaff generator* (invented by American physicist Robert J. Van de Graaff in 1931 to supply the high voltage needed for early particle accelerators). These accelerators were known as atom smashers because they accelerated subatomic particles to very high speeds and then "smashed" them into the target atoms. The resulting collisions could knock protons and neutrons out of atomic nuclei and create high-energy radiation such as X-rays and gamma rays. The ability to create these high-energy collisions is essential for particle and nuclear physics.

FIGURE 22.29
Practical capacitors.

Van de Graaff generators are also the lightning machines that mad scientists used in old science-fiction movies. A classroom model of a Van de Graaff generator provides the static charge to make Lillian's hair stand out in the opening photo to this chapter, and likewise for her friend in Figure 22.30.

Figure 22.31 shows the interior of a simple model of the generator. A hollow metal sphere is supported by a cylindrical insulating stand. A motor-driven rubber belt inside the support stand passes by a comblike set of metal tips that are maintained at a large negative potential relative to ground. Discharge by the tips deposits a continuous supply of electrons on the belt, which are carried up into the hollow conducting sphere. Since the electric field inside the sphere is zero, the charge is not prevented from leaking onto metal points (tiny lightning rods) inside the sphere. The electrons repel one another to the outer surface of the sphere, just as static charge always lies on the outside surface of any conductor. This leaves the inside uncharged and able to receive more electrons as they are brought up by the belt. The process is continuous and the charge builds up until the negative potential on the sphere is much greater than at the voltage source at the bottom—on the order of millions of volts.

A sphere with a radius of 1 m can be raised to a potential of 3 million V before electrical discharge occurs through the air. The voltage can be further increased by increasing the radius of the sphere or by placing the entire system in a container filled with high-pressure gas. Van de Graaff generators can produce voltages as high as 20 million V. Touching one can be a hair-raising experience.

FIGURE 22.30
Both Lori and the dome of the Van de Graaff generator are charged to a high voltage. Why does her hair stand out?

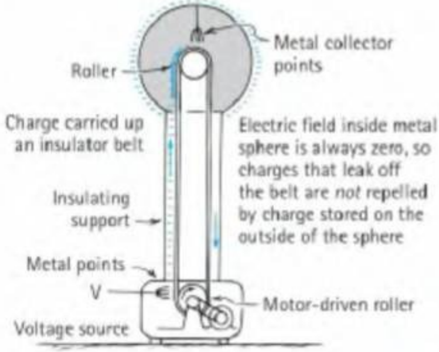


FIGURE 22.31
A simple model of a Van de Graaff generator.

SUMMARY OF TERMS

Electricity General term for electrical phenomena, much like gravity has to do with gravitational phenomena, or sociology with social phenomena.

Electrostatics The study of electric charge at rest (not *in motion*, as in electric currents).

Conservation of charge Electric charge is neither created nor destroyed. The total charge before an interaction equals the total charge after.

Coulomb's law The relationship between electrical force, charge, and distance:

$$F = k\frac{q_1 q_2}{d^2}$$

If the charges are alike in sign, the force is repulsive; if the charges are unlike, the force is attractive.

Coulomb The SI unit of electrical charge. One coulomb (symbol C) is equal to the total charge of 6.25×10^{18} electrons.

Conductor Any material having free charged particles that easily flow through it when an electric force acts on them.

Insulator A material without free charged particles and through which charge does not easily flow.

Semiconductor A material with properties that fall between a conductor and an insulator and whose resistance can be affected by adding impurities.

Superconductor A material that is a perfect conductor with zero resistance to the flow of electric charge.

Charging by contact Transfer of electric charge between objects by rubbing or simple touching.

Charging by induction Redistribution of electric charges in and on objects caused by the electrical influence of a charged object close by but not in contact.

Electrically polarized Term applied to an atom or molecule in which the charges are aligned so that one side has a slight excess of positive charge and the other side a slight excess of negative charge.

Electric field Defined as electric force per unit charge, it can be considered to be an "aura" surrounding charged objects and is a storehouse of electric energy. About a charged point, the field decreases with distance according to the inverse-square law, like a gravitational field. Between oppositely charged parallel plates, the electric field is uniform.

$$\text{Electric field} = \frac{F}{q}$$

Electric potential energy The energy a charged object possesses by virtue of its location in an electric field.

Electric potential The electric potential energy per unit of charge, measured in volts, and often called *voltage*:

$$\text{Voltage} = \frac{\text{electric potential energy}}{\text{charge}}$$

Capacitor An electrical device—in its simplest form, a pair of parallel conducting plates separated by a small distance—that stores electric charge and energy.

REVIEW QUESTIONS

Electricity

1. What term is used for "electricity at rest"?

Electrical Forces

2. Why does the gravitational force between Earth and Moon predominate over electrical forces?

Electric Charges

3. What part of an atom is *positively* charged and what part is *negatively* charged?
4. How does the charge of one electron compare to that of another electron? How does it compare with the charge of a proton?
5. What is normally the net charge of an atom?

Conservation of Charge

6. What is a positive ion? A negative ion?
7. What is meant by saying charge is *conserved?*
8. What is meant by saying charge is *quantized?*
9. What particle has exactly one quantum unit of charge?

Coulomb's Law

10. How does one *coulomb* of charge compare with the charge of a *single* electron?
11. How is Coulomb's law similar to Newton's law of gravitation? How is it different?

Conductors and Insulators

12. Why are metals good conductors both of heat and of electricity?
13. Why are materials such as glass and rubber good insulators?
14. How does a *semiconductor* differ from a *conductor* or an *insulator*?
15. What is a transistor composed of, and what are some of its functions?

Superconductors

16. How does the flow of current differ in a superconductor compared with the flow in ordinary conductors?

Charging

17. What happens to electrons in any charging process?
18. Cite an example of something charged by friction.
19. Cite an example of something charged by contact.
20. Give an example of something charged by induction.
21. What is the primary purpose of a lightning rod?

Charge Polarization

22. How does an electrically *polarized* object differ from an electrically *charged* object?
23. What is an electric dipole?

Electric Field

24. How is the magnitude of an electric field defined? Its direction?
25. Why is there no electric field at the center of a charged spherical conductor?
26. When charges mutually repel and distribute themselves on the surface of conductors, what becomes of the electric field inside the conductor?

Electric Potential

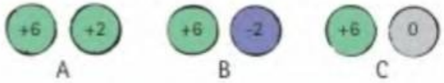
27. How much energy is given to each coulomb of charge that flows through a 1.5-V battery?
28. A balloon may easily be charged to several thousand volts. Does that mean it has several thousand joules of energy? Explain.

Electric Energy Storage

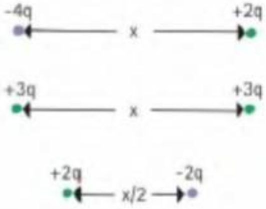
29. Where is the energy stored in a capacitor?
30. What is the magnitude of the electric field inside the dome of a charged van de Graaff generator?

RANKING

1. The three pairs of metal same-size spheres have different charges on their surfaces, as indicated. Each pair is brought together, allowed to touch, and then separated. Rank from greatest to least the total amount of charge on the pairs of spheres after separation.



2. Shown are three separate pairs of point charges. Assume the pairs interact only with each other. Rank the magnitudes of the force between the pairs from largest to smallest.



PROJECTS

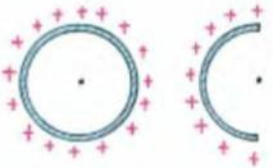
1. Demonstrate charging by friction and discharging from points with a friend who stands at the far end of a carpeted room. Scuff your way across the rug until your noses are close together. This can be a delightfully tingling experience, depending on how dry the air is and how pointed your noses are.
2. Write a letter to Grandpa and tell him why he'd be safe in a lightning storm if he's inside an automobile.
3. Briskly rub a comb through your hair or on a woolen garment and bring it near a small but smooth stream of running water. Is the stream of water deflected?

EXERCISES

1. At the atomic level, what is meant by saying something is electrically charged?
2. Why is charge usually transferred by electrons rather than by protons?
3. Why are objects with vast numbers of electrons normally not electrically charged?
4. Why do clothes often cling together after tumbling in a clothes dryer?
5. Why will dust be attracted to a DVD wiped with a dry cloth?
6. When you remove your wool suit from the dry cleaner's garment bag, the bag becomes positively charged. Explain how this occurs.
7. Plastic wrap becomes electrically charged when pulled from its box. As a result, it is attracted to objects such as food containers. Does the wrap stick better to plastic containers or to metal containers?
8. When combing your hair, you scuff electrons from your hair onto the comb. Is your hair then positively or negatively charged? How about the comb?
9. At some automobile toll booths, a thin metal wire protrudes from the road, making contact with cars before they reach the toll collector. What is the purpose of this wire?
10. Why are the tires for trucks carrying gasoline and other flammable fluids manufactured to be electrically conducting?
11. An electroscope is a simple device consisting of a metal ball that is attached by a conductor to two thin leaves of metal foil protected from air disturbances in a jar, as shown. When the ball is touched by a charged body, the leaves that normally hang straight down spread apart. Why? (Electroscopes are useful not only as charge detectors but also for measuring the quantity of charge: the more charge transferred to the ball, the more the leaves diverge.)

12. The leaves of a charged electroscope collapse in time. At higher altitudes, they collapse more rapidly. Why is this true? (*Hint:* The existence of cosmic rays was first indicated by this observation.)
13. Is it necessary for a charged body actually to touch the ball of the electroscope for the leaves to diverge? Defend your answer.
14. Strictly speaking, when an object acquires a positive charge by the transfer of electrons, what happens to its mass? What happens to its mass when it acquires a negative charge? (Think small!)
15. Strictly speaking, will a penny be slightly more massive if it has a negative charge or a positive charge? Explain.
16. A crystal of salt consists of electrons and positive ions. How does the net charge of the electrons compare with the net charge of the ions? Explain.
17. How can you charge an object negatively with only the help of a positively charged object?
18. It is relatively easy to strip the outer electrons from a heavy atom like that of uranium (which then becomes a uranium ion), but it is very difficult to remove the inner electrons. Why do you suppose this is so?
19. When one material is rubbed against another, electrons jump readily from one to the other but protons do not. Why is this? (Think in atomic terms.)
20. If electrons were positive and protons were negative, would Coulomb's law be written the same or differently?
21. What does the inverse-square law tell you about the relationship between force and distance?
22. The 5000 billion billion (5×10^{21}) freely moving electrons in a penny repel one another. Why don't they fly out of the penny?

23. How does the magnitude of electrical force between a pair of charged particles change when the particles are moved half as far apart? One-third as far apart?
24. How does the magnitude of electric force compare between a pair of charged particles when they are brought to half their original distance of separation? To one-quarter their original distance? To 4 times their original distance? (What law guides your answers?)
25. When you double the distance between a pair of charged particles, what happens to the force between them? Does it depend on the sign of the charges? What law defends your answer?
26. When you double the charge on only one of a pair of particles, what effect does this have on the force between them? Does the effect depend on the sign of the charge?
27. When you double the charge on both particles in a pair, what effect does this have on the force between them? Does it depend on the sign of the charge?
28. The proportionality constant k in Coulomb's law is huge in ordinary units, whereas the proportionality constant G in Newton's law of gravitation is tiny. What does this indicate about the relative strengths of these two forces?
29. How do electrical field lines indicate the strength of an electric field?
30. How is the direction of an electric field indicated with electrical field lines?
31. Suppose that the strength of the electric field about an isolated point charge has a certain value at a distance of 1 m. How will the electric field strength compare at a distance of 2 m from the point charge? What law guides your answer?
32. In the phenomenon of superconductivity, what happens to electrical resistance at low temperatures?
33. Measurements show that there is an electric field surrounding Earth. Its magnitude is about 100 N/C at Earth's surface, and it points inward toward Earth's center. From this information, can you state whether Earth is negatively or positively charged?
34. Why are lightning rods normally at a higher elevation than the buildings they protect?
35. Why are metal-spiked shoes not a good idea for golfers on a stormy day?
36. If you are caught outdoors in a thunderstorm, why should you not stand under a tree? Can you think of a reason why you should not stand with your legs far apart? Or why lying down can be dangerous? (*Hint:* Consider electric potential difference.)
37. If a large enough electric field is applied, even an insulator will conduct an electric current, as is evident in lightning discharges through the air. Explain how this happens, taking into account the opposite charges in an atom and how ionization occurs.
38. If you rub an inflated balloon against your hair and place it against a door, by what mechanism does it stick? Explain.
39. When a car is moved into a painting chamber, a mist of paint is sprayed around its body. When the body is given a sudden electric charge and mist is attracted to it—presto—the car is quickly and uniformly painted. What does the phenomenon of polarization have to do with this?
40. How can a charged atom (an ion) attract a neutral atom?
41. If you place a free electron and a free proton in the same electric field, how will the forces acting on them compare?
42. How will the accelerations of the proton and electron in the previous problem compare?
43. How will the directions of travel compare for the electron and proton in the previous problem?
44. Two pieces of plastic, a full ring and a half ring, have the same radius and charge density. Which electric field at the center has the greater magnitude? Defend your answer.



45. Why is the magnitude of the electric field zero midway between identical point charges?
46. Imagine a proton at rest a certain distance from a negatively charged plate. It is released and collides with the plate. Then imagine the similar case of an electron at rest the same distance away from a positively charged plate. In which case will the moving particle have the greater speed when the collision occurs? Why?
47. A gravitational field vector points toward Earth; an electric field vector points toward an electron. Why do electric field vectors point away from protons?
48. By what specific means do the bits of fine threads align in the electric fields shown in Figure 22.19?
49. Suppose that a metal file cabinet is charged. How will the charge concentration at the corners of the cabinet compare with the charge concentration on the flat parts of the cabinet?
50. If you were to expend 10 J of work to push a 1-C charge against an electric field, what would be its change of voltage?
51. When released, what will be the kinetic energy of the 1-C charge of the previous problem if it flies past its starting position?
52. You are not harmed by contact with a charged metal ball, even though its voltage may be very high. Is the reason similar to why you are not harmed by the greater-than-1000°C sparks from a Fourth-of-July sparkler? Defend your answer in terms of the energies that are involved.
53. What is the voltage at the location of a 0.0001-C charge that has an electric potential energy of 0.5 J (both measured relative to the same reference point)?
54. Why is it safe to remain inside a car during a lightning storm?
55. How do the charges on opposing plates of a capacitor compare?
56. In order to store more energy in a parallel-plate capacitor whose plates differ by a fixed voltage, what change would you make in the plates?
57. Why is it dangerous to touch the terminals of a high-voltage capacitor even after the charging circuit is turned off?

58. An electron volt, eV, is a unit of energy. Which is larger, a GeV or a MeV?

59. Would you feel any electrical effects if you were inside the charged sphere of a Van de Graaff generator? Why or why not?

60. A friend says that the reason one's hair stands out while touching a charged Van de Graaff generator is simply that the hair strands become charged and are light enough so that the repulsion between strands is visible. Do you agree or disagree?

PROBLEMS

1. Two point charges are separated by 6 cm. The attractive force between them is 20 N. Find the force between them when they are separated by 12 cm. (Why can you solve this problem without knowing the magnitudes of the charges?)

2. Suppose that the charges attracting each other in the preceding problem have equal magnitude. Rearrange Coulomb's law and show that the magnitude of each charge is 2.8×10^{-6} C (2.8 microcoulombs).

3. Two pellets, each with a charge of 1 microcoulomb (10^{-6} C), are located 3 cm (0.03 m) apart. Show that the electric force between them is 10 N. What would be the mass of an object that would experience this same force in Earth's gravitational field?

4. Electronic types neglect the force of gravity on electrons. To see why, compute the force of Earth's gravity on an electron and compare it with the force exerted on the electron by an electric field of magnitude 10,000 V/m (a relatively small field). The mass and charge of an electron are given on the inside back cover.

5. Atomic physicists ignore the effect of gravity within an atom. To see why, calculate and compare the gravitational and electrical forces between an electron and a proton separated by 10^{-10} m. The charges and masses are given on the inside back cover.

6. A droplet of ink in an industrial ink-jet printer carries a charge of 1.6×10^{-10} C and is deflected onto paper by a force of 3.2×10^{-4} N. Show that the strength of the electric field to produce this force is 2 million N/C.

7. The potential difference between a storm cloud and the ground is 100 million V. If a charge of 2 C flashes in a bolt from cloud to Earth, what is the change of potential energy of the charge?

8. An energy of 0.1 J is stored in the metal sphere on top of a Van de Graaff generator. A spark carrying 1 microcoulomb (10^{-6} C) discharges the sphere. Show that the sphere's potential relative to ground is 100,000 V?

9. Find the voltage change when (a) an electric field does 12 J of work on a 0.0001-C charge; (b) the same electric field does 24 J of work on a 0.0002-C charge.

•10. In 1909, Robert Millikan was the first to find the charge of an electron in his now-famous oil-drop experiment. In that experiment tiny oil drops were sprayed into a uniform electric field between a horizontal pair of oppositely charged plates. The drops were observed with a magnifying eyepiece, and the electric field was adjusted so that the upward force on some negatively charged oil drops was just sufficient to balance the downward force of gravity. That is, when suspended, upward force qE just equaled mg. Millikan accurately measured the charges on many oil drops and found the values to be whole-number multiples of 1.6×10^{-19}C—the charge of the electron. For this he won the Nobel Prize.

a. If a drop of mass 1.1×10^{-14} kg remains stationary in an electric field of 1.68×10^{5} N/C, what is the charge of this drop?

b. How many extra electrons are on this particular oil drop (given the presently known charge of the electron)?

CHAPTER 22 ONLINE RESOURCES

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Interactive Figures

- 22.1, 22.2, 22.7, 22.8, 22.12, 22.17, 22.18

Tutorial

- Electrostatics

Videos

- Electric Potential
- Van de Graaff Generator

Quizzes

Flashcards

Links

23 Electric Current

1 David Housden constructs a parallel circuit by fastening lamps to extended terminals of a common car battery. He asks his class to predict the relative brightness of the identical lamps in the top branch. 2 Juliet Layugan leads her class in a discussion of the relative efficiencies of a compact fluorescent lamp and an incandescent bulb. 3 Will Maynez shows his lab class how to connect batteries in series, and then in parallel, and predict their effects on lighting the lamps.

Electric current is the flow of charge, pressured into motion by voltage, and hampered by resistance. The mathematical relationship among the three quantities current, voltage, and resistance is credited to the German scientist Georg Simon Ohm, who was born in 1789. His father was a locksmith and his mother was the daughter of a tailor. Neither had formal education. Ohm's self-educated father gave his sons an excellent home education, with his brother Martin going on to become a well-known mathematician.

Georg Simon Ohm (1789–1854)

In 1805, at age 15, Ohm entered the University of Erlangen. But instead of concentrating on his studies, he spent much time dancing, ice skating, and playing billiards. Ohm's father, angry that Georg was wasting his educational opportunity, sent him to Switzerland, where, in September 1806, at a mere 16 years of age, he became a mathematics teacher. He left his teaching post 2½ years later and became a tutor, continuing with his passion of studying mathematics. His studies paid off. Returning to the University of Erlangen, he earned his doctorate in 1811, joining the staff of that university as a mathematics lecturer. But the lectureship paid so little that he soon gave it up and spent the next 6 years teaching in undistinguished schools in Bavaria. During this time he wrote an elementary book on geometry. The book impressed King Wilhelm III of Prussia, who offered Ohm a teaching position in Cologne. Luckily, the physics lab at the school was well equipped, so Ohm devoted himself to experimentation on physics. His practical experience with his father's locksmith activities proved helpful.

Ohm wrote extensively, and his Ohm's law was not fully appreciated at the time. His work was eventually recognized in 1841 by the Royal Society with its award of the prestigious Copley Medal. Ohm became a professor of experimental physics at the University of Munich, where he remained until he died at age 65.

The SI unit of electrical resistance, the ohm (symbol Ω), is named after him.

Flow of Charge

From our study of heat and temperature, recall that when the ends of a conducting material are at different temperatures, heat energy flows from the higher temperature to the lower temperature. The flow ceases when both ends reach the same temperature. Similarly, when the ends of an electrical conductor are at different electric potentials—when there is a **potential difference**—charge flows from one end to the other.[1] The flow of charge persists for as long as there is a potential difference. Without a potential difference, no charge flows. Connect one end of a wire to the charged sphere of a Van de Graaff generator, for example, and the other end to the ground, and a surge of charge will flow through the wire. The flow will be brief, however, because the sphere will quickly reach a common potential with the ground.

To attain a sustained flow of charge in a conductor, some arrangement must be provided to maintain a difference in potential while charge flows from one end to the other. The situation is analogous to the flow of water from a higher reservoir to a lower one (Figure 23.1a). Water will flow in a pipe that connects the reservoirs only as long as a difference in water level exists. The flow of water in the pipe, like the flow of charge in the wire that connects the Van de Graaff generator to the ground, will cease when the pressures at each end are equal (we imply this when we say that water seeks its own level). A continuous flow is possible if the difference in water levels—hence the difference in water pressures—is maintained with the use of a suitable pump (Figure 23.1b).

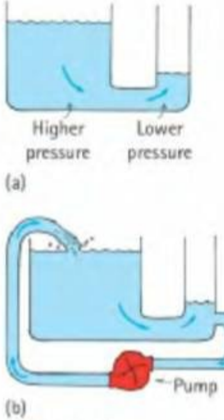

FIGURE 23.1
(a) Water flows from the reservoir of higher pressure to the reservoir of lower pressure. The flow ceases when the difference in pressure ceases.
(b) Water continues to flow because a difference in pressure is maintained with the pump.

CHECK POINT

Okay, so a potential difference across the ends of a wire produces current. Instead of saying *potential difference*, can we as well say *voltage?*

Check Your Answer

Yes. Recall from the previous chapter that potential difference and voltage are interchangeable terms—the difference in electrical potential between two points in a conducting path. Both are measured in units of volts.

Electric Current

Just as water current is the flow of H_2O molecules, **electric current** is simply the flow of electric charge. In circuits of metal wires, electrons make up the flow of charge. This is because one or more electrons from each metal atom are free to move throughout the atomic lattice. These charge carriers are called *conduction electrons*. Protons, on the other hand, do not move because they are bound inside the nuclei of atoms that are more or less locked in fixed positions. In conducting fluids, however—such as in a car battery—positive ions as well as electrons compose the flow of electric charge.

We often think of current flowing through a circuit, but don't say this around somebody who is picky about grammar because the expression "current flows" is redundant. More properly, charge flows—which is current.

[1] When we say that charge flows, we mean that charged *particles* flow. Charge is a property of particular particles, most significantly electrons, protons, and ions. When the flow is of negative charge, electrons or negative ions constitute the flow. When the flow of charge is positive, protons or positive ions are flowing.

fyi

- Andre Marie Ampere is often referred to as "the Newton of electricity." In the 1820s, he showed that parallel wires carrying current in the same direction attract each other, and he postulated that circulating charge is responsible for magnetism. In his honor, the unit for current is amperes, often shortened to *amps*.

The *rate* of electrical flow is measured in *amperes*. One ampere is a rate of flow equal to 1 coulomb of charge per second. (Recall that 1 coulomb, the standard unit of charge, is the electric charge of 6.25 billion billion electrons.) In a wire that carries 5 amperes, for example, 5 coulombs of charge pass any cross section in the wire each second. So that's a lot of electrons! In a wire that carries 10 amperes, twice as many electrons pass any cross section each second.

FIGURE 23.2

Each coulomb of charge made to flow in a circuit that connects the ends of this 1.5-V flashlight cell is energized with 1.5 J.

Voltage Sources

Charges flow only when they are "pushed" or "driven." A sustained current requires a suitable pumping device to provide a difference in electric potential—a voltage. If we charge one metal sphere positively and another negatively, we can develop a large voltage between the spheres. This voltage source is not a good electrical pump because, when the spheres are connected by a conductor, the potentials equalize in a single brief surge of moving charges—like discharging a Van de Graaff generator. It is not practical. Generators or chemical batteries, on the other hand, are suitable pumps in electric circuits and can maintain a steady flow.

Batteries and electric generators do work to pull negative charges away from positive ones. In chemical batteries, this work is usually, but not always, done by the chemical disintegration of zinc or lead in acid, and the energy stored in the chemical bonds is converted to electric potential energy.[2] Generators, such as alternators in automobiles, separate charge by electromagnetic induction, a process we will describe in Chapter 25. The work done by whatever means in separating the opposite charges is available at the terminals of the battery or generator. These different values of energy per charge create a difference in potential (voltage). This voltage provides the "electrical pressure" to move electrons through a circuit.

fyi

- A single flashlight cell supplies 1.5 V. Inside a 9-V battery are six little cells of 1.5 V each.

The unit of electric potential difference (voltage) is the *volt*.[3] A common automobile battery will provide an electrical pressure of 12 V to a circuit connected across its terminals. Then 12 J of energy are supplied to each coulomb of charge that is made to flow in the circuit joined to these terminals.

There is often some confusion about charge flowing *through* a circuit and voltage placed, or impressed, *across* a circuit. We can distinguish between these ideas by considering a long pipe filled with water. Water will flow *through* the pipe if

FIGURE 23.3

An unusual source of voltage. The electric potential between the head and tail of the electric eel *(Electrophorus electricus)* can be up to 600 V.

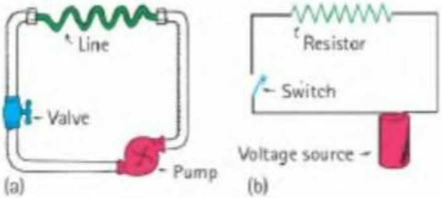

FIGURE 23.4

(a) In a hydraulic circuit, a narrow pipe (green) offers resistance to water flow. (b) In an electric circuit, a lamp or other device (shown by the zigzag symbol for resistance) offers resistance to electron flow.

[2]The life of a battery depends on the length of time it shares its chemical energy with circuit devices. Like water pipes that become clogged with overuse and time, batteries build up resistance that further shortens their useful lives. An explanation of how batteries operate can be found in almost any chemistry textbook.

[3]The terminology of this area of physics can be confusing, so a repetition of terms may be useful: *Electric potential* and *potential* mean the same thing—electrical potential energy per unit charge. Its units are volts. The term *voltage* is usually used to indicate the *difference* in electrical potential between two points in a conducting path. Units of voltage are also volts.

there is a difference in pressure *across* (or between) its ends. Water flows from the high-pressure end to the low-pressure end. Only the water flows, not the pressure. Similarly, electric charge flows because of the differences in electrical pressure (voltage). You say that charges flow *through* a circuit because of an applied voltage *across* the circuit. You don't say that voltage flows through a circuit. Voltage doesn't go anywhere, for it is the charges that move. Voltage produces current (if there is a complete circuit).

Store your batteries in a cool, dry place. If you put them in a refrigerator they'll last a bit longer.

CHECK POINT

Is the voltage between two points in an electric circuit related to the flow of electrons between the points?

Check Your Answer

Yes, and we will soon see it relates to the amount of energy given to the electrons.

fyi

- While Alessandro Volta was experimenting with metals and acids in 1791 he touched a silver spoon and a piece of tin to his tongue (saliva is slightly acidic) and connected them with a piece of copper wire. The sour taste indicated electricity. He went on to assemble a pile of cells to form a battery. In Volta's honor, electric potential is measured in units of "volts." (Touch the two terminals of a 9-volt battery to your tongue to experience this for yourself.)

Electrical Resistance

We know that a battery or generator of some kind is the prime mover and source of voltage in an electric circuit. How much current exists depends not only on the voltage but also on the **electrical resistance** the conductor offers to the flow of charge. This is similar to the rate of water flow in a pipe, which depends not only on the pressure difference between the ends of the pipe but also on the resistance offered by the pipe itself. A short pipe offers less resistance to water flow than a long pipe; the wider the pipe, the less the resistance. Likewise for the resistance of wires that carry current. The resistance of a wire depends both on the thickness and length of the wire and on its particular conductivity. Thick wires have less resistance than thin wires. Longer wires have more resistance than short wires. Copper wire has less resistance than steel wire of the same size. Electrical resistance also depends on temperature. The greater the jostling about of atoms within the conductor, the greater resistance the conductor offers to the flow of charge. For most conductors, increased temperature means increased resistance.[4] The resistance of some materials reaches zero at very low temperatures. These are the superconductors discussed briefly in the previous chapter.

Electrical resistance is measured in units called *ohms*. The Greek letter *omega*, Ω, is commonly used as the symbol for the ohm. As mentioned at the beginning of this chapter, this unit is named after Georg Simon Ohm, who, in 1826, discovered a simple and very important relationship among voltage, current, and resistance.

FIGURE 23.5

More water flows through a thick hose than through a thin one connected to a city's water system (same water pressure). Likewise for electric current in thick and thin wires connected across the same potential difference.

CHECK POINT

When electrons flow in a thin lamp filament they experience "friction." What is the practical outcome of this?

Check Your Answer

Heat and light!

The unit of electrical resistance is the ohm, Ω, like the song of old: "Ω, Ω on the Range."

[4]Carbon is an interesting exception. As temperature increases, more carbon atoms shake loose an electron. This increases the electric current. So the resistance of carbon lowers with increasing temperature. This and (primarily) its high melting point are why carbon is used in arc lamps.

Ohm's Law

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Ohm's Law

The relationship among voltage, current, and resistance is summarized by a statement called **Ohm's law.** Ohm discovered that the current in a circuit is directly proportional to the voltage established across the circuit and is inversely proportional to the resistance of the circuit. In short,

$$\text{Current} = \frac{\text{voltage}}{\text{resistance}}$$

Or, in units form,

$$\text{Amperes} = \frac{\text{volts}}{\text{ohms}}$$

So, for a given circuit of constant resistance, current and voltage are proportional to each other.[5] This means that we'll get twice the current for twice the voltage. The greater the voltage, the greater the current. But, if the resistance of a circuit is doubled, the current will be half what it would be otherwise. The greater the resistance, the smaller the current. Ohm's law makes good sense.

FIGURE 23.6
Resistors. The symbol of resistance in an electric circuit is -/\/\/-.

Ohm's law tells us that a potential difference of 1 V established across a circuit that has a resistance of 1 Ω will produce a current of 1 A. If a voltage of 12 V is impressed across the same circuit, the current will be 12 A. The resistance of a typical lamp cord is much less than 1 Ω, while a typical incandescent bulb has a resistance of more than 100 Ω. An iron or an electric toaster has a resistance of 15–20 Ω. Remember that for a given potential difference, less resistance means more current. In the interior of such electrical devices as computers and television receivers, current is regulated by circuit elements called *resistors,* whose resistance may be a few ohms or millions of ohms.

CHECK POINT

1. How much current is drawn by a 60-Ω resistor when a voltage of 12 V is impressed across it?
2. What is the resistance of an electric frying pan that draws 12 A when connected to a 120-V circuit?

Check Your Answers

1. 1/5 A. From Ohm's law: $\text{Current} = \frac{\text{voltage}}{\text{resistance}} = \frac{12\text{ V}}{60\ \Omega} = 0.2\text{ A}$.
2. 10 Ω. Rearrange Ohm's law: $\text{Resistance} = \frac{\text{voltage}}{\text{current}} = \frac{120\text{ V}}{12\text{ A}} = 10\ \Omega$.

Current is a flow of charge, pressured into motion by voltage and hampered by resistance.

OHM'S LAW AND ELECTRIC SHOCK

The damaging effects of electric shock are the result of current passing through the body. What causes electric shock in the body—current or voltage? From Ohm's law, we can see that this current depends both on the voltage that is applied and on the electrical resistance of the human body. The resistance of one's body, which depends on its condition, ranges from about 100 Ω if it is soaked with saltwater to about 500,000 Ω if the skin is very dry. If we touch the two electrodes of a battery with

[5]Many texts use V for voltage, I for current, and R for resistance, and express Ohm's law as $V = IR$. It then follows that $I = \frac{V}{R}$, or $R = \frac{V}{I}$, so if any two variables are known, the third can be found. Units are abbreviated V for volts, A for amperes, and Ω for ohms.

dry fingers, completing the circuit from one hand to the other, we can expect to offer a resistance of about 100,000 Ω. We usually cannot feel the current produced by 12 V, and 24 V just barely tingles. If our skin is moist, 24 V can be quite uncomfortable. Table 23.1 describes the effects of different amounts of current on the human body.

Many people are killed each year by current from common 120-V electric circuits. If you touch a faulty 120-V light fixture with your hand while you are standing on the ground, there is a 120-V "electrical pressure" between your hand and the ground, so the current would probably not be enough to do serious harm. But if you are standing barefoot in a wet bathtub connected through its plumbing to the ground, the resistance between you and the ground is very small. Your overall resistance is so low that the 120-V potential difference may produce a harmful current in your body. Handling electrical devices while taking a bath is a definite no-no. Drops of water that collect around the on–off switches of such devices as a hair dryer can conduct current to the user. Although distilled water is a good insulator, the ions in ordinary tap water greatly reduce the electrical resistance. These ions are contributed by dissolved materials, especially salts. There is usually a layer of salt left from perspiration on your skin, which, when your skin is wet, lowers your skin resistance to a few hundred ohms or less, depending on the distance over which the voltage acts.

To receive a shock, there must be a *difference* in electric potential between one part of your body and another part. Most of the current will pass along the path of least electrical resistance connecting these two points. Suppose you fell from a bridge and managed to grab onto a high-voltage power line, halting your fall. So long as you touch nothing else of different potential, you will receive no shock at all. Even if the wire is a few thousand volts above ground potential and you hang by it with two hands, no appreciable charge will flow from one hand to the other. This is because there is no appreciable difference in electric potential between your hands. If, however, you reach over with one hand and grab onto a wire of different potential . . . *zap!* We have all seen birds perched on high-voltage wires. Every part of their bodies is at the same high potential as the wire, so they feel no ill effects.

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Video
Handling Electric Wires
Birds and High-Voltage Wires

FIGURE 23.7
The bird can stand harmlessly on one wire of high potential, but it had better not reach over and grab a neighboring wire!

TABLE 23.1
Effect of Electric Currents on the Body

Current (A)	Effect
0.001	Can be felt
0.005	Is painful
0.010	Causes involuntary muscle contractions (spasms)
0.015	Causes loss of muscle control
0.070	If through the heart, causes serious disruption; probably fatal if current lasts for more than 1 s

CHECK POINT

If the two feet of a bird on the high-potential wire of a power line are widely spaced, won't it get a shock?

Check Your Answer

No, because there is no appreciable *difference* in potential between its feet.

Most electric plugs and sockets today are wired with three, instead of two, connectors. The principal two flat prongs on an electrical plug are for the current-carrying

FIGURE 23.8
The round prong connects the body of the appliance directly to ground (Earth). Any charge that builds up on an appliance is therefore conducted to the ground, thereby preventing accidental shock.

double wire, one part of which is "live" (energized) and the other neutral, while the round prong connects to a wire in the electrical system that is grounded—connected directly to the ground (Figure 23.8). The electric appliance at the other end of the plug is, therefore, connected to all three wires. If the live wire of the appliance accidentally comes in contact with the metal surface of the appliance and you touch the appliance, you could receive a dangerous shock. This won't occur when the appliance casing is grounded via the ground wire, which assures that the appliance casing is always at zero ground potential.

Electric shock can overheat tissues in the body and disrupt normal nerve functions. It can upset the rhythmic electrical patterns that maintain proper heartbeat, and it can upset the nerve center that controls breathing. In rescuing shock victims, the first thing to do is to locate and turn off the power source. Then do CPR until help arrives. For heart-attack victims, on the other hand, a properly administered electric shock can sometimes be beneficial in getting the heartbeat started again.

CHECK POINT

1. If your body resistance is 100,000 Ω, how much current will you experience if you touch the terminals of a 12-V battery?
2. If your skin is very moist, so that your resistance is only 1000 Ω, and you again touch the battery terminals, how much current will you experience?

Check Your Answers

1. $\text{Current} = \frac{\text{voltage}}{\text{resistance}} = \frac{12\text{ V}}{100{,}000\ \Omega} = 0.00012\text{ A}.$
2. $\text{Current} = \frac{\text{voltage}}{\text{resistance}} = \frac{12\text{ V}}{1{,}000\ \Omega} = 0.012\text{ A}.$ Ouch!

Direct Current and Alternating Current

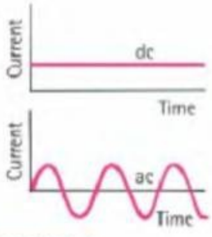

FIGURE 23.9
Time graphs of dc and ac.

Electric current may be dc or ac. By *dc*, we mean **direct current,** which refers to the flowing of charges in *one direction*. A battery produces direct current in a circuit because each terminal of a battery always has the same sign: the positive terminal is always positive, and the negative terminal is always negative. Electrons move from the repelling negative terminal toward the attracting positive terminal, always moving through the circuit in the same direction. Even if the current occurs in unsteady pulses, so long as electrons move in one direction only, it is dc.

Alternating current (ac) acts as the name implies. Electrons in the circuit are moved first in one direction and then in the opposite direction, alternating to and fro about relatively fixed positions. This is accomplished by alternating the polarity of voltage at the generator or other voltage source. Nearly all commercial ac circuits in North America involve voltages and currents that alternate back and forth at a frequency of 60 cycles per second. This is 60-hertz current. In some places, 25-hertz, 30-hertz, or 50-hertz current is used. Throughout the world, most residential and commercial circuits are ac because electric energy in the form of ac can easily be stepped up to high voltage for long-distance transmission with small heat losses, then stepped down to convenient voltages where the energy is consumed. Why this is so will be discussed in Chapter 25.

In ac circuits, 120 V is the "root-mean-square" average of the voltage. The actual voltage in a 120-V ac circuit varies between −170 volts and 170 volts, delivering the same power to an iron or a toaster as a 120-V dc circuit.

The voltage of ac in North America is normally 120 V. In the early days of electricity, higher voltages burned out the filaments of electric lightbulbs. Tradition has it that 110 V was first adopted as the standard because it made bulbs of the day glow as brightly as a gas lamp. So the hundreds of power plants built in the United States prior to 1900 produced electricity at 110 V (or 115 or 120 V). By the time electricity became popular in Europe, engineers had figured out how to manufacture lightbulbs that would not burn out so fast at higher voltages. Power transmission is more efficient at higher voltages, so Europe adopted 220 volts as their standard. The United States continued with 110 V (today officially 120 V) because so much 110-V equipment was already installed. (Certain appliances, such as electric stoves and clothes dryers, presently use higher voltage.)

The primary use of electric current, whether dc or ac, is to transfer energy quietly, flexibly, and conveniently from one place to another.

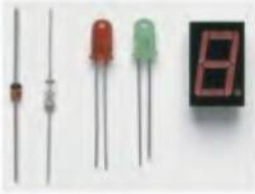

FIGURE 23.10

Diodes. As the symbol suggests, current flows in the direction of the arrow but not in the reverse direction.

CONVERTING AC TO DC

Household current is ac. The current in a battery-operated device, such as a laptop computer, is dc. You can operate these devices on ac instead of batteries with an ac–dc converter. In addition to a transformer to lower the voltage (Chapter 25), the converter uses a *diode*, a tiny electronic device that acts as a one-way valve to allow electron flow in one direction only (Figure 23.10). Since alternating current changes its direction each half-cycle, current passes through a diode only half of each period. The output is a rough dc, and it is off half the time. To maintain continuous current while smoothing the bumps, a capacitor is used (Figure 23.11).

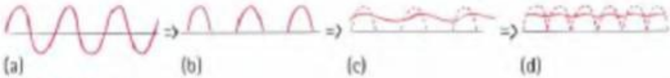

FIGURE 23.11

(a) When input to a diode is ac, (b) output is pulsating dc. (c) Slow charging and discharging of a capacitor provides continuous and smoother current. (d) In practice, a pair of diodes is used, so there are no gaps in current output. The pair of diodes reverses the polarity of alternate half-cycles instead of eliminating them.

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Alternating Current

Recall, from the previous chapter, that a capacitor acts as a storage reservoir for charge. Just as it takes time to raise the water level in a reservoir when water is added, it takes time to add or remove electrons from the plates of a capacitor. A capacitor, therefore, produces a retarding effect on changes in the flow of charge. It opposes changes in voltage and smoothes the pulsed output.

FIGURE 23.12

Water input to the reservoir may be in repeated spurts or pulses, but the output is a fairly smooth stream. Likewise with a capacitor.

Speed and Source of Electrons in a Circuit

When we flip the light switch on a wall and the circuit is completed, either ac or dc, the lamp appears to glow immediately. Current is established through the wires at nearly the speed of light. It is *not* the electrons that move at this speed.[6] Although electrons inside metal at room temperature have an average speed of a few million kilometers per hour, they make no current because they are moving in all possible directions. There is no net flow in any preferred direction. But, when a battery or generator is connected, an electric field is established inside the conductor. The electrons continue their random motions while simultaneously being nudged by this field. It is the electric field that can travel through a circuit at nearly the speed of light. The conducting wire acts as a guide or "pipe" for electric field lines (Figure 23.13). In the space outside the wire, the electric field has a pattern determined by the location of electric charges, including some charges that accumulate on the surface of the wire. Inside the wire, the electric field is directed along the wire.

[6]Much effort and expense are expended in building particle accelerators that accelerate electrons and protons to speeds near that of light. If electrons in a common circuit traveled that fast, one would only have to bend a wire at a sharp angle and electrons traveling through the wire would possess so much momentum that they would fail to make the turn and would fly off, providing a beam comparable to that produced by the accelerators!

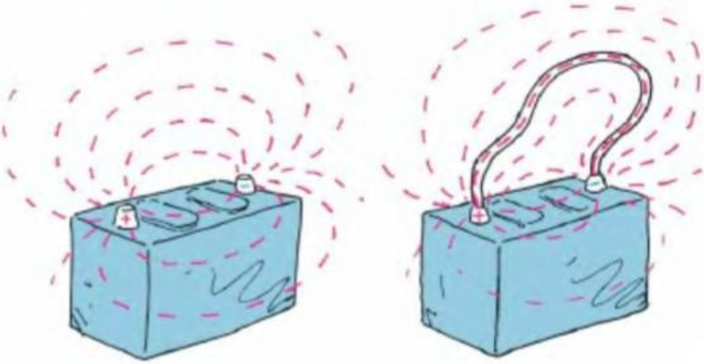

FIGURE 23.13
The electric field lines between the terminals of a battery are directed mainly through a conductor that joins the terminals. A thick metal wire is shown here, but the path from one terminal to the other is usually an electric circuit. (You won't be shocked if you touch this connecting wire, but you might be burned because the wire would likely be very hot!)

FIGURE 23.14
The solid lines suggest the random path of an electron jostling about in an atomic lattice at an average speed of about 1/200 the speed of light. The dashed lines suggest an exaggerated and idealized view of how this path is altered when an electric field is applied. The electron drifts toward the right with a *drift velocity* that is very slow.

After failing more than 6000 times before perfecting the first electric lightbulb, Edison stated that his trials were not failures, because he successfully discovered 6000 ways that don't work.

If the voltage source is dc, like the battery shown in Figure 23.13, the electric field lines are maintained in one direction in the conductor. Conduction electrons are accelerated by the field in a direction parallel to the field lines. Before they gain appreciable speed, they "bump into" the anchored metallic ions in their paths and transfer some of their kinetic energy to them. This is why current-carrying wires become hot. These collisions interrupt the motion of the electrons, so the speed at which they migrate along a wire is extremely low. This net flow of electrons is the *drift velocity*. In a typical dc circuit—the electrical system of an automobile, for example—electrons have a drift velocity that averages about a hundredth of a centimeter per second. At this rate, it would take about 3 hours for an electron to travel through 1 meter of wire! Large currents are possible because of large numbers of flowing electrons. So although an electric signal travels at nearly the speed of light in a wire, the electrons that move in response to this signal actually travel slower than a snail's pace.

In an ac circuit, the conduction electrons don't progress along the wire at all. They oscillate rhythmically to and fro about relatively fixed positions. When you talk to your friend on a conventional land telephone, it is the *pattern* of oscillating motion that is transmitted across town at nearly the speed of light. The electrons already in the wires vibrate to the rhythm of the traveling pattern.

A common misconception regarding electrical currents is that the current is propagated through the conducting wires by electrons bumping into one another—that an electrical pulse is transmitted in a manner similar to the way the pulse of a tipped domino is transferred along a row of closely spaced standing dominoes. This simply isn't true. The domino idea is a good model for the transmission of sound, but not for the transmission of electric energy. Electrons that are free to move in a conductor are accelerated by the electric field impressed upon them, but not because they bump into one another. True, they do bump into one another and other atoms, but this slows them down and offers resistance to their motion. Electrons throughout the entire closed path of a circuit all react simultaneously to the electric field.

Another common misconception about electricity is the source of electrons. In a hardware store, you can buy a water hose that is empty of water. But you can't buy a piece of wire, an "electron pipe," that is empty of electrons. The source of electrons in a circuit is the conducting circuit material itself. Some people think that the electrical outlets in the walls of their homes are a source of electrons. They incorrectly assume that electrons flow from the power utility through the power lines and into the wall outlets of their homes. This assumption is false. The outlets in homes are ac. Electrons make no net migration through a wire in an ac circuit.

When you plug a lamp into an outlet, *energy* flows from the outlet into the lamp, not electrons. Energy is carried by the pulsating electric field and causes vibratory motion of the electrons that already exist in the lamp filament. If a voltage of 120 V is impressed on a lamp, then an average of 120 J of energy is dissipated by each coulomb of charge that is made to vibrate. Most of this electrical energy appears as heat, while some transforms to light. Power utilities do not sell electrons. They sell *energy*. You supply the electrons.

So, when you are jolted by an electric shock, the electrons making up the current in your body originate in your body. Electrons do not emerge from the wire and pass through your body and into the ground; energy does. The energy simply causes free electrons already existing in your body to vibrate in unison. Small vibrations tingle; large vibrations can be fatal.

fyi

- Thomas Edison did much more than invent a functioning incandescent bulb in 1879. He solved the problems of building the dynamos, cable systems, and connections to light New York City. He made the phone work properly, and he gave us recorded music and movies. He also invented a method of inventing: His New Jersey lab was the forerunner of the modern industrial research lab.

CHECK POINT

Consider members of a marching band standing at rest. You can set them into motion in two ways: (1) Give the last person in line a shove that cascades to the first person in line. (2) Issue the command "forward, march." Which of these two is analogous to the way electrons move in a circuit when the switch is closed, and which is analogous to the way sound travels?

Check Your Answer

Issuing the command "forward, march" is analogous to the way electrons move when they sense the electric field that energizes the circuit when the switch is closed. One marcher lurching against the other is analogous to the way sound travels.

Why is it correct to say that the energy from a car battery ultimately comes from the fuel the car consumes?

Electric Power

Unless it is in a superconductor, a charge moving in a circuit expends energy. This may result in heating the circuit or in turning a motor. The rate at which electric energy is converted into another form, such as mechanical energy, heat, or light, is called **electric power.** Electric power is equal to the product of current and voltage.[7]

$$\text{Power} = \text{current} \times \text{voltage}$$

If the voltage is expressed in volts and the current in amperes, then the power is expressed in watts. So, in units form,

$$\text{Watts} = \text{amperes} \times \text{volts}$$

An incandescent bulb rated at 60 W draws a current of 0.5 A (60 W = 0.5 A × 120 V). A 100-W bulb draws about 0.8 A. Interestingly, a 26-W compact fluorescent lamp (CFL) provides about the same amount of light as a 100-W incandescent bulb—only one-quarter of the power for the same light![8]

The relationship between energy and power is a practical matter. From the definition, power = energy per unit time, it follows that energy = power × time.

[7]Recall, from Chapter 7, that Power = work/time; 1 Watt = 1 J/s. Note that the units for mechanical power and electrical power check (work and energy are both measured in joules):

$$\text{Power} = \frac{\text{charge}}{\text{time}} \times \frac{\text{energy}}{\text{charge}} = \frac{\text{energy}}{\text{time}}$$

[8]It turns out that the power formula, $P = IV$, doesn't hold for CFLs. This is because in a CFL, the alternating voltage and current are out of step with each other (out of phase), and the product of current and voltage is larger than the actual power consumption. How much larger? Check the printed data at the base of a CFL and you can find out.

FIGURE 23.15
The power and voltage on a compact fluorescent lamp (CFL) reads "13 W 120 V."

So an energy unit can be a power unit multiplied by a time unit, such as kilowatt-hours (kWh). One kilowatt-hour is the amount of energy transferred in 1 hour at the rate of 1 kW. Therefore in a locality in which electric energy costs 15 cents per kWh, a 1000-W iron can operate for 1 hour at a cost of 15 cents. A refrigerator, typically rated at around 500 W, costs less for an hour, but much more over the course of a month.

CHECK POINT

At 15¢/kWh, what does it cost to operate a 1200-W hair dryer for 1 h?

Check Your Answer

18¢: 1200 W = 1.2 kW; so 1.2 kW × 1 h × 15¢/kWh = 18¢.

Compact Fluorescent Lamps (CFLs)

The brightness of incandescent lightbulbs can be judged by wattage. A 100-W bulb, for example, glows brighter than a 60-W bulb. But most of the power dissipated by these bulbs is not light—it is heat. At least 90% of the energy transferred by an incandescent bulb is heat. Fluorescent lamps, on the other hand, emit much less heat, which is why you can touch them without burning yourself. Incandescent bulbs are today being replaced by compact fluorescent lamps (CFLs), which are a type of fluorescent lamp that fits into a standard lightbulb socket. For the same wattage, CFLs emit much more light and much less heat than incandescents. That's why you can replace a 100-W incandescent with a CFL of about 25 W and get about the same amount of light. So unless you're using incandescent bulbs to heat a room (which farmers do in chicken coops in the winter), you'll probably benefit by using lower-wattage CFLs. And the lifetimes of CFLs are typically more than 10 times that of incandescent bulbs.

A light source even more long-lasting is the light-emitting diode (LED), the most primitive being the little red lights that tell you whether your stereo is on or off. Between CFLs and LEDs, watch for common-use incandescent bulbs to be history. We'll return to the physics of CFLs and LEDs in Chapter 30.

FIGURE 23.16
Another common light source for tomorrow is the light-emitting diode (LED).

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Video
Electric Circuits

A downside to CFLs is the trace amounts of mercury in them. But the single largest source of mercury emissions in the environment is coal-fired power plants. According to the EPA, when coal power is used to illuminate a single incandescent lamp, more mercury is released in the air than exists in a comparably luminous CFL.

Electric Circuits

Any path along which electrons can flow is a *circuit*. For a continuous flow of electrons, there must be a complete circuit with no gaps. A gap is usually provided by an electric switch that can be opened or closed to either cut off or allow energy flow. Most circuits have more than one device that receives electric energy. These devices are commonly connected in a circuit in one of two ways, *series* or *parallel*. When connected in series, they form a single pathway for electron flow between the terminals of the battery, generator, or wall socket (which is simply an extension of these terminals). When connected in parallel, they form branches, each of which is a separate path for the flow of electrons. Both series and parallel connections have their own distinctive characteristics. We shall briefly treat circuits using these two types of connections.

SERIES CIRCUITS

A simple **series circuit** is shown in Figure 23.17. All devices, lamps in this case, are connected end-to-end, forming a single path for electrons to flow. The same current

Fuel Cells

A battery is an energy-storage device. Once its stored chemical energy is converted to electrical energy, its energy is depleted. Then it must be discarded (if it is a disposable battery) or recharged with an opposite flow of electricity.

A *fuel cell*, on the other hand, converts the chemical energy of a fuel to electrical energy continuously and indefinitely as long as fuel is supplied to it. In one version, hydrogen fuel reacts chemically with oxygen from the air to produce electrons and ions—and water. The ions flow internally within the cell in one direction; the electrons flow externally through an attached circuit in the other direction. Because this reaction directly converts chemical energy to electricity, it is more efficient than if the fuel were burned to produce heat, which, in turn, produces steam to turn turbines to generate electricity. The only "waste product" of such a fuel cell is pure water, suitable for drinking!

The space shuttle uses hydrogen fuel cells to meet its electrical needs. (Its hydrogen and oxygen are both brought on board in pressurized containers.) The cells also produce more than 100 gallons of drinking water for the astronauts during a typical week-long mission. Back on Earth, researchers are perfecting fuel cells for a variety of vehicles. Some fuel-cell buses operate in several cities, such as Vancouver, British Columbia, and Chicago, Illinois. In the future, commercial buildings as well as individual homes may be outfitted with fuel cells as an alternative to receiving electricity from regional power stations.

So why aren't fuel cells more widespread today? Currently, they are more costly than other sources of electricity. But mainly, there is the question of the availability of the choice fuel—hydrogen. Although hydrogen is the most plentiful element in the universe, and is plentiful in our immediate surroundings, it is locked away in water and hydrocarbon molecules. It is not available in a free state (a fact overlooked by people cheering for hydrogen-fueled vehicles NOW). Energy is required to separate hydrogen from molecules in which it is tightly bonded. The energy needed to make hydrogen is presently supplied by conventional energy sources.

Hydrogen is, in effect, an energy-storage medium. Like electricity, it is created in one place and used in another. Hydrogen is a highly volatile gas that is difficult to store, transport, and use safely. Fuel cells will be attractive in the future when these difficulties are minimized, when the cost of fuel cells comes down, and mainly, when the hydrogen needed to fuel them is generated by alternative energy sources such as wind or solar.

exists almost immediately in all three lamps, and also in the battery, when the switch is closed. The greater the current in a lamp, the brighter it glows. Electrons do not "pile up" in any lamp but flow *through* each lamp—simultaneously. Some electrons move away from the negative terminal of the battery, some move toward the positive terminal, and some move through the filament of each lamp. Eventually, the electrons may move all the way around the circuit (the same amount of current passes through the battery). This is the only path of the electrons through the circuit. A break anywhere in the path results in an open circuit, and the flow of electrons ceases. Burning out one of the lamp filaments or simply opening the switch could cause such a break.

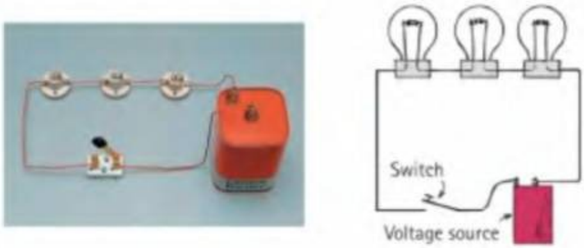

FIGURE 23.17
INTERACTIVE FIGURE

A simple series circuit. The 6-V battery provides 2 V across each lamp.

The circuit shown in Figure 23.17 illustrates the following important characteristics of series connections:

1. Electric current has only a single pathway through the circuit. This means that the current passing through the resistance of each electrical device along the pathway is the same.
2. This current is resisted by the resistance of the first device, the resistance of the second, and that of the third also, so the total resistance to current in the circuit is the sum of the individual resistances along the circuit path.

What is it that gets "used up" in an electric circuit—current or energy?

3. The current in the circuit is numerically equal to the voltage supplied by the source divided by the total resistance of the circuit. This is in accord with Ohm's law.
4. The supply voltage is equal to the sum of the individual "voltage drops" across each device. This is consistent with the total energy supplied to the circuit being equal to the sum of the energies supplied to each device.
5. The voltage drop across each device is proportional to its resistance—Ohm's law applies separately to each device. This follows from the fact that more energy is dissipated when a current passes through a large resistance than when the same current passes through a small resistance.

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- The words *open* and *closed* applied to a door are different when applied to electric circuits. For a door, "open" means free passage and "closed" means blockage. With electrical switches, the terms are opposite: "open" means no flow while "closed" means free passage of electrons.

It is easy to see the main disadvantage of a series circuit: If one device fails, current in the whole circuit ceases. In days of yore, Christmas tree lights were connected in series. When one bulb burned out, it was fun and games (or frustration) trying to locate which bulb to replace.

Most circuits are wired so that it is possible to operate several electrical devices, each independently of the other. In your home, for example, a lamp can be turned on or off without affecting the operation of other lamps or electrical devices. This is because these devices are connected not in series but in parallel with one another.

CHECK POINT

1. What happens to current in other lamps if one lamp in a series circuit burns out?
2. What happens to the brightness of light from each lamp in a series circuit when more lamps are added to the circuit?

Check Your Answers

1. The circuit is broken and all lamps will go out.
2. Adding more lamps in series produces a greater circuit resistance. This decreases the current in the circuit and therefore in each lamp, so the lamps dim. Since all voltages have to add up to the same total voltage, the voltage drop across each lamp will be less.

PARALLEL CIRCUITS

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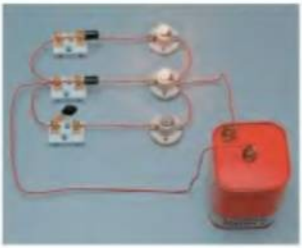
A simple **parallel circuit** is shown in Figure 23.18. Three lamps are connected to the same two points, A and B. Electrical devices connected to the same two points of an electrical circuit are said to be *connected in parallel*. The pathway for current from one terminal of the battery to the other is completed if only *one* lamp is lit. In this illustration, the circuit branches into three separate pathways from A to B. A break in any one path does not interrupt the flow of charge in the other paths. Each device operates independently of the other devices.



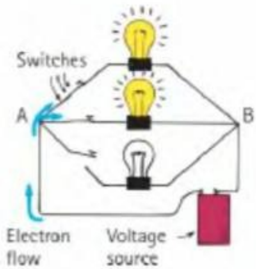


FIGURE 23.18
INTERACTIVE FIGURE

A simple parallel circuit. A 6-V battery provides 6 V across each lamp.

The circuit shown in Figure 23.18 illustrates the following major characteristics of parallel connections:

1. Each device connects the same two points A and B of the circuit. The voltage is therefore the same across each device.
2. The current divides among the parallel branches. Ohm's law applies separately to each branch.
3. The total current in the circuit equals the sum of the currents in its parallel branches. This sum equals the current in the battery or other voltage source.
4. As the number of parallel branches is increased, the overall resistance of the circuit is *decreased*. Overall resistance is lowered with each added path between any two points of the circuit. This means the overall resistance of the circuit is less than the resistance of any one of the branches.

CHECK POINT

1. What happens to the current in other lamps if one of the lamps in a parallel circuit burns out?
2. What happens to the brightness of light from each lamp in a parallel circuit when more lamps are added in parallel?
3. What happens to the current in the battery when more lamps are added in parallel?

Check Your Answers

1. If one lamp burns out, the other lamps are unaffected. This is because current in each branch, according to Ohm's law, is equal to voltage/resistance, and since neither voltage nor resistance is affected in the other branches, the current in those branches is unaffected.
2. The brightness of each lamp is unchanged as other lamps are introduced (or removed).
3. Current in the battery increases by an amount that feeds the added branch(es). In the overall circuit, added paths means decreased resistance. (There is resistance in a battery also, which we assume is negligible here.)

PARALLEL CIRCUITS AND OVERLOADING

Electricity is usually fed into a home by way of two wires called *lines*. These lines, which are very low in resistance, branch into parallel circuits connecting ceiling lights and wall outlets in each room. Lights and wall outlets are connected in parallel, so all are impressed with the same voltage, usually about 110–120 V. As more devices are plugged in and turned on, more pathways for current result in lowering of the combined resistance of each circuit. Therefore, a greater amount of current occurs in the circuits. The sum of these currents equals the line current, which may be more than is safe. The circuit is then said to be *overloaded*.

We can see how overloading occurs by considering the circuit in Figure 23.19. The supply line is connected in parallel to an electric toaster that draws 8 A, to an electric heater that draws 10 A, and to an electric lamp that draws 2 A. When only the toaster is operating and drawing 8 A, the total line current is 8 A. When the heater is also operating, the total line current increases to 18 A (8 A to the toaster and 10 A to the heater). If you turn on the lamp, the line current increases to 20 A. Connecting any more devices increases the current still more. Connecting too many devices into the same circuit results in overheating that may cause a fire.

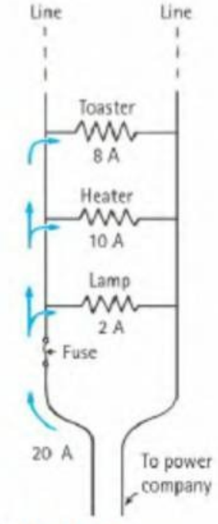


FIGURE 23.19
Circuit diagram for appliances connected to a household circuit.

SAFETY FUSES

To prevent overloading in circuits, fuses may be connected in series along the supply line. In this way, the entire line current must pass through the fuse. The fuse shown in Figure 23.20 is constructed with a wire ribbon that will heat and melt at a given

FIGURE 23.20
A safety fuse.

current. If the fuse is rated at 20 A, it will pass 20 A, but no more. A current above 20 A will melt the fuse, which "blows out" and breaks the circuit. Before a blown fuse is replaced, the cause of overloading should be determined and remedied. Often, insulation that separates the wires in a circuit erodes and allows the wires to touch. This greatly reduces the resistance in the circuit, effectively shortening the circuit path, and is called a *short circuit*.

In modern buildings, fuses have been largely replaced by circuit breakers, which use magnets or bimetallic strips to open a switch when the current is too great. Utility companies use circuit breakers to protect their lines all the way back to the generators.

FIGURE 23.21
Electrician Dave Hewitt with a safety fuse and a circuit breaker. He favors the old fuses, which he has found more reliable.

SUMMARY OF TERMS

Potential difference The difference in electric potential between two points, measured in volts. When two points of different electric potential are connected by a conductor, charge flows so long as a potential difference exists. (Synonymous with *voltage difference*.)

Electric current The flow of electric charge that transports energy from one place to another. Measured in amperes, where 1 A is the flow of 6.25×10^{18} electrons per second, or 1 coulomb per second.

Electrical resistance The property of a material that resists electric current. Measured in ohms (Ω).

Ohm's law The statement that the current in a circuit varies in direct proportion to the potential difference or voltage across the circuit and inversely with the circuit's resistance.

$$\text{Current} = \frac{\text{voltage}}{\text{resistance}}$$

A potential difference of 1 V across a resistance of 1 Ω produces a current of 1 A.

Direct current (dc) Electrically charged particles flowing in one direction only.

Alternating current (ac) Electrically charged particles that repeatedly reverse direction, vibrating about relatively fixed positions. In the United States, the vibrational rate is commonly 60 Hz.

Electric power The rate of energy transfer, or the rate of doing work; the amount of energy per unit time, which electrically can be measured by the product of current and voltage.

$$\text{Power} = \text{current} \times \text{voltage}$$

Electric power is measured in watts (or kilowatts), where $1\text{ W} = 1\text{ A} \times 1\text{ V} = 1\text{ J/s}$.

Series circuit An electric circuit in which electrical devices are connected along a single wire such that the same electric current exists in all of them.

Parallel circuit An electric circuit in which electrical devices are connected in such a way that the same voltage acts across each one, and any single one completes the circuit independently of all the others.

REVIEW QUESTIONS

Flow of Charge

1. What condition is necessary for the flow of heat? What analogous condition is necessary for the flow of charge?
2. What condition is necessary for the sustained flow of water in a pipe? What analogous condition is necessary for the sustained flow of charge in a wire?

Electric Current

3. Why are *electrons*, rather than *protons*, the principal charge carriers in metal wires?
4. What exactly is an *ampere*?

Voltage Sources

5. Name two kinds of practical "electric pumps."
6. How much energy is supplied to each coulomb of charge that flows through a 12-V battery?
7. Does charge flow *through* a circuit or *into* a circuit? Does voltage flow *through* a circuit, or is voltage established *across* a circuit?

Electrical Resistance

8. Will water flow more easily through a wide pipe or a narrow pipe? Will current flow more easily through a thick wire or a thin wire?
9. Does heating a metal wire increase or decrease its electrical resistance?

Ohm's Law

10. If the voltage impressed across a circuit is held constant while the resistance doubles, what change occurs in the current?
11. If the resistance of a circuit remains constant while the voltage across the circuit decreases to half its former value, what change occurs in the current?
12. How does wetness affect the resistance of your body?
13. What is the function of the round third prong in a modern household electric plug?

Direct Current and Alternating Current

14. Does a battery produce dc or ac? Does the generator at a power station produce dc or ac?
15. What does it mean to say that a certain current is 60 Hz?
16. What property of a diode enables it to convert ac to pulsed dc?
17. A diode converts ac to pulsed dc. What electrical device smoothes the pulsed dc to a smoother dc?

Speed and Source of Electrons in a Circuit

18. What is the error in saying that electrons in a common battery-driven circuit travel at about the speed of light?
19. Why does a wire that carries electric current become hot?
20. What is meant by *drift velocity?*
21. A tipped domino sends a pulse along a row of standing dominoes. Is this a good analogy for the way electric current, sound, or both travel?
22. What is the error in saying the source of electrons in a circuit is the battery or generator?
23. When you make your household electric payment at the end of the month, which of the following are you billed for: voltage, current, power, energy?
24. From where do the electrons originate that produce an electric shock when you touch a charged conductor?

Electric Power

25. What is the relationship among electric power, current, and voltage?
26. Which of these is a unit of power and which is a unit of energy—a watt, a kilowatt, a kilowatt-hour?

Compact Fluorescent Lamps (CFLs)

27. How does the heat emitted by lamps affect their efficiency?

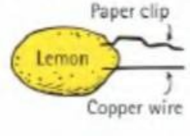
Electric Circuits

28. In a circuit of two lamps in series, if the current through one lamp is 1 A, what is the current through the other lamp? Defend your answer.
29. If a voltage of 6 V is impressed across the circuit in the preceding question and the voltage across the first lamp is 2 V, what is the voltage across the second lamp? Defend your answer.
30. In a circuit of two lamps in parallel, if there is a voltage of 6 V across one lamp, what is the voltage across the other lamp?
31. How does the sum of the currents through the branches of a simple parallel circuit compare with the current that flows through the voltage source?
32. What is the function of fuses or circuit breakers in a circuit?

PROJECTS

1. An electric cell is made by placing two plates made of different materials that have different affinities for electrons in a conducting solution. The voltage of a cell depends on the materials used and the solutions they are placed in, not on the size of the plates. (A cell is often called a battery, but strictly speaking, a battery is a series of cells—for instance, six cells in a 12-V car battery.) You can make a simple 1.5-V cell by placing a strip of copper and a strip of zinc in a tumbler of saltwater.

   An easy cell to construct is the citrus cell. Stick a straightened paper clip and a piece of copper wire into a lemon. Hold the ends of the wire close together, but not touching, and place the ends on your tongue. The slight tingle you feel and the metallic taste you experience result from a slight electric current from the citrus cell through the wires when your moist tongue closes the circuit.



2. Examine the electric meter in your house. It is probably in the basement or on the outside of the house. You will see that, in addition to the clocklike dials in the meter, there is a circular aluminum disk that spins between the poles of magnets when electric current goes into the house. The more electric current, the faster the disk turns. The speed of the disk is directly proportional to the number of watts used; for example, it spins 5 times as fast for 500 W as for 100 W.

   You can use the meter to determine how many watts an electrical device uses. First, see that all electrical devices in your home are disconnected (okay to neglect electric clocks and other 2-W devices, which will hardly be noticeable). The disk will be practically stationary. Then connect a 100-W bulb and note how many seconds it takes for the disk to make five complete revolutions. The black spot painted on the edge of the disk makes this easy. Disconnect the 100-W bulb and plug in a device of unknown wattage. Again, count the seconds for five revolutions. If it takes the same time, it's a

100-W device; if it takes twice the time, it's a 50-W device; half the time, a 200-W device; and so forth. In this way you can estimate the power consumption of devices fairly accurately.

3. Write a letter to Grandma and convince her that whatever electric shocks she may have received over the years have been due to the movement of electrons already in her body—not electrons from somewhere else.

PLUG AND CHUG

Ohm's Law: $I = \dfrac{V}{R}$

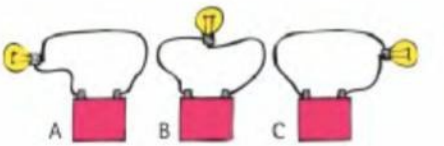
1. Calculate the current in a toaster that has a heating element of 15 Ω when connected to a 120-V outlet.
2. Calculate the current that moves through your fingers (resistance 1000 Ω) when you touch them to the terminals of a 6-V battery.
3. Calculate the current in the 240-Ω filament of a bulb connected to a 120-V line.

Power $= I \times V$

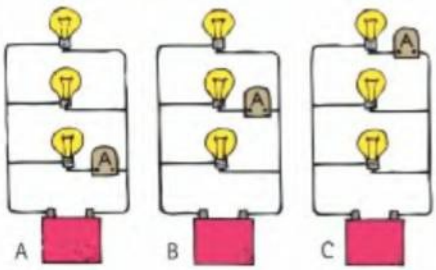
4. Calculate the power of a device that carries 0.5 A when impressed with 120 V.
5. Calculate the power of a hair dryer that operates on 120 V and draws a current of 10 A.
6. Given that the power consumed by a device is 1200 W operating on a 120-V line, calculate the amount of current it draws.

RANKING

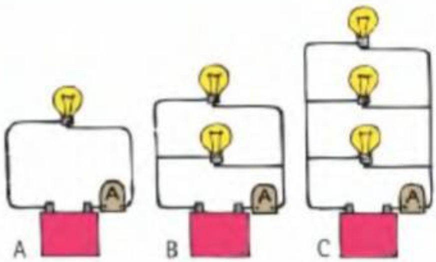
1. Rank the circuits illustrated according to the brightness of the identical bulbs, from brightest to dimmest.



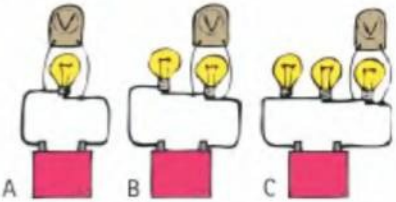
2. The bulbs shown are identical. An ammeter is placed in different locations, as shown. Rank the current readings in the ammeter from greatest to least.



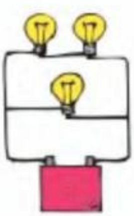
3. All bulbs are identical in the circuits shown. An ammeter is connected next to the battery, as shown. Rank the current readings in the ammeter, from greatest to least.



4. All bulbs are identical in the following circuits. A voltmeter is connected across a single bulb to measure the voltage drop across it. Rank the voltage readings from greatest to least.



5. Consider the three parts of the circuit: A, the top branch with two bulbs; B, the middle branch with one bulb; C, the battery.
   a. Rank the current through each, from greatest to least.
   b. Rank the voltage across each from greatest to least.



EXERCISES

1. What two things can be done to increase the amount of flow in a water pipe? Similarly, what two things can be done to increase the current in an electrical circuit?
2. Consider a water pipe that branches into two smaller pipes. If the flow of water is 10 gallons per minute in the main pipe and 4 gallons per minute in one of the branches, how much water per minute flows in the other branch?
3. Consider a circuit with a main wire that branches into two other wires. If the current is 10 A in the main wire and 4 A in one of the branches, how much current is in the other branch?
4. One example of a water system is a garden hose that waters a garden. Another is the cooling system of an automobile. Which of these exhibits behavior more analogous to an electric circuit? Explain.
5. What happens to the brightness of light emitted by a lightbulb when the current flowing through it increases?
6. Your friend says that a battery supplies the electrons in an electric circuit. Do you agree or disagree? Defend your answer.
7. Is a current-carrying wire electrically charged because of the electrons moving in it?
8. Your tutor tells you that an *ampere* and a *volt* really measure the same thing and that the different terms only serve to make a simple concept seem confusing. Why should you consider getting a different tutor?
9. In which of the circuits shown does a current exist to light the bulb?

10. Does more current flow out of a battery than into it? Does more current flow into a lightbulb than out of it? Explain.
11. Something gets "used up" in a battery that eventually dies and goes flat. One friend says that current is used up. Another friend says that energy is used up. Who, if either, do you agree with, and why?
12. Suppose you leave your car lights on while at a movie. When you return, your battery is too "weak" to start your car. A friend gives you a jump-start with his battery and battery cables. What physics is occurring here?
13. Your friend says that, when jump-starting a dead battery, you should connect your live battery in parallel with the dead battery, which, in effect, replaces the dead one. Do you agree?
14. An electron moving in a wire collides repeatedly with atoms and travels an average distance between collisions called the *mean free path*. If the mean free path is less in some metals, what can you say about the resistance of these metals? For a given conductor, what can be done to lengthen the mean free path?
15. Why is the current in an incandescent bulb greater immediately after it is turned on than it is a few moments later? (That's why bulbs usually burn out just as they are being turned on.)
16. Only a small percentage of the electric energy fed into a common lightbulb is transformed into light. What happens to the remaining energy?
17. Why are all compact fluorescent lamps more efficient than incandescent lamps?
18. A simple lie detector consists of an electric circuit, often from one finger to another. A sensitive meter shows the current that flows when a small voltage is applied. How does this technique indicate that a person is lying? (And when does this technique *not* indicate when someone is lying?)
19. Why are thick wires rather than thin wires usually used to carry large currents?
20. Why does the filament of a lightbulb glow while the connecting wires do not?
21. It is commonly said that a certain resistor draws a certain current. Does this mean that the resistor "attracts" the current? Defend your answer.
22. Will a lamp with a thick filament draw more current or less current than a lamp with a thin filament?
23. What causes electric shock—current or voltage?
24. If a current of one- or two-tenths of an ampere were to flow into one of your hands and out the other, you would probably be electrocuted. But if the same current were to flow into your hand and out the elbow above the same hand, you would survive even though the current might be large enough to burn your flesh. Explain.
25. Would you expect to find dc or ac in the filament of a lightbulb in your home? In the headlight of an automobile?
26. Are automobile headlights wired in parallel or in series? What is your evidence?
27. As more lanes are added to toll booths, the resistance to vehicles passing through is reduced. How is this similar to what happens when more branches are added to a parallel circuit?
28. A car's headlights dissipate 40 W on low beam and 50 W on high beam. Is there more or less resistance in the high-beam filament?
29. What unit is represented by (a) joule per coulomb, (b) coulomb per second, (c) watt-second?
30. To connect a pair of resistors so that their combined (equivalent) resistance will be greater than the resistance of either one, should you connect them in series or in parallel?
31. To connect a pair of resistors so that their combined (equivalent) resistance will be less than the resistance of either one, should you connect them in series or in parallel?
32. Between current and voltage, which remains the same for a 10-Ω and a 20-Ω resistor in series in a series circuit?
33. Between current and voltage, which remains the same for a 10-Ω and a 20-Ω resistor in parallel in a parallel circuit?
34. The damaging effects of electric shock result from the amount of current that flows in the body. Why, then, do

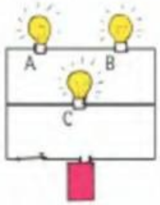
we see signs that read "Danger—High Voltage" rather than "Danger—High Current"?

35. Comment on the warning sign shown in the sketch.

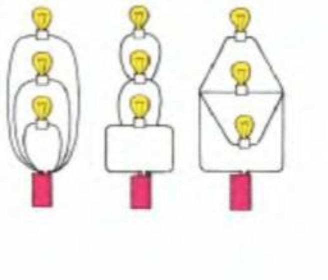
36. Is the following label on a household product cause for concern? "Caution: This product contains tiny, electrically charged particles moving at speeds in excess of 100,000,000 kilometers per hour."

37. Which will do less damage—plugging a 110-V hairdryer into a 220-V circuit or a 220-V hairdryer into a 110-V circuit? Defend your answer.
38. Why are the wingspans of birds a consideration in determining the spacing between parallel wires in a power line?
39. Estimate the number of electrons that a power company delivers annually to the homes of a typical town of 40,000 people.
40. If electrons flow very slowly through a circuit, why does it not take a noticeably long time for a lamp to glow when you turn on a distant switch?
41. Why is the speed of an electric signal so much greater than the speed of sound?
42. If a glowing incandescent lightbulb is jarred and oxygen leaks inside, the bulb will momentarily brighten considerably before burning out. Putting excess current through a lightbulb will also burn it out. What physical change occurs when a lightbulb burns out?
43. Consider a pair of flashlight bulbs connected to a battery. Will they glow brighter if they are connected in series or in parallel? Will the battery run down faster if they are connected in series or in parallel?
44. What happens to the brightness of Bulb A when the switch is closed and Bulb B lights up?

45. If several bulbs are connected in series to a battery, they may feel warm to the touch but not visibly glow. What is your explanation?
46. In the circuit shown, how do the brightnesses of the identical lightbulbs compare? Which bulb draws the most current? What will happen if Bulb A is unscrewed? If Bulb C is unscrewed?



47. As more and more bulbs are connected in series to a flashlight battery, what happens to the brightness of each bulb? Assuming that heating inside the battery is negligible, what happens to the brightness of each bulb when more and more bulbs are connected in parallel?
48. What changes occur in the line current when more devices are introduced in a series circuit? In a parallel circuit? Why are your answers different?
49. Why is there no effect on other branches in a parallel circuit when one branch of the circuit is opened or closed?
50. Your friend says that the equivalent (combined) resistance of resistors connected in series is always more than the resistance of the largest resistor. Do you agree?
51. Your friend says that the equivalent (combined) resistance of resistors connected in parallel is always less than the resistance of the smallest resistor. Do you agree?
52. Your electronics friend needs a 20-Ω resistor but has only 40-Ω resistors. He tells you that he can combine them to produce a 20-Ω resistor. How?
53. Your electronics friend needs a 10-Ω resistor, but only has 40-Ω ones. How can he combine them to produce an equivalent resistance of 10 Ω?
54. When a pair of identical resistors are connected in series, which of the following is the same for both resistors—(a) voltage across each, (b) power dissipated in each, (c) current through each? Do any of your answers change if the resistors are different from each other?
55. When two identical resistors are connected in parallel, which of the following is the same for both resistors—(a) voltage across each, (b) power dissipated in each, (c) current through each? Do any of your answers change if the resistors are different from each other?
56. Batteries do have internal resistance, which is not always negligible. It shows when the current a battery supplies increases, whereupon the voltage it supplies decreases. Taking internal resistance of the battery into consideration, will the brightness of many bulbs diminish when connected in parallel? Defend your answer.
57. Are these three circuits equivalent to one another? Why or why not?



58. Figure 23.19 shows a fuse placed in a household circuit. In what other locations might a fuse be placed in this circuit to be useful, melting only if a problem arises?

59. Is the resistance of a 100-W bulb greater or less than the resistance of a 60-W bulb? Assuming the filaments in each bulb are of the same length and made of the same material, which bulb has the thicker filament?

60. If a 60-W bulb and a 100-W bulb are connected in series in a circuit, across which bulb will there be a greater voltage drop? How about if they are connected in parallel?

PROBLEMS

1. What is the effect on the current in a wire if both the voltage across it and its resistance are doubled? If both are halved?

2. The wattage marked on a lightbulb is not an inherent property of the bulb, but depends on the voltage to which it is connected, usually 110 or 120 V. How many amperes flow through a 60-W bulb connected in a 120-V circuit?

3. Rearrange the equation current = voltage/resistance to express *resistance* in terms of current and voltage. Then solve the following: A certain device in a 120-V circuit has a current rating of 20 A. What is the resistance of the device (how many ohms)?

4. Using the formula power = current × voltage, find the current drawn by a 1200-W toaster connected to 120 V. Then, using the method from the previous problem, show that the resistance of the toaster is 12 Ω.

5. The total charge that an automobile battery can supply without being recharged is given in terms of ampere-hours. A typical 12-V battery has a rating of 60 ampere-hours (60 A for 1 h, 30 A for 2 h, and so on). Suppose that you forget to turn the headlights off in your parked automobile. If each of the two headlights draws 3 A, how long will it be before your battery is "dead"?

6. Show that operating a 100-W lamp continuously for 1 week when the power utility rate is 15¢/kWh costs $2.52.

7. A 4-W night-light is plugged into a 120-V circuit and operates continuously for 1 year. Find the following: (a) the current it draws, (b) the resistance of its filament, (c) the energy consumed in a year. (d) Then show that for a utility rate of 15¢/kWh the cost for a year's operation is $5.25.

8. An electric iron connected to a 110-V source draws 9 A of current. Show that the amount of heat it generates in a minute is nearly 60,000 J.

9. Show in the previous problem that 540 C of charge flow through the iron in 1 minute.

•10. In periods of peak demand, power companies lower their voltage. This saves them power (and saves you money!). To see the effect, consider a 1200-W coffeemaker that draws 10 A when connected to 120 V. Suppose the voltage is lowered by 10% to 108 V. By how much does the current decrease? By how much does the power decrease? (*Caution:* The 1200-W label is valid only when 120 V is applied. When the voltage is lowered, it is the resistance of the toaster, not its power, that remains constant.)

CHAPTER 23 ONLINE RESOURCES

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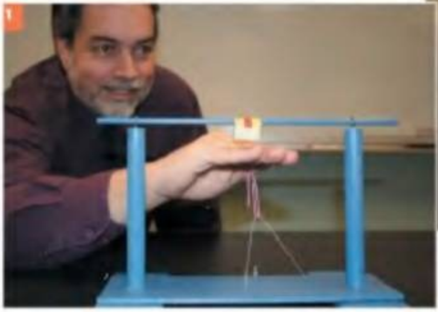
24 Magnetism



1 Fred Myers shows that the magnetic field of a ceramic magnet penetrates flesh and the plastic coating on a paper clip. 2 Ken Ganezer shows the bluish-green glow of electrons circling the magnetic field lines inside a Thompson tube. 3 Paul Callaghan is about to load a nuclear magnetic resonance sample into the room temperature bore of a 7 Tesla superconducting magnet at Victoria University of Wellington in New Zealand.

During the time that whale oil was being used to light lamps and electric lighting was making its debut, a pressing question was what form of energy would power electric lighting. The person who best answered that question was Nikola Tesla, an ethnic Serb who emigrated to America from the Austrian Empire in 1884.

Tesla, an electrical engineer, was a prolific inventor and a genius who spoke seven languages. When he came to America he had little besides a letter of recommendation from his former employer to Thomas Edison. The letter was brief: "I know two great men, one is you and the other is this young man." Edison hired Tesla to work for his Edison Machine Works. Tesla was soon solving the company's most difficult problems. He worked day and night redesigning Edison's inefficient motors and generators, thinking that he was promised a handsome bonus if he were successful. When the bonus didn't materialize, Tesla quit. He then found himself digging ditches for a short period of time, ironically, for the Edison company.

Nikola Tesla (1857–1943)

The major dispute between Tesla and Edison was about whether electric power should be carried by direct current or alternating current. Edison championed direct current, which didn't carry well over long distances. Tesla's alternating current did. Edison was furious with Tesla and aggressively campaigned against Tesla's alternating current. The two remained bitter antagonists over their lifetimes. But Tesla prevailed and formed his own company, which led to many patents that helped power modern cities and industry. Tesla was repeatedly honored and hailed as the patron saint of modern electricity.

In 1888 he teamed up with George Westinghouse and together they harnessed the energy of Niagara Falls to light up the nearby city of Buffalo. For sending electricity over longer distances, Westinghouse perfected a device called a transformer (next chapter). Power from Niagara Falls soon reached New York City and beyond. The efforts of Tesla and Westinghouse truly lit up the world.

Magnetism

Youngsters are fascinated with magnets, largely because they act at a distance. They act at a distance even when your hand is between them, as Fred Myers shows in the chapter-opening photo. Likewise, a neurosurgeon can guide a pellet through brain tissue to inoperable tumors, pull a catheter into position, or implant electrodes while doing little harm to brain tissue. The use of magnets grows daily.

The term *magnetism* comes from the name Magnesia, a coastal district of ancient Thessaly, Greece, where unusual stones were found by the Greeks more than 2000 years ago. These stones, called *lodestones*, had the intriguing property of attracting pieces of iron. Magnets were first fashioned into compasses and used for navigation by the Chinese in the 12th century.

In the 16th century, William Gilbert, Queen Elizabeth's physician, made artificial magnets by rubbing pieces of iron against lodestone, and he suggested that a compass always points north and south because Earth has magnetic properties. Later, in 1750, John Michell, an English physicist and astronomer, found that magnetic poles obey the inverse-square law, and his results were confirmed by Charles Coulomb. The subjects of magnetism and electricity developed almost independently of each other until 1820, when a Danish physicist named Hans Christian Oersted discovered, in a classroom demonstration, that an electric current affects a magnetic compass.[1] He saw confirming evidence that magnetism was related to electricity. Shortly thereafter, the French physicist André Marie Ampere proposed that electric currents are the source of all magnetic phenomena.

PhysicsPlace.com
Video
Oersted's Discovery

There's much bunk about magnetism. Hence the need of a *knowledge filter* to tell the difference between what's true and what's not. The best knowledge filter ever invented is science.

Magnetic Forces

In Chapter 22, we discussed the forces that electrically charged particles exert on one another: The force between any two charged particles depends on the magnitude of the charge on each and their distance of separation, as specified in Coulomb's law. But Coulomb's law is not the whole story when the charged particles are moving with respect to each other. The force between electrically charged particles depends also, in a complicated way, on their motion. We find that, in addition to *electric force*, there is a force due to the motion of the charged particles that we call the **magnetic force.** The source of magnetic force is the motion of charged particles, usually electrons. Both electrical and magnetic forces are actually different aspects of the same phenomenon of electromagnetism.

CHECK POINT

Do both electric forces and magnetic forces depend on motion?

Check Your Answer

Only the magnetic force requires motion. Read on.

[1]We can only speculate about how often such relationships become evident when they "aren't supposed to" and are dismissed as "something wrong with the apparatus." Oersted, however, had the insight—characteristic of a good scientist—to see that nature was revealing another of its secrets.

Magnetic Poles

The forces that magnets exert on one another are similar to electrical forces, for they can both attract and repel without touching, depending on which ends of the magnets are held near one another. Also like electrical forces, the strength of their interaction depends on the separation distance between the two magnets. Whereas electric charge is responsible for electrical forces, regions called *magnetic poles* give rise to magnetic forces.

FIGURE 24.1
A horseshoe magnet.

If you suspend a bar magnet at its center by a piece of string, you'll have a compass. One end, called the *north-seeking pole*, points northward, and the opposite end, called the *south-seeking pole*, points southward. More simply, these are called the *north* and *south poles*. All magnets have both a north and a south pole (some have more than one of each). Refrigerator magnets, popular in recent years, have narrow strips of alternating north and south poles. These magnets are strong enough to hold sheets of paper against a refrigerator door, but they have a very short range because the north and south poles are close together and cancel at short distances. In a simple bar magnet, a single north pole and a single south pole are located at opposite ends. A common horseshoe magnet is simply a bar magnet that has been bent into a U shape. Its poles are also at its two ends (Figure 24.1).

When the north pole of one magnet is brought near the north pole of another magnet, they repel.[2] The same is true of a south pole near a south pole. If opposite poles are brought together, however, attraction occurs. We find that

Like poles repel each other; opposite poles attract.

This rule is similar to the rule for the forces between electric charges, where like charges repel one another and unlike charges attract. But there is a very important difference between magnetic poles and electric charges. Whereas electric charges can be isolated, magnetic poles cannot. Negatively charged electrons and positively charged protons are entities by themselves. A cluster of electrons need not be accompanied by a cluster of protons, and vice versa. But a north magnetic pole never exists without the presence of a south pole, and vice versa.

If magnets won't stick to your stainless steel refrigerator door, the door is probably a mixture of steel and nickel. But magnets will stick to stainless steel when made with chromium instead of nickel.

If you break a bar magnet in half, each half still behaves as a complete magnet. Break the pieces in half again, and you have four complete magnets. You can continue breaking the pieces in half and never isolate a single pole.[3] Even when your piece is one atom thick, there are two poles, which suggests that atoms themselves are magnets.

CHECK POINT

Does every magnet necessarily have a north and south pole?

Check Your Answer

Yes, just as every coin has two sides, a "head" and a "tail." Some "trick" magnets have more than one pair of poles, but, nevertheless, poles always occur in pairs.

[2] The force of interaction between magnetic poles is given by $F \sim \frac{p_1 p_2}{d^2}$, where p_1 and p_2 represent magnetic pole strengths and d represents the separation distance between the poles. Note the similarity of this relationship to Coulomb's law.

[3] Theoretical physicists have speculated for more than 75 years about the possible existence of discrete magnetic "charges," called *magnetic monopoles*. These tiny particles would carry either a single north or a single south magnetic pole and would be the counterparts to the positive and negative charges in electricity. Various attempts have been made to find monopoles, but none have proved successful. All known magnets always have at least one north pole and one south pole.

Magnetic Fields

If you sprinkle some iron filings on a sheet of paper placed on a magnet, you'll see that the filings trace out an orderly pattern of lines that surround the magnet. The space around the magnet contains a **magnetic field.** The shape of the field is revealed by the filings, which align with the magnetic field lines that spread out from one pole and return to the other. It is interesting to compare the field patterns in Figures 24.2 and 24.4 with the electric field patterns in 22.19 back in Chapter 22.

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Tutorial
Magnetic Fields

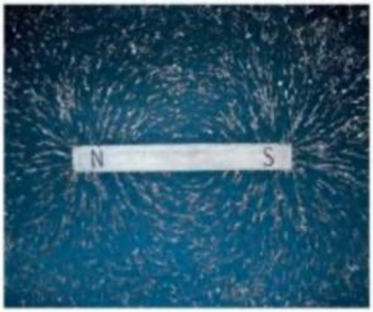


FIGURE 24.2
INTERACTIVE FIGURE

Top view of iron filings sprinkled around a magnet tracing a pattern of magnetic field lines. Interestingly, the magnetic field lines continue inside the magnet (not revealed by the filings) and form closed loops.

The direction of the field outside a magnet is from the north pole to the south pole. Where the lines are closer together, the field is stronger. The concentration of iron filings at the poles of the magnet in Figure 24.2 shows the magnetic field strength is greater there. If we place another magnet or a small compass anywhere in the field, its poles line up with the magnetic field.

Magnetism is very much related to electricity. Just as an electric charge is surrounded by an electric field, the same charge is also surrounded by a magnetic field if it is moving. This magnetic field is due to the "distortions" in the electric field caused by motion and was explained by Albert Einstein in 1905 in his special theory of relativity. We won't go into the details except to acknowledge that a magnetic field is a relativistic by-product of the electric field. Charged particles in motion have associated with them both an electric field and a magnetic field. A magnetic field is produced by the motion of electric charge.[4]

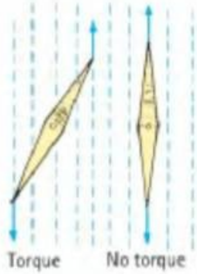


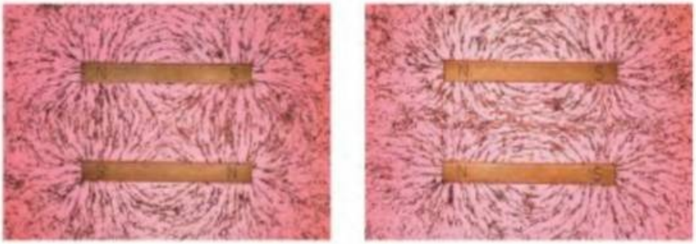
FIGURE 24.3

When the compass needle is not aligned with the magnetic field (left), the oppositely directed forces on the needle produce a pair of torques (called a *couple*) that twist the needle into alignment (right).

If the motion of electric charges produces magnetism, where is this motion in a common bar magnet? The answer is, in the electrons of the atoms that make up the magnet. These electrons are in constant motion. Two kinds of electron motion contribute to magnetism: electron spin and electron revolution. Electrons spin about their own axes like tops, and they also revolve about the atomic nucleus. In most common magnets, electron spin is the chief contributor to magnetism.

Every spinning electron is a tiny magnet. A pair of electrons spinning in the same direction makes up a stronger magnet. A pair of electrons spinning in opposite directions, however, work against each other. The magnetic fields cancel. This is why most substances are not magnets. In most atoms, the various fields cancel one another because the electrons spin in opposite directions. But in such materials as iron, nickel, and cobalt the fields do not cancel each other entirely. Each iron atom

[4]Interestingly, since motion is relative, the magnetic field is relative. For example, when a charge moves by you, there is a definite magnetic field associated with the moving charge. But if you move along with the charge so that there is no motion relative to you, you'll find no magnetic field associated with the charge. Magnetism is relativistic. In fact, it was Albert Einstein who first explained this when he published his first paper on special relativity, "On the Electrodynamics of Moving Bodies." (More on relativity in Chapters 35 and 36.)



(a) (b)

FIGURE 24.4
The magnetic field patterns for a pair of magnets. (a) Opposite poles are nearest each other, and (b) like poles are nearest each other.

has four electrons whose spin magnetism is not canceled. Thus, each iron atom is a tiny magnet. The same is true, to a lesser extent, for the atoms of nickel and cobalt. Most common magnets are made from alloys containing iron, nickel, and cobalt in various proportions.[5]

Magnetic Domains

FIGURE 24.5
A microscopic view of magnetic domains in a crystal of iron. The blue arrows pointing in different directions tell us that these domains are not aligned.

The magnetic field of an individual iron atom is so strong that interactions among adjacent atoms cause large clusters of them to line up with one another. These clusters of aligned atoms are called **magnetic domains.** Each domain is made up of billions of aligned atoms. The domains are microscopic (Figure 24.5), and there are many of them in a crystal of iron. Like the alignment of iron atoms within domains, domains themselves can align with one another.

Not every piece of iron, however, is a magnet. This is because the domains in ordinary iron are not aligned. Consider a common iron nail: The domains in the nail are randomly oriented. Many of them are induced into alignment, however, when a magnet is brought nearby. (It is interesting to listen with an amplified stethoscope to the clickity-clack of domains undergoing alignment in a piece of iron when a strong magnet approaches.) The domains align themselves much as electrical charges in a piece of paper align themselves in the presence of an electrically charged rod. When you remove the nail from the magnet, ordinary thermal motion causes most or all of the domains in the nail to return to a random arrangement. If the field of the permanent magnet is very strong, however, the nail may retain some permanent magnetism of its own after the two are separated.

FIGURE 24.6
Wai Tsan Lee shows iron nails that have become induced magnets.

Permanent magnets are made by simply placing pieces of iron or certain iron alloys in strong magnetic fields. Alloys of iron differ; soft iron is easier to magnetize than steel. It helps to tap the iron to nudge any stubborn domains into alignment. Another way of making a permanent magnet is to stroke a piece of iron with a magnet. The stroking motion aligns the domains in the iron. If a permanent magnet is dropped or heated, some of the domains are jostled out of alignment and the magnet becomes weaker.

Cows often swallow metal objects that puncture their stomachs. That's why farmers feed *cow magnets* (long narrow alnico magnets) to cows, which attract metal pieces and lower the chance of stomach puncture.

[5]Electron spin contributes virtually all of the magnetic properties in magnets made from alloys containing iron, nickel, cobalt, and aluminum. In the rare earth metals such as gadolinium, the orbital motion is more significant.

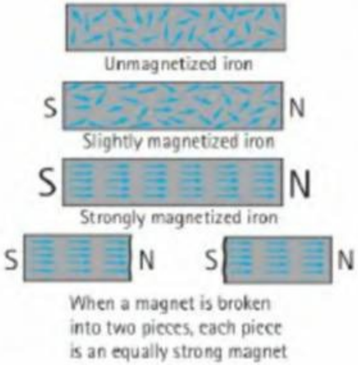


FIGURE 24.7
INTERACTIVE FIGURE

Pieces of iron in successive stages of magnetization. The arrows represent domains; the head is a north pole and the tail is a south pole. Poles of neighboring domains neutralize each other's effects, except at the two ends of a piece of iron.

fyi

- A magstripe on a credit card contains millions of tiny magnetic domains held together by a resin binder. Data are encoded in binary code, with zeros and ones distinguished by the frequency of domain reversals. It's quite amazing how quickly your name pops up when a clerk swipes your card.

CHECK POINT

How can a magnet attract a piece of iron that is not magnetized?

Check Your Answer

Domains in the unmagnetized piece of iron are induced into alignment by the magnetic field of the nearby magnet. See the similarity of this to Figure 22.13 back in Chapter 22. Like the pieces of paper that jump to the comb, pieces of iron will jump to a strong magnet when it is brought nearby. But, unlike the pieces of paper, they are not then repelled. Can you think of the reason why?

Electric Currents and Magnetic Fields

Since a moving charge produces a magnetic field, it follows that a current of charges also produces a magnetic field. The magnetic field that surrounds a current-carrying conductor can be demonstrated by arranging an assortment of compasses around a wire (Figure 24.8) and passing a current through it. The compass needles line up with the magnetic field produced by the current and they show the field to be a pattern of concentric circles about the wire. When the current reverses direction, the compass needles turn around, showing that the direction of the magnetic field changes also. This is the effect that Oersted first demonstrated in his classroom.

If the wire is bent into a loop, the magnetic field lines become bunched up inside the loop (Figure 24.9). If the wire is bent into another loop, overlapping the first,

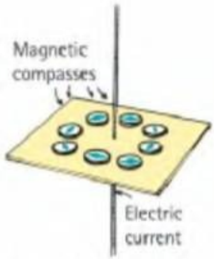


FIGURE 24.8

The compasses show the circular shape of the magnetic field surrounding the current-carrying wire.

Practicing Physics

Most iron objects around you are magnetized to some degree. A filing cabinet, a refrigerator, or even cans of food on your pantry shelf have north and south poles induced by Earth's magnetic field. If you bring a magnetic compass near the tops of iron or steel objects in your home, you will find that the north pole of the compass needle points to the tops of these objects, and the south pole of the compass needle points to their bottoms. This shows that the objects are magnets, having a south pole on top and a north pole on the bottom. Turn cans of food that have been in a vertical position upside down and see how many days it takes for the poles to reverse themselves!

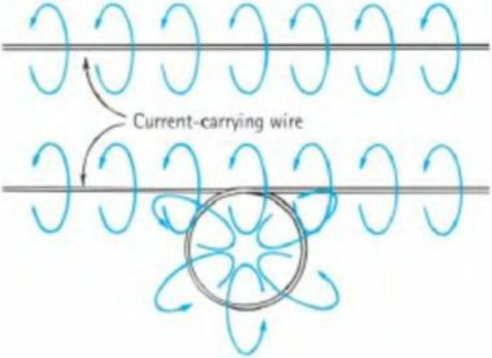


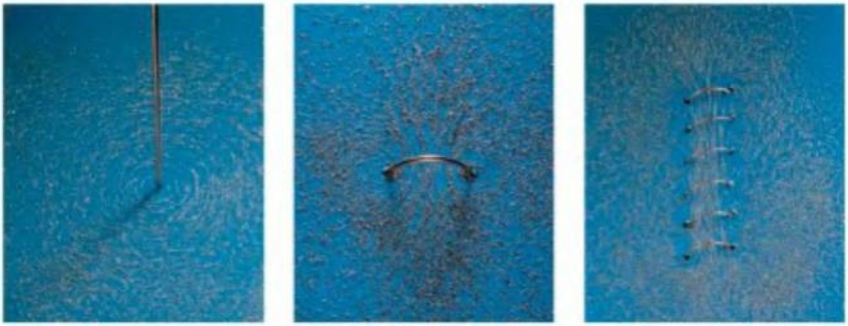
FIGURE 24.9

Magnetic field lines about a current-carrying wire crowd up when the wire is bent into a loop.

the concentration of magnetic field lines inside the loops is doubled. It follows that the magnetic field intensity in this region is increased as the number of loops is increased. The magnetic field intensity is appreciable for a current-carrying coil of many loops.

Electromagnets

A current-carrying coil of wire is an **electromagnet.** The strength of an electromagnet is increased by simply increasing the current through the coil and the number of turns in the coil. Industrial magnets gain additional strength by having a piece of iron within the coil. Electromagnets powerful enough to lift automobiles are a common sight in junkyards. Magnetic domains in the iron core are induced into alignment, adding to the field. For extremely strong electromagnets, such as those used to control charged-particle beams in high-energy accelerators, iron is not used, because, beyond a certain point, all of its domains are aligned. The magnet is said to be saturated and increasing the electric current flowing around the core no longer affects the magnetization of the core itself and it no longer adds to the field.



(a) (b) (c)

FIGURE 24.10

Iron filings sprinkled on paper reveal the magnetic field configurations about (a) a current-carrying wire, (b) a current-carrying loop, and (c) a current-carrying coil of loops.

Electromagnets need not have iron cores. Electromagnets without iron cores are used in magnetically levitated, or "maglev," transportation. Figure 24.11 shows a maglev train, which has no diesel or other conventional engine. Already operating in different countries, various designs are still being engineered. In one design already in commercial use, levitation is accomplished by magnetic coils that run along the track, called a guideway. The coils repel large magnets on the train's undercarriage. Once levitated a few centimeters, power is supplied to the coils within the guideway walls that propels the train. This is accomplished by continually alternating the electric current fed to the coils, which continually alternates their magnetic polarity. In this way a magnetic field pulls the vehicle forward, while a magnetic field farther back pushes. The alternating pushes and pulls produce a forward thrust. Since maglev trains float on a cushion of air, friction experienced by conventional trains is eliminated. Maglev speeds, about half that of commercial aircraft, are limited only by air friction and passenger comfort. Watch for expansion of this growing technology.

FIGURE 24.11
A magnetically levitated vehicle—a *magplane*. Whereas conventional trains vibrate as they ride on rails at high speeds, magplanes can travel vibration-free at high speeds because they levitate above the guideway.

SUPERCONDUCTING ELECTROMAGNETS

The most powerful electromagnets without iron cores use superconducting coils through which large electrical currents flow with ease. Recall, from Chapter 22, that there is no electrical resistance in a superconductor to limit the flow of electric charge and, therefore, no heating, even if the current is enormous. Electromagnets that utilize superconducting coils produce extremely strong magnetic fields—and they do so very economically because there are no heat losses (although energy is used to keep the superconductors cold). At the Large Hadron Collider in Geneva, Switzerland, superconducting magnets guide high-energy particles around an accelerator 17 miles in circumference. Superconducting magnets are used in magnetic resonance imaging (MRI) devices in hospitals.

Whether superconducting or not, electromagnets are part of everyday life. They're in sound systems, electric motors, in our automobiles, and even in shredded garbage recycling systems to remove metal bits. Cheers for electromagnets.

FIGURE 24.12
A permanent magnet levitates above a superconductor because its magnetic field cannot penetrate the superconducting material.

Magnetic Force on Moving Charged Particles

A charged particle at rest will not interact with a static magnetic field. But if the charged particle is moving in a magnetic field, the magnetic character of a charge in motion becomes evident. It experiences a deflecting force.[6] The force is greatest when the particle moves in a direction perpendicular to the magnetic field lines. At other angles, the force is less, and it becomes zero when the particles move parallel to the field lines. In any case, the direction of the force is always perpendicular to the magnetic field lines and to the velocity of the charged particle (Figure 24.13). So a moving charged particle is deflected when it crosses through a magnetic field, but, when it travels parallel to the field, no deflection occurs.

This deflecting force is very different from the forces that occur in other interactions, such as the gravitational forces between masses, the electric forces between charges, and the magnetic forces between magnetic poles. The force that acts on a moving charged

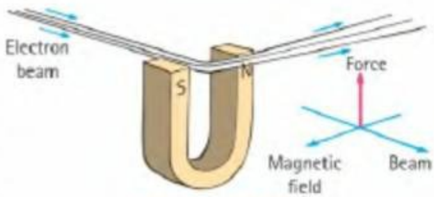


FIGURE 24.13
A beam of electrons is deflected by a magnetic field.

[6] When particles of electric charge q and velocity v move perpendicularly into a magnetic field of strength B, the force F on each particle is simply the product of the three variables: $F = qvB$. For nonperpendicular angles, v in this relationship must be the component of velocity perpendicular to B.

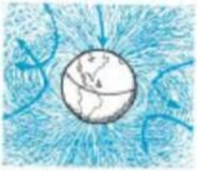


FIGURE 24.14

The magnetic field of Earth deflects many charged particles that make up cosmic radiation.

particle does not act along the line that joins the sources of interaction but, instead, acts perpendicularly to both the magnetic field and the electron beam.

We are fortunate that charged particles are deflected by magnetic fields. Charged particles in cosmic rays are deflected by Earth's magnetic field. Although Earth's atmosphere absorbs most of these, cosmic ray intensity at Earth's surface would be much more intense without Earth's protective magnetic field.

Magnetic Force on Current-Carrying Wires

Simple logic tells you that if a charged particle moving through a magnetic field experiences a deflecting force, then a current of charged particles moving through a magnetic field also experiences a deflecting force. If the particles are trapped inside a wire when they respond to the deflecting force, the wire will also be pushed (Figure 24.15).

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Video
Magnetic Forces on Current-Carrying Wires

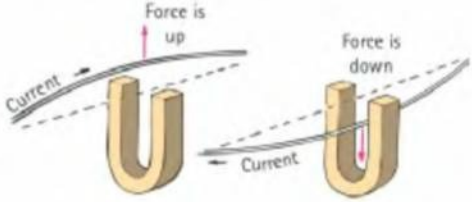
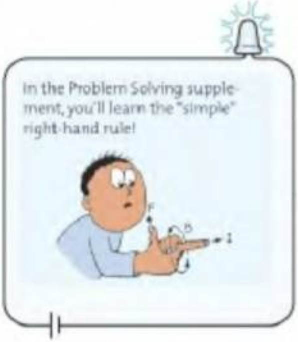


FIGURE 24.15

INTERACTIVE FIGURE

A current-carrying wire experiences a force in a magnetic field. (Can you see that this is a follow-up of what happens in Figure 24.13?)



If we reverse the direction of the current, the deflecting force acts in the opposite direction. The force is strongest when the current is perpendicular to the magnetic field lines. The direction of force is not along the magnetic field lines or along the direction of current. The force is perpendicular to both field lines and current. It is a sideways force.

We see that, just as a current-carrying wire will deflect a magnet such as a compass needle (again, as discovered by Oersted), a magnet will deflect a current-carrying wire. Discovering these complementary links between electricity and magnetism created much excitement, and people began harnessing the electromagnetic force for useful purposes almost immediately—with great sensitivity in electric meters and with great force in electric motors.

CHECK POINT

What law of physics tells you that if a current-carrying wire produces a force on a magnet, a magnet must produce a force on a current-carrying wire?

Check Your Answer

Newton's third law, which applies to *all* forces in nature.

ELECTRIC METERS

The simplest meter to detect electric current is a magnet that is free to turn—a compass. The next simplest meter is a compass in a coil of wires (Figure 24.16).

FIGURE 24.16

A very simple galvanometer.

When an electric current passes through the coil, each loop produces its own effect on the needle, so a very small current can be detected. A sensitive current-indicating instrument is called a *galvanometer,* named after Luigi Galvani, who in the 18th century discovered that dissimilar metals caused twitching in a frog's leg that he was dissecting.

A common galvanometer design is shown in Figure 24.17. It employs many loops of wire and is therefore more sensitive. The coil is mounted for movement, and the magnet is held stationary. The coil turns against a spring, so the greater the current in its windings, the greater its deflection. A galvanometer may be calibrated to measure current (amperes), in which case it is called an *ammeter*. Or it may be calibrated to measure electric potential (volts), in which case it is called a *voltmeter*.

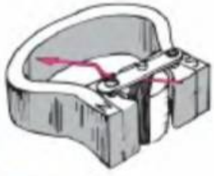


FIGURE 24.17
A common galvanometer design.

FIGURE 24.18
Both the ammeter and the voltmeter are basically galvanometers. (The electrical resistance of the instrument is made to be very low for the ammeter and very high for the voltmeter.)

Galvani's chance discovery of the twitching frog led him to invent the chemical cell and the battery. The next time you pick up a galvanized pail, think of Luigi Galvani in his anatomy laboratory.

ELECTRIC MOTORS

If we modify the design of the galvanometer slightly, so deflection makes a complete rather than a partial rotation, we have an *electric motor*. The principal difference is that in a motor, the current is made to change direction every time the coil makes a half rotation. After being forced to turn one-half rotation, the coil continues in motion just in time for the current to reverse, whereupon, instead of the coil reversing direction, it is forced to continue another half rotation in the same direction. This happens in cyclic fashion to produce continuous rotation, which has been harnessed to run clocks, operate gadgets, and lift heavy loads.

In Figure 24.19, we can see the principle of the electric motor in bare outline. A permanent magnet produces a magnetic field in a region in which a rectangular loop of wire is mounted to turn about the dashed axis shown. The current in the loop flips direction with each half-turn, and continuous rotation results.

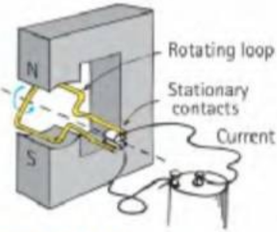


FIGURE 24.19
INTERACTIVE FIGURE
A simplified electric motor.

Any current in the loop moves in one direction in the upper side of the loop and the opposite direction in the lower side (because charges flowing into one end of the loop must flow out the other end). If the upper side of the loop is forced to the left by the magnetic field, the lower side is forced to the right, as if it were a galvanometer. But, unlike the situation in a galvanometer, the current in a motor is reversed during each half-revolution by means of stationary contacts on the shaft. The parts of the wire that rotate and brush against these contacts are called *brushes*. In this way, the current in the loop alternates so that the forces on the upper and lower regions do not change directions as the loop rotates. The rotation is continuous as long as current is supplied.

A motor and a generator are actually the same device, with input and output reversed. The electrical device in a hybrid car is such a motor/generator combination.

We have described here only a very simple dc motor. Larger motors, dc or ac, are usually manufactured by replacing the permanent magnet with an electromagnet that is energized by the power source. Of course, more than a single loop is used. Many loops of wire are wound about an iron cylinder, called an *armature,* which then rotates when the wire carries current.

The advent of electric motors brought to an end much human and animal toil in many parts of the world. Electric motors have greatly changed the way people live.

CHECK POINT

What is the major similarity between a galvanometer and a simple electric motor? What is the major difference?

Check Your Answers

Both are similar, as coils are positioned in a magnetic field. A force produces rotation when current passes through the coils. The major difference is that the maximum rotation of the coil in a galvanometer is one half-turn, whereas, in a motor, the coil (wrapped on an armature) rotates through many complete turns—accomplished by alternating the current with each half-turn of the armature.

Earth's Magnetic Field

FIGURE 24.20
Earth is a magnet.

A suspended magnet or compass points northward because Earth itself is a huge magnet. The compass aligns with the magnetic field of Earth. The magnetic poles of Earth, however, do not coincide with the geographic poles—in fact, the magnetic and geographical poles are widely separated. The magnetic pole in the Northern Hemisphere, for example, is now located nearly 1800 kilometers from the geographic pole, somewhere in the Hudson Bay region of northern Canada. The other pole is located south of Australia (Figure 24.20). This means that compasses do not generally point to the true north. The discrepancy between the orientation of a compass and true north is known as the *magnetic declination.*

We do not know exactly why Earth itself is a magnet. The configuration of Earth's magnetic field is like that of a strong bar magnet placed near the center of Earth. But Earth is not a magnetized chunk of iron like a bar magnet. It is simply too hot for individual atoms to hold to a proper orientation. So the explanation likely involves electric currents deep in the interior. About 2000 kilometers below the outer rocky mantle (which itself is almost 3000 kilometers thick) lies the molten part that surrounds the solid center. Most Earth scientists think that moving charges looping around within the molten part of Earth create the magnetic field. Some Earth scientists speculate that the electric currents are the result of convection currents—from heat rising from the central core (Figure 24.21)—and that such convection currents combined with the rotational effects of Earth produce Earth's magnetic field. Because of Earth's great size, the speed of moving charges need only be about a millimeter per second to account for the field. A firmer explanation awaits more study.

Being certain about things is not science. The certitude responsible for disasters throughout history is absent in science. Scientists accept "not knowing" all the answers.

Whatever the cause, the magnetic field of Earth is not stable; it has wandered throughout geologic time. Evidence of this comes from the analysis of magnetic properties of rock strata. Iron atoms in a molten state are disoriented because of thermal motion, but a slight predominance of the iron atoms align with the magnetic field of Earth. When cooling and solidification occur, this predominance records the direction of Earth's magnetic field in the resulting igneous rock. It's similar for sedimentary rocks, where magnetic domains in grains of iron that settle in sediments tend to align themselves with Earth's magnetic field and become locked into the rock that forms. The slight magnetism that results can be measured with sensitive instruments. As samples of rock are tested from different strata formed throughout geologic time, the magnetic field of Earth for different periods can be charted. This evidence shows that there have been times when the magnetic field of Earth has diminished to zero, followed by reversal of the poles. More than 20 reversals have taken place in the past 5 million years. The most recent occurred 700,000 years ago. Prior reversals happened 870,000 and 950,000 years ago. Studies of deep-sea sediments indicate that the field was virtually switched off for 10,000 to 20,000 years just over 1 million years ago. We cannot predict when the next reversal will occur because the reversal sequence is not

FIGURE 24.21
Convection currents in the molten parts of Earth's interior may drive electric currents to produce Earth's magnetic field.

regular. But there is a clue in recent measurements that show a decrease of more than 5% of Earth's magnetic field strength in the last 100 years. If this change is maintained, we may well have another reversal within 2000 years.

The reversal of magnetic poles is not unique to Earth. The Sun's magnetic field reverses regularly, with a period of 22 years. This 22-year magnetic cycle has been linked, through evidence in tree rings, to periods of drought on Earth. Interestingly enough, the long-known, 11-year sunspot cycle is just half the time during which the Sun gradually reverses its magnetic polarity.

Like tape from a tape recorder, history of the ocean's bottom is preserved in a magnetic record.

Varying ion winds in Earth's atmosphere cause more rapid but much smaller fluctuations in Earth's magnetic field. Ions in this region are produced by the energetic interactions of solar ultraviolet rays and X-rays with atmospheric atoms. The motion of these ions produces a small but important part of Earth's magnetic field. Like the lower layers of air, the ionosphere is churned by winds. The variations in these winds are responsible for nearly all of the fast fluctuations in Earth's magnetic field. Interestingly, solar winds that reach Earth collide with Earth's magnetic field rather than with the atmosphere.

COSMIC RAYS

The universe is a shooting gallery of charged particles. They are called **cosmic rays** and consist of protons, alpha particles, and other atomic nuclei stripped of electrons, as well as high-energy electrons. The protons may be remnants of the Big Bang; the heavier nuclei probably boiled off from exploding stars. In any event, they travel through space at fantastic speeds and make up the cosmic radiation that is hazardous to astronauts. This radiation is intensified when the Sun is active and contributes added energetic particles. Cosmic rays are also a hazard to electronic instrumentation in space; impacts of cosmic-ray nuclei can cause computer memory bits to "flip" or small microcircuits to fail. Fortunately for those of us on Earth's surface, most of these charged particles don't reach us due to the thickness of the atmosphere. Cosmic rays are also deflected away by the magnetic field of Earth. Some of them are trapped in the outer reaches of Earth's magnetic field and make up the Van Allen radiation belts (Figure 24.22).

FIGURE 24.22
A cross section of the Van Allen radiation belts, shown here undistorted by the solar wind.

The Van Allen radiation belts consist of two doughnut-shaped rings about Earth, named after James A. Belts, who suggested their existence from data gathered by the U.S. satellite *Explorer I* in 1958.[7] The inner ring is centered about 3200 kilometers above Earth's surface, and the outer ring, which is a larger and wider doughnut, is centered about 16,000 kilometers overhead. Astronauts orbit at safe distances well below these belts of radiation. Most of the charged particles—protons and electrons—trapped in the outer belt probably come from the Sun. Storms on the Sun hurl charged particles out in great fountains, many of which pass near Earth and are trapped by its magnetic field. The trapped particles follow corkscrew paths around the magnetic field lines of Earth and bounce between Earth's magnetic poles high above the atmosphere. Disturbances in Earth's field often allow the ions to dip into the atmosphere, causing it to glow like a fluorescent lamp. This is the beautiful *aurora borealis* (or northern lights); in the Southern Hemisphere, it is an *aurora australis*.

The particles trapped in the inner belt probably originated from Earth's atmosphere. This belt gained newer electrons from high-altitude hydrogen-bomb explosions in 1962.

In spite of Earth's protective magnetic field, many "secondary" cosmic rays reach Earth's surface.[8] These are particles created when "primary" cosmic rays—those

FIGURE 24.23
The aurora borealis lighting of the sky caused by charged particles in the Van Allen belts striking atmospheric molecules.

[7]Actually, humor aside, the name is James A. Van Allen (with his permission).

[8]Some biological scientists speculate that Earth's magnetic changes played a significant role in the evolution of life forms. One hypothesis is that in the early phases of primitive life, Earth's magnetic field was strong enough to shield the delicate life forms from high-energy charged particles. But, during periods of zero strength, cosmic radiation and the spilling of the Van Allen belts increased the rate of mutation of more robust life forms—not unlike the mutations produced by X-rays in the famous heredity studies of fruit flies. Coincidences between the dates of increased life changes and the dates of the magnetic pole reversals in the last few million years lend support to this hypothesis.

coming from outer space—strike atomic nuclei high in the atmosphere. Cosmic-ray bombardment is greatest at the magnetic poles, because charged particles that hit Earth there do not travel *across* the magnetic field lines but, rather, *along* the field lines and are not deflected. Cosmic-ray bombardment decreases away from the poles, and it is smallest in equatorial regions. At middle latitudes, about five particles strike each square centimeter each minute at sea level; this number increases rapidly with altitude. So cosmic rays are penetrating your body as you are reading this—and even when you aren't reading this!

Biomagnetism

Certain bacteria biologically produce single-domain grains of magnetite (a compound equivalent to iron ore) that they string together to form internal compasses. They then use these compasses to detect the dip of Earth's magnetic field. Equipped with a sense of direction, the organisms are able to locate food supplies. Amazingly, those bacteria that live south of the equator build the same single-domain magnets as their counterparts that live north of the equator, but they align them in the opposite direction to coincide with the oppositely directed magnetic field in the Southern Hemisphere! Bacteria are not the only living organisms with built-in magnetic compasses: Pigeons have multiple-domain magnetite magnets within their skulls that are connected with a large number of nerves to the pigeon brain. Pigeons have a magnetic sense, and not only can they discern longitudinal directions along Earth's magnetic field, they can also detect latitude by the dip of Earth's field. Magnetic material is also in the abdomens of bees, whose behavior is affected by small magnetic fields. Some wasps, Monarch butterflies, sea turtles, and fish join the ranks of creatures with a magnetic sense. Magnetite crystals that resemble the crystals found in magnetic bacteria have been found in human brains. No one knows if these are linked to our sensations. Like the creatures mentioned above, we may share a common magnetic sense.

MRI: Magnetic Resonance Imaging

Magnetic resonance imaging (MRI) is a noninvasive way to provide high-resolution pictures of the tissues inside a body. Superconducting coils produce a strong magnetic field up to 60,000 times stronger than the intensity of Earth's magnetic field, which is used to align the protons of hydrogen atoms in the body of the patient.

Like electrons, protons have a "spin" property, so they will align with a magnetic field. Unlike a compass needle that aligns with Earth's magnetic field, the proton's axis wobbles about the applied magnetic field. Wobbling protons are slammed with a burst of radio waves tuned to push the proton's spin axis sideways, perpendicular to the applied magnetic field. When the radio waves pass and the protons quickly return to their wobbling pattern, they emit faint electromagnetic signals whose frequencies depend slightly on the chemical environment in which the proton resides. The signals, which are detected by sensors, are then analyzed by a computer to reveal varying densities of hydrogen atoms in the body and their interactions with surrounding tissue. The images clearly distinguish fluid and bone.

It is interesting to note that MRI was formerly called NMRI (nuclear magnetic resonance imaging), because hydrogen nuclei resonate with the applied fields. Because of public phobia of anything "nuclear," the devices are now called MRI scanners. Tell phobic friends that every atom in their bodies contains a nucleus!

SUMMARY OF TERMS

Magnetic force (1) Between magnets, it is the attraction of unlike magnetic poles for each other and the repulsion between like magnetic poles. (2) Between a magnetic field and a moving charged particle, it is a deflecting force due to the motion of the particle: The deflecting force is perpendicular to the velocity of the particle and perpendicular to the magnetic field lines. This force is greatest when the charged particle moves perpendicular to the field lines and is smallest (zero) when it moves parallel to the field lines.

Magnetic field The region of magnetic influence around a magnetic pole or a moving charged particle.

Magnetic domains Clustered regions of aligned magnetic atoms. When these regions themselves are aligned with one another, the substance containing them is a magnet.

Electromagnet A magnet whose field is produced by an electric current. It is usually in the form of a wire coil with a piece of iron inside the coil.

Cosmic rays Various high-speed particles that travel throughout the universe.

REVIEW QUESTIONS

Magnetism

1. By whom, and in what setting, was the relationship between electricity and magnetism discovered?

Magnetic Forces

2. The force between electrically charged particles depends on the magnitude of each charge, the distance of separation, and what else?
3. What is the source of magnetic force?

Magnetic Poles

4. Is the rule for the interaction between magnetic poles similar to the rule for the interaction between electrically charged particles?
5. In what way are *magnetic poles* very different from *electric charges?*

Magnetic Fields

6. How does magnetic field strength relate to the closeness of magnetic field lines about a bar magnet?
7. What produces a magnetic field?
8. What two kinds of rotational motion are exhibited by electrons in an atom?

Magnetic Domains

9. What is a magnetic domain?
10. At the micro level, what is the difference between an unmagnetized iron nail and a magnetized iron nail?
11. Why will dropping an iron magnet on a concrete sidewalk make it a weaker magnet?

Electric Currents and Magnetic Fields

12. In Chapter 22, we learned that the direction of the electric field about a point charge is radial to the charge. What is the direction of the magnetic field surrounding a current-carrying wire?
13. What happens to the direction of the magnetic field about an electric current when the direction of the current is reversed?
14. Why is the magnetic field strength greater inside a current-carrying loop of wire than about a straight section of wire?

Electromagnets

15. Why does a piece of iron in a current-carrying loop increase the magnetic field strength?
16. Why are the magnetic fields of superconducting magnets often stronger than those of conventional magnets?

Magnetic Force on Moving Charged Particles

17. In what direction relative to a magnetic field does a charged particle move in order to experience maximum deflecting force? Minimum deflecting force?

Magnetic Force on Current-Carrying Wires

18. What effect does Earth's magnetic field have on the intensity of cosmic rays striking Earth's surface?
19. What relative direction between a magnetic field and a current-carrying wire results in the greatest force?
20. How does a galvanometer detect electric current?
21. What is a galvanometer called when it has been calibrated to read current? When it has been calibrated to read voltage?
22. How often is current reversed in the loops of an electric motor?

Earth's Magnetic Field

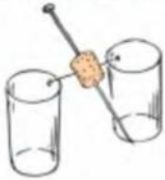
23. Why are there probably no permanently aligned magnetic domains in Earth's core?
24. What are *magnetic pole reversals?*

Biomagnetism

25. What is the cause of the aurora borealis (northern lights)?
26. Name at least six creatures that are known to harbor tiny magnets within their bodies.

PROJECTS

1. Find the direction and dip of Earth's magnetic field lines in your locality. Magnetize a large steel needle or a straight piece of steel wire by stroking it a couple of dozen times with a strong magnet. Run the needle or wire through a cork in such a way that, when the cork floats, your thin magnet remains horizontal (parallel to the water's surface). Float the cork in a plastic or wooden container of water. The needle will point toward the magnetic pole. Then press a pair of unmagnetized common pins into the sides of the cork. Rest the pins on the rims of a pair of drinking glasses so that the needle or wire points toward the magnetic pole. It should dip in line with Earth's magnetic field.



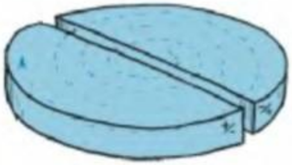
2. An iron bar can be easily magnetized by aligning it with the magnetic field lines of Earth and striking it lightly a few times with a hammer. This works best if the bar is tilted down to match the dip of Earth's field. The hammering jostles the domains so they are better able to fall into alignment with Earth's field. The bar can be demagnetized by striking it when it is oriented in an east-west direction.

EXERCISES

1. Many dry cereals are fortified with iron, which is added to the cereal in the form of small iron particles. How might these particles be separated from the cereal?
2. In what sense are all magnets electromagnets?
3. All atoms have moving electric charges. Why, then, aren't all materials magnetic?
4. To make a compass, point an ordinary iron nail along the direction of Earth's magnetic field (which, in the Northern Hemisphere, is angled downward as well as northward) and repeatedly strike it for a few seconds with a hammer or a rock. Then suspend it at its center of gravity by a string. Why does the act of striking magnetize the nail?
5. If you place a chunk of iron near the north pole of a magnet, attraction will occur. Why will attraction also occur if you place the same iron near the south pole of the magnet?
6. Do the poles of a horseshoe magnet attract each other? If you bend the magnet so that the poles get closer together, what happens to the force between the poles?
7. Why is it inadvisable to make a horseshoe magnet from a flexible material?
8. Your study buddy claims that an electron always experiences a force in an electric field, but not always in a magnetic field. Do you agree? Why or why not?
9. What kind of force field surrounds a stationary electric charge? What additional field surrounds it when it moves?
10. What is different about the magnetic poles of common refrigerator magnets and those of common bar magnets?
11. A friend tells you that a refrigerator door, beneath its layer of white-painted plastic, is made of aluminum. How could you check to see if this is true (without any scraping)?
12. Why will a magnet attract an ordinary nail or paper clip but not a wooden pencil?
13. Why aren't permanent magnets really permanent?
14. Will either pole of a magnet attract a paper clip? Explain what is happening inside the attracted paper clip. (*Hint:* Consider Figure 22.13.)
15. One way to make a compass is to stick a magnetized needle into a piece of cork and float it in a glass bowl full of water. The needle will align itself with the horizontal component of Earth's magnetic field. Since the north pole of this compass is attracted northward, will the needle float toward the north side of the bowl? Defend your answer.

16. A "dip needle" is a small magnet mounted on a horizontal axis so that it can swivel up or down (like a compass turned on its side). Where on Earth will a dip needle point most nearly vertically? Where on Earth will it point most nearly horizontally?
17. In what direction would a compass needle point, if it were free to point in all directions, when located near Earth's north magnetic pole in Canada?
18. What is the net magnetic force on a compass needle? By what mechanism does a compass needle align with a magnetic field?
19. Since the iron filings that align with the magnetic field of the bar magnet shown in Figure 24.2 are not solely little individual magnets, by what mechanism do they align themselves with the field of the magnet?
20. The north pole of a compass is attracted to the north magnetic pole of Earth, yet like poles repel. Can you resolve this apparent dilemma?
21. We know that a compass points northward because Earth is a giant magnet. Will the northward-pointing needle point northward when the compass is brought to the Southern Hemisphere?
22. Your friend says that, when a compass is taken across the equator, it turns around and points in the opposite direction. Your other friend says that this is not true, that people in the Southern Hemisphere use the south magnetic pole of the compass to point toward the nearest pole. You're on; what do you say?
23. In what position can a current-carrying loop of wire be located in a magnetic field so that it doesn't tend to rotate?
24. Magnet A has twice the magnetic field strength of magnet B (at equal distance) and, at a certain distance, it pulls on magnet B with a force of 50 N. With how much force, then, does magnet B pull on magnet A?
25. In Figure 24.15 we see a magnet exerting a force on a current-carrying wire. Does a current-carrying wire exert a force on a magnet? Why or why not?
26. A strong magnet attracts a paper clip to itself with a certain force. Does the paper clip exert a force on the strong magnet? If not, why not? If so, does it exert as much force on the magnet as the magnet exerts on it? Defend your answers.
27. A current-carrying wire is in a north-south orientation. When a compass needle is placed below or above it, in what direction does the compass needle point?

28. A loudspeaker consists of a cone attached to a current-carrying coil located in a magnetic field. What is the relationship between vibrations in the current and vibrations of the cone?
29. Will a superconducting magnet use less electric power than a traditional copper-wire electromagnet of the same field strength? Defend your answer.
30. When iron-hulled naval ships are built, the location of the shipyard and the orientation of the ship in the shipyard are recorded on a brass plaque permanently attached to the ship. Why?
31. A beam of electrons passes through a magnetic field without being deflected. What can you conclude about the orientation of the beam relative to the magnetic field? (Neglect any other fields.)
32. Can an electron at rest in a magnetic field be set into motion by the magnetic field? What if it were at rest in an electric field?
33. A proton moves in a circular path perpendicular to a constant magnetic field. If the field strength of the magnet is increased, does the diameter of the circular path increase, decrease, or remain the same?
34. A cyclotron is a device for accelerating charged particles to high speed as they follow an expanding spiral-like path. The charged particles are subjected to both an electric field and a magnetic field. One of these fields increases the speed of the charged particles, and the other field causes them to follow a curved path. Which field performs which function?



35. A magnet can exert a force on a moving charged particle, but it cannot change the particle's kinetic energy. Why not?
36. A beam of high-energy protons emerges from a cyclotron. Do you suppose that there is a magnetic field associated with these particles? Why or why not?
37. Two charged particles are projected into a magnetic field that is perpendicular to their velocities. If the particles are deflected in opposite directions, what does this tell you about them?
38. A magnetic field can deflect a beam of electrons, but it cannot do work on the electrons to change their speed. Why?
39. Inside a laboratory room there is said to be either an electric field or a magnetic field, but not both. What experiments might be performed to establish what kind of field is in the room?
40. Residents of northern Canada are bombarded by more intense cosmic radiation than residents of Mexico. Why is this so?
41. Why do astronauts keep to altitudes beneath the Van Allen radiation belts when doing space walks?
42. What changes in cosmic-ray intensity at Earth's surface would you expect during periods in which Earth's magnetic field passed through a zero phase while undergoing pole reversals?
43. In a mass spectrometer (Figure 34.14), ions are directed into a magnetic field, where they curve and strike a detector. If a variety of singly ionized atoms travel at the same speed through the magnetic field, would you expect them all to be deflected by the same amount, or would different ions be bent different amounts? Defend your answer.
44. One way to shield a habitat in outer space from cosmic rays is with an absorbing blanket of some kind, which would function much like the atmosphere that protects Earth. Speculate on a second way for shielding the habitat that would also be similar to Earth's natural shielding.
45. If you had two bars of iron—one magnetized and one unmagnetized—and no other materials at hand, how could you determine which bar was the magnet?

46. Historically, replacing dirt roads with paved roads reduced friction on vehicles. Replacing paved roads with steel rails reduced friction further. What recent step eliminates rail friction of vehicles? What friction remains after rail friction is eliminated?
47. Will a pair of parallel current-carrying wires exert forces on each other?
48. What is the magnetic effect of placing two wires with equal but oppositely directed currents close together or twisted about each other?
49. When a current is passed through a helically coiled spring, the spring contracts as if it's compressed. What's your explanation?
50. When preparing to undergo an MRI scan, why are patients advised to remove eyeglasses, watches, jewelry, and other metal objects?

CHAPTER 24 ONLINE RESOURCES

PhysicsPlace.com

Interactive Figures

- 24.2, 24.7, 24.15, 24.19

Tutorial

- Magnetic Fields

Videos

- Oersted's Discovery
- Magnetic Forces on Current-Carrying Wires

Quizzes

Flashcards

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25 Electromagnetic Induction

1 Jean Curtis prompts a check-your-neighbor discussion to explain why the copper ring levitates about the iron core of the electromagnet. 2 A common neighborhood transformer typically steps 2400 volts down to 240 volts for houses and small businesses. The 240 volts can divide to safer 120 volts. 3 Sheron Snyder converts mechanical energy into electromagnetic energy, which in turn, converts to light.

In previous times, most great scientific contributors were men of financial means. People with little or no money were too busy making a living to spend the time required for serious scientific inquiry. Michael Faraday was an exception.

Michael Faraday was one of four children of James Faraday, a village blacksmith in Southeast London. Michael had only a basic school education and was largely self-educated. At the age of 13 he became an apprentice to a local bookbinder and, during his seven-year apprenticeship, he read many books in the bindery. He became very interested in science, especially electricity. In 1812, at the end of his apprenticeship and then 20 years old, Faraday attended lectures by the world-renowned English chemist Sir Humphry Davy of the Royal Institution and Royal Society. Faraday took detailed notes, put them in book form, and sent Davy a more-than-300-page book of the lectures. Davy was most impressed and congratulated Faraday, although at first he advised him to stay in the bookbinding business. But the next year, when Davy's assistant was fired for fighting, Davy invited Faraday to take his place.

Michael Faraday (1791–1867)

In the class-based English society of the time, Faraday was not considered a gentleman. When Davy went on an 18-month tour to the continent with his new wife, Faraday went along but traveled outside the coach and ate with the servants because Davy's wife refused to treat him as an equal. Faraday nevertheless had an opportunity to meet Europe's scientific elite and gain a host of stimulating ideas.

Faraday went on to be one of the most important experimental scientists of the time. He made significant discoveries in chemistry, electrolysis, and mainly electricity and magnetism. In 1831, he made his most remarkable discovery. When he moved a magnet into loops of wire, electric current was induced in them. This is *electromagnetic induction*, coincidentally discovered at about the same time in America by Joseph Henry (the insulation for Henry's wire loops was tearfully donated by his wife, who sacrificed part of the silk from her wedding gown to cover the wires). At this time the only way of producing substantial electric current was with batteries. Electromagnetic induction ushered in the age of electricity.

Faraday's mathematical abilities were limited to simple algebra and did not extend as far as trigonometry. As a result, he conveyed his ideas pictorially and with simple language. He visualized electric and magnetic effects being conveyed by "lines of force." We now call them lines of electric and magnetic fields, and they remain useful tools in science and engineering.

Faraday refused to participate in the production of chemical weapons for the Crimean War, citing ethical reasons. He was deeply religious and met his wife, Sarah Barnard, while attending church. They had no children. He was elected to membership in prestigious societies and enjoyed high scientific status in his later years. He rejected knighthood and twice refused to be President of the Royal Society. He put great effort into service projects for private companies and the British government—increasing the safety of coal mines, new ways of operating lighthouses, and controlling pollution. Faraday was an original "green."

The unit of electrical capacitance, the farad, is named after Faraday. He died at the age of 75 in 1867. Before his death he turned down future burial in Westminster Abbey. A memorial plaque for him is there, near Isaac Newton's tomb. He was, instead, buried in a plot at the church he attended.

Electromagnetic Induction

Faraday and Henry both discovered that electric current can be produced in a wire simply by moving a magnet in or out of loops of wire without an additional voltage source (Figure 25.1). No battery or other voltage source is needed—only the motion of a magnet in a wire loop. This phenomenon of inducing voltage by changing the magnetic field in loops of wire is called **electromagnetic induction.** Voltage is caused, or *induced,* by the relative motion between a wire and a magnetic field—that is, whether the magnetic field of a magnet moves near a stationary conductor or the conductor moves in a stationary magnetic field (Figure 25.2).

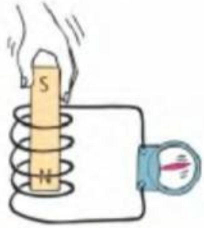


FIGURE 25.1
When the magnet is plunged into the coil, voltage is induced in the coil and charges in the coil are set in motion.

FIGURE 25.2
Voltage is induced in the wire loop either when the magnetic field moves past the wire or the wire moves through the magnetic field.

The greater the number of loops of wire that move in a magnetic field, the greater the induced voltage (Figure 25.3). Pushing a magnet into a coil with twice as many loops will induce twice as much voltage; pushing it into a coil with 10 times as many loops will induce 10 times as much voltage; and so on. It may seem that we get something (energy) for nothing simply by increasing the number of loops in a coil of wire. But, assuming that the coil is connected to a resistor or other energy-dissipating

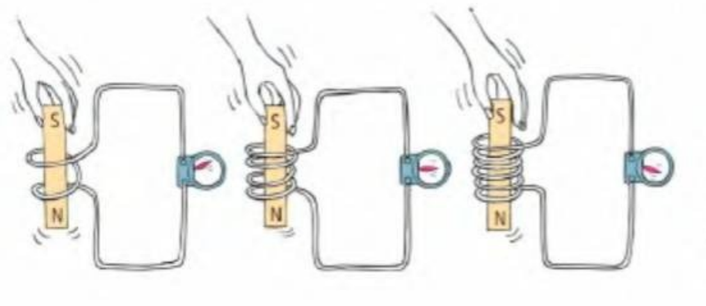


FIGURE 25.3
When a magnet is plunged into a coil of twice as many loops as another, twice as much voltage is induced. If the magnet is plunged into a coil with 3 times as many loops, then 3 times as much voltage is induced.

FIGURE 25.4

It is more difficult to push the magnet into a coil with more loops because the magnetic field of each current loop resists the motion of the magnet.

device, we don't. We find that it is more difficult to push the magnet into a coil made up of a greater number of loops.

This is because the induced voltage makes a current, which makes an electromagnet, which repels the magnet in our hand. More loops mean more voltage, which means we do more work to induce it (Figure 25.4). The amount of voltage induced depends on how fast the magnetic field lines are entering or leaving the coil. Very slow motion produces hardly any voltage at all. Quick motion induces a greater voltage.

Electromagnetic induction is all around us. On the road, it triggers traffic lights when a car drives over—and changes the magnetic field in—coils of wire beneath the road surface. Hybrid cars utilize it to convert braking energy into electric energy in their batteries. We sense electromagnetic induction in the security systems of airports as we walk through upright coils and, if we are carrying any significant quantities of iron, change the magnetic field of the coils and trigger an alarm. We use it with an ATM card when its magnetic strip is swiped through a scanner. As we shall see, at the end of this chapter and at the beginning of the following chapter, it even underlies the electromagnetic waves we call light.

CHECK POINT

Is electromagnetic induction (EMI) an energy source?

Check Your Answer

No. EMI is not a source of energy, but a method of transforming mechanical energy to electrical energy. Work must be done to produce energy by EMI.

Changing a magnetic field in a closed loop induces voltage. If the loop is in an electrical conductor, then current is induced.

Faraday's Law

Electromagnetic induction is summarized by **Faraday's law,** which states,[1]

The induced voltage in a coil is proportional to the product of its number of loops, the cross-sectional area of each loop, and the rate at which the magnetic field changes within those loops.

The amount of *current* produced by electromagnetic induction depends not only on the induced voltage but also on the resistance of the coil and the circuit to which it is connected.[2] For example, we can plunge a magnet in and out of a closed loop of rubber and in and out of a closed loop of copper. The voltage induced in each is the same, provided that the loops are the same size and the magnet moves with the same speed. But the current in each is quite different. Electrons in the rubber sense the same electric field as those in the copper, but their bonding to the fixed atoms prevents the movement of charge that so freely occurs in copper.

We have mentioned two ways in which voltage can be induced in a loop of wire: by moving the loop near a magnet or by moving a magnet near the loop. There is a

fyi

- Shake flashlights need no batteries. Shake the flashlight for 30 seconds or so and generate up to 5 minutes of bright illumination. Electromagnetic induction occurs as a built-in magnet slides to and fro between coils that charge a capacitor. When brightness diminishes, shake again. You provide the energy to charge the capacitor.

[1] In equation form,

$$\text{Voltage induced} \sim \text{number of loops} \times \text{area of each loop} \times \frac{\Delta\ \text{magnetic field}}{\Delta\ \text{time}}$$

[2] Current also depends on the "inductance" of the coil. Inductance measures the tendency of a coil to resist a change in current because the magnetism produced by one part of the coil acts to oppose the change of current in other parts of the coil. In ac circuits, it is akin to resistance, depending on the frequency of the ac source and the number of loops in the coil. We'll not cover this topic here.

third way, by changing a current in a nearby loop. All three cases possess the same essential ingredient—a changing magnetic field in the loop.

PhysicsPlace.com
Video
Faraday's Law

CHECK POINT

1. What happens when a magnetically stored bit of information on a computer disk spins under a reading head that contains a small coil?
2. If you push a magnet into a coil connected to a resistor, as shown in Figure 25.4, you'll feel a resistance to your push. Why is this resistance greater in a coil with more loops?

Check Your Answers

1. The changing magnetic field in the coil induces voltage. In this way, information stored magnetically on the disk is converted to electric signals.
2. Simply put, more work is required to provide more energy to be dissipated by more current in the resistor. You can also look at it this way: When you push a magnet into a coil, you cause the coil to become a magnet (an electromagnet). The more loops there are in the coil, the stronger the electromagnet that you produce and the stronger it pushes back against the magnet you are moving. (If the coil's electromagnet attracted your magnet instead of repelling it, energy would be created from nothing and the law of energy conservation would be violated. So the coil must repel your magnet.)

FIGURE 25.5
Guitar pickups are tiny coils with magnets inside them. The magnets magnetize the steel strings. When the strings vibrate, voltage is induced in the coils and boosted by an amplifier, and sound is produced by a speaker.

Generators and Alternating Current

When one end of a magnet is repeatedly plunged into and back out of a coil of wire, the direction of the induced voltage alternates. As the magnetic field strength inside the coil is increased (as the magnet enters the coil), the induced voltage in the coil is directed one way. When the magnetic field strength diminishes (as the magnet leaves the coil), the voltage is induced in the opposite direction. The frequency of the alternating voltage that is induced equals the frequency of the changing magnetic field within the loop.

It is more practical to induce voltage by moving a coil than it is by moving a magnet. This can be done by rotating the coil in a stationary magnetic field (Figure 25.6). This arrangement is called a **generator.** The construction of a generator is, in principle, identical to that of a motor. They look the same, but the roles of input and output are reversed. In a motor, electric energy is the input and mechanical energy is the output; in a generator, mechanical energy is the input and electric energy is the output. Both devices simply transform energy from one form to another.

PhysicsPlace.com
Video
Application of E & M Induction

It is interesting to compare the physics of a motor and a generator and to see that both operate according to the same underlying principle: that moving electrons experience a force that is mutually perpendicular to both their velocity and the magnetic

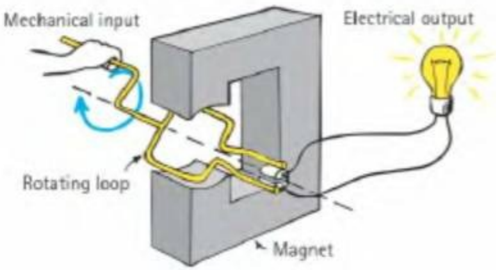


FIGURE 25.6
INTERACTIVE FIGURE
A simple generator. Voltage is induced in the loop when it is rotated in the magnetic field.

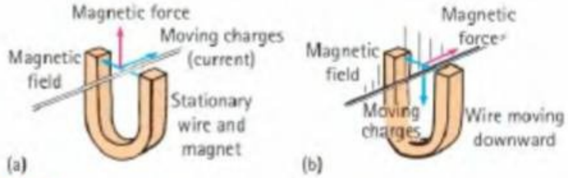


FIGURE 25.7

INTERACTIVE FIGURE

(a) Motor effect: When charge moves along the wire, there is a perpendicular upward force on the charge. Since there is no conducting path upward, the force on the charge tugs the wire upward. (b) Generator effect: When a wire with no initial current is moved downward, the charge in the wire experiences a deflecting force perpendicular to its motion. There is a conducting path in this direction, so the charge moves, constituting a current.

field they traverse (Figure 25.7). We will call the deflection of the wire (motion as a result of current) the *motor effect*, and we will call what happens as a result of the law of induction (current as a result of motion) the *generator effect*. These effects are summarized in (a) and (b) of the figure (where by convention, current and force arrows apply to positive charge). Study them. Can you see that the two effects are related?

We can see the electromagnetic induction cycle in Figure 25.8. Note that when the loop of wire is rotated in the magnetic field, there is a change in the number of magnetic field lines within the loop. When the plane of the loop is perpendicular to the field lines, the maximum number of lines is enclosed. As the loop rotates, it in effect chops the lines, so that fewer lines are enclosed. When the plane of the loop is parallel to the field lines, none are enclosed. Continued rotation increases and decreases the number of enclosed lines in cyclic fashion, with the greatest rate of change of field lines occurring when the number of enclosed field lines goes through zero. Hence, the induced voltage is greatest as the loop rotates through its parallel-to-the-lines orientation. Because the voltage induced by the generator alternates, the current produced is ac, an alternating current.[3] The alternating current in our homes is produced by generators standardized so that the current goes through 60 cycles of change each second—60 hertz.

When you step on the brakes in a hybrid car, the electric motor becomes a generator and charges a battery.

FIGURE 25.8

As the loop rotates, the induced voltage (and current) changes in magnitude and direction. One complete rotation of the loop produces one complete cycle in voltage (and in current).

CHECK POINT

When is work input necessary for energy output by electromagnetic induction?

Check Your Answer

Always.

[3]With appropriate brushes and by other means, the ac in the loop(s) can be converted to dc to make a dc generator.

Power Production

Fifty years after Michael Faraday and Joseph Henry discovered electromagnetic induction, Nikola Tesla and George Westinghouse put those findings to practical use and showed the world that electricity could be generated reliably and in sufficient quantities to light entire cities.

TURBOGENERATOR POWER

Tesla built generators much like those in operation today, but quite a bit more complicated than the simple model we have discussed. Tesla's generators had armatures—iron cores wrapped with bundles of copper wire—that were made to spin within strong magnetic fields by means of a turbine, which, in turn, was spun by the energy of steam or falling water. The rotating loops of wire in the armature cut through the magnetic field of the surrounding electromagnets, thereby inducing alternating voltage and current.

FIGURE 25.9
Steam drives the turbine, which is connected to the armature of the generator.

We can look at this process from an atomic point of view. When the wires in the spinning armature cut through the magnetic field, oppositely directed electromagnetic forces act on the negative and positive charges. Electrons respond to this force by momentarily swarming relatively freely in one direction throughout the crystalline copper lattice; the copper atoms, which are actually positive ions, are forced in the opposite direction. Because the ions are anchored in the lattice, however, they hardly move at all. Only the electrons move, sloshing back and forth in alternating fashion with each rotation of the armature. The energy of this electronic sloshing is tapped at the electrode terminals of the generator.

In making a great discovery, being at the right place at the right time is not enough—curiosity and hard work are also important.

MHD POWER

An interesting device similar to the turbogenerator is the MHD (magnetohydrodynamic) generator, which eliminates the turbine and spinning armature altogether. Instead of making charges move in a magnetic field via a rotating armature, a plasma of electrons and positive ions expands through a nozzle and moves at supersonic speed through a magnetic field. Like the armature in a turbogenerator, the motion of charges through a magnetic field gives rise to a voltage and flow of current in accordance with Faraday's law of induction. Whereas in a conventional generator "brushes" carry the current to the external load circuit, in the MHD generator the same function is performed by conducting plates, or *electrodes* (Figure 25.10). Unlike the turbogenerator, the MHD generator can operate at any temperature to which the plasma can be heated, either by combustion or nuclear processes.

The high temperature results in a high thermodynamic efficiency, which means more power for the same amount of fuel and less waste heat. Efficiency is further boosted when the "waste" heat is used to convert water into steam to run a conventional steam-turbine generator.

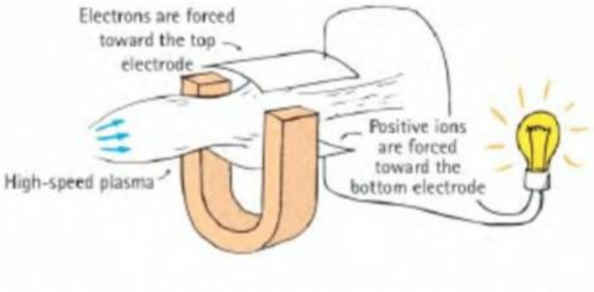


FIGURE 25.10

A simplified MHD generator. Oppositely directed forces act on the positive and negative particles in the high-speed plasma moving through the magnetic field. The result is a voltage difference between the two electrodes. Current then flows from one electrode to the other through an external circuit. There are no moving parts; only the plasma moves. In practice, superconducting electromagnets are used.

This substitution of a flowing plasma for rotating copper coils in a generator has become operational only since development of the technology to produce sufficiently high-temperature plasmas. Current plants use a high-temperature plasma formed by combustion of fossil fuels in air or oxygen.[4]

It's important to know that generators don't produce energy—they simply convert energy from some other form to electric energy. As we discussed in Chapter 7, energy from a source, whether fossil or nuclear fuel or wind or water, is converted to mechanical energy to drive the turbine. The attached generator converts most of this mechanical energy to electrical energy. Some people think that electricity is a primary source of energy. It is not. It is a carrier of energy that requires a source.

TRANSFORMERS

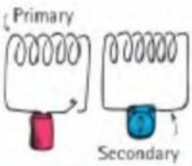


FIGURE 25.11

Whenever the primary switch is opened or closed, voltage is induced in the secondary circuit.

Electric energy can certainly be carried along wires, and now we'll see how it can be carried across empty space. Energy can be transferred from one device to another with the simple arrangement shown in Figure 25.11. Note that one coil is connected to a battery and the other is connected to a galvanometer. It is customary to refer to the coil connected to the power source as the *primary* (input) and to the other as the *secondary* (output). As soon as the switch is closed in the primary and current passes through its coil, a current occurs in the secondary also—even though there is no material connection between the two coils. Only a brief surge of current occurs in the secondary, however. Then, when the primary switch is opened, a surge of current again registers in the secondary, but in the opposite direction.

This is the explanation: A magnetic field builds up around the primary when the current begins to flow through the coil. This means that the magnetic field is growing (that is, *changing*) about the primary. But, since the coils are near each other, this changing field extends into the secondary coil, thereby inducing a voltage in the secondary. This induced voltage is only temporary, for when the current and the magnetic field of the primary reach a steady state—that is, when the magnetic field is no longer changing—no further voltage is induced in the secondary. But, when the switch is turned off, the current in the primary drops to zero. The magnetic field about the coil collapses, thereby inducing a voltage in the secondary coil, which senses the change. We see that voltage is induced whenever a magnetic field is *changing* through the coil, regardless of the reason.

[4]Lower temperatures are sufficient when the electrically conducting fluid is liquid metal, usually lithium. A liquid-metal MHD power system is referred to as a LMMHD power system.

CHECK POINT

When the switch of the primary in Figure 25.11 is opened or closed, the galvanometer in the secondary registers a current. But when the switch remains closed, no current is registered on the galvanometer of the secondary. Why?

Check Your Answer

When the switch remains in the closed position, there is a steady current in the primary and a steady magnetic field about the coil. This field extends to the secondary, but unless there is a *change* in the field, electromagnetic induction does not occur.

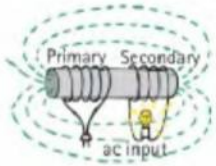
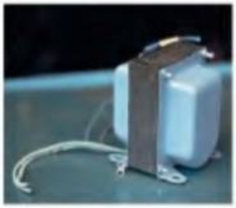


FIGURE 25.12
A simple transformer.

If you place an iron core inside the primary and secondary coils of the arrangement of Figure 25.11, the magnetic field within the primary is intensified by the alignment of magnetic domains. The field is also concentrated in the core and extends into the secondary, which intercepts more of the field change. The galvanometer will show greater surges of current when the switch of the primary is opened or closed. Instead of opening and closing a switch to produce the change of magnetic field, suppose that alternating current is used to power the primary. Then the frequency of periodic changes in the magnetic field is equal to the frequency of the alternating current. Now we have a **transformer** (Figure 25.12). A more efficient arrangement is shown in Figure 25.13.

If the primary and secondary have equal numbers of wire loops (usually called *turns*), then the input and output alternating voltages will be equal. But if the secondary coil has more turns than the primary, the alternating voltage produced in the secondary coil will be greater than that produced in the primary. In this case, the voltage is said to be *stepped up*. If the secondary has twice as many turns as the primary, the voltage in the secondary will be double that of the primary.

We can see this with the arrangements in Figure 25.14. First consider the simple case of a single primary loop connected to a 1-volt alternating source, and a single secondary loop connected to the ac voltmeter (a). The secondary intercepts the changing magnetic field of the primary, and a voltage of 1 V is induced in the secondary. If another loop is wrapped around the core so that the transformer has two secondaries (b), it intercepts the same magnetic field change. We see that 1 V is induced in it also. There is no need to keep both secondaries separate, for we could join them (c) and still have a total induced voltage of 1 V + 1 V, or 2 V. This is equivalent to saying that a voltage of 2 V will be induced in a single secondary that has twice the number of loops as the primary. If the secondary is wound with 3 times as many loops, then 3 times as much voltage will be induced. Stepped-up voltage may light a neon sign or send power over a long distance.



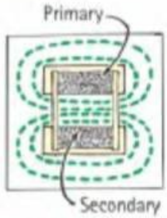


FIGURE 25.13
A practical and more efficient transformer. Both primary and secondary coils are wrapped on the inner part of the iron core (yellow), which guides alternating magnetic lines (green) produced by ac in the primary. The alternating field induces ac voltage in the secondary. Thus power at one voltage from the primary is transferred to the secondary at a different voltage.

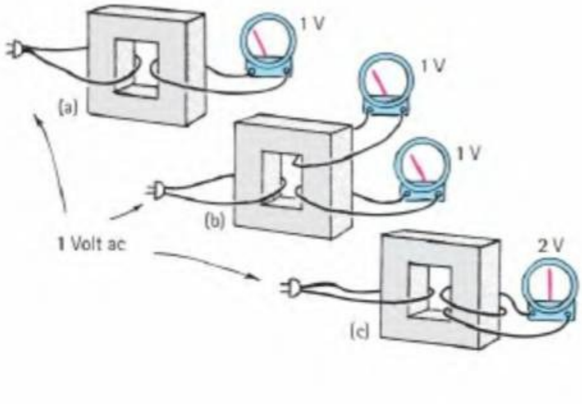


FIGURE 25.14
(a) The voltage of 1 V induced in the secondary equals the voltage of the primary. (b) A voltage of 1 V is also induced in the added secondary because it intercepts the same magnetic field change from the primary. (c) The voltages of 1 V each induced in the two one-turn secondaries are equivalent to a voltage of 2 V induced in a single two-turn secondary.

If the secondary has fewer turns than the primary, the alternating voltage produced in the secondary will be *lower* than that produced in the primary. The voltage is said to be *stepped down*. This stepped-down voltage may safely operate a toy electric train. If the secondary has half as many turns as the primary, then only half as much voltage is induced in the secondary. So electric energy can be fed into the primary at a given alternating voltage and taken from the secondary at a greater or lower alternating voltage, depending on the relative number of turns in the primary and secondary coil windings. The relationship between primary and secondary voltages with respect to the relative number of turns is given by

$$\frac{\text{Primary voltage}}{\text{Number of primary turns}} = \frac{\text{secondary voltage}}{\text{number of secondary turns}}$$

It might seem that we get something for nothing with a transformer that steps up the voltage. Not so, for energy conservation always regulates what can happen. When voltage is stepped up, current in the secondary is less than in the primary. The transformer actually transfers energy from one coil to the other. Make no mistake about this point: It can in no way step up energy—a conservation of energy no-no. A transformer steps voltage up or down without a change in energy. The rate at which energy is transferred is called *power*. The power used in the secondary is supplied by the primary. The primary gives no more than the secondary uses, in accord with the law of conservation of energy. If the slight power losses due to heating of the core are neglected, then

$$\text{Power into primary} = \text{power out of secondary}$$

Electric power is equal to the product of voltage and current, so we can say

$$(\text{Voltage} \times \text{current})_{\text{primary}} = (\text{voltage} \times \text{current})_{\text{secondary}}$$

We see that if the secondary has more voltage than the primary, it will have less current than the current in the primary. The ease with which voltages can be stepped up or down with a transformer is the principal reason that most electric power is ac rather than dc.

CHECK POINT

1. If 100 V of ac is put across a 100-turn transformer primary, what will be the voltage output if the secondary has 200 turns?
2. Assuming the answer to the previous question is 200 V, and the secondary is connected to a flood lamp with a resistance of 50 Ω, what will be the ac current in the secondary circuit?
3. What is the power in the secondary coil?
4. What is the power in the primary coil?
5. What is the ac current drawn by the primary coil?
6. The voltage has been stepped up, and the current has been stepped down. Ohm's law says that increased voltage will produce increased current. Is there a contradiction here, or does Ohm's law not apply to circuits that have transformers?

Check Your Answers

1. From $\frac{100\text{ V}}{100\text{ primary turns}} = \frac{x\text{ V}}{200\text{ secondary turns}}$, you should see that $x = 200$ V.
2. From Ohm's law, 200 V/50 Ω = 4 A.
3. Power = voltage × current = 200 V × 4 A = 800 W.
4. By the law of conservation of energy, the power in the primary is the same, 800 W.

5. 8 A, twice as much (100 V × ? A = 800 W).
6. Ohm's law remains alive and well. The voltage induced across the secondary circuit divided by the load (resistance) of the secondary circuit equals the current in the secondary circuit. In the primary circuit, on the other hand, there is no conventional resistance. What "resists" the current in the primary is the transfer of energy to the secondary.

Self-Induction

Current-carrying loops in a coil interact not only with loops of other coils but also with loops of the same coil. Each loop in a coil interacts with the magnetic field around the current in other loops of the same coil. This is *self-induction*. A self-induced voltage is produced. This voltage is always in a direction opposing the changing voltage that produces it and is commonly called the "back electromotive force," or simply "back emf."[5] We won't treat self-induction and back emfs here, except to acknowledge a common and dangerous effect.

Suppose that a coil with a large number of turns is used as an electromagnet and is powered with a dc source, perhaps a small battery. Current in the coil is then accompanied by a strong magnetic field. When we disconnect the battery by opening a switch, we had better be prepared for a surprise. When the switch is opened, the current in the circuit falls rapidly to zero and the magnetic field in the coil undergoes a sudden decrease (Figure 25.15). What happens when a magnetic field suddenly changes in a coil, even if it is the same coil that produced it? The answer is that a voltage is induced. The rapidly collapsing magnetic field with its store of energy may induce an enormous voltage, large enough to develop a strong spark across the switch—or to you, if you are opening the switch! For this reason, electromagnets are connected to a circuit that absorbs excess charge and prevents the current from dropping too suddenly. This reduces the self-induced voltage. This is also, by the way, why you should disconnect appliances by turning off the switch, not by pulling out the plug. The circuitry in the switch may prevent a sudden change in current.

FIGURE 25.15
When the switch is opened, the magnetic field of the coil collapses. This sudden change in the field can induce a huge voltage.

Power Transmission

Almost all electric energy sold today is in the form of ac, traditionally because of the ease with which it can be transformed from one voltage to another.[6] Large currents in wires produce heat and energy losses, so power is transmitted great distances at high voltages and correspondingly low currents (power = voltage × current). Power is generated at 25,000 V or less and is stepped up near the power station to as much as 750,000 V for long-distance transmission, then stepped down in stages at substations and distribution points to voltages needed in industrial applications (often 440 V or more) and for the home (240 and 120 V).

Note transformers on utility poles in your neighborhood. They are the go-between from power stations to individual consumers, often humming as they do their thing.

[5] The opposition of an induced effect to an inducing cause is called *Lenz's law*; it is a consequence of the conservation of energy.

[6] Nowadays, power utilities can transform dc voltages using semiconductor technology. Keep an eye on the present advances in superconductor technology, and watch for resulting changes in power transmission.

FIGURE 25.16
Power transmission.

Energy, then, is transferred from one system of conducting wires to another by electromagnetic induction. It is but a short step further to find that the same principles account for eliminating wires and sending energy from a radio-transmitter antenna to a radio receiver many kilometers away. Extend these principles just a tiny step further to the transformation of the energy of vibrating electrons in the Sun to life energy on Earth. The effects of electromagnetic induction are very far-reaching.

Field Induction

Electromagnetic induction explains the induction of voltages and currents. Actually, the more basic *fields* are at the root of both voltages and currents. The modern view of electromagnetic induction states that electric and magnetic fields are induced. These, in turn, produce the voltages we have considered. So induction occurs whether or not a conducting wire or any material medium is present. In this more general sense, Faraday's law states:

An electric field is induced in any region of space in which a magnetic field is changing with time.

200 years ago, people got light from whale oil. Whales should be glad that humans discovered how to harness electricity!

There is a second effect, an extension of Faraday's law. It is the same except that the roles of electric and magnetic fields are interchanged. It is one of nature's many symmetries. This effect was advanced by the British physicist James Clerk Maxwell in about 1860 and is known as **Maxwell's counterpart to Faraday's law:**

A magnetic field is induced in any region of space in which an electric field is changing with time.

Electromagnetic waves scarcely ever interact with each other. The space around you is filled with radio waves, TV signals, cell-phone messages, and light, each "doing its own thing" and ignoring all the others. How fortunate for us.

In each case, the strength of the induced field is proportional to the rate of change of the inducing field. Induced electric and magnetic fields are at right angles to each other.

Maxwell saw the link between electromagnetic waves and light.[7] If electric charges are set into vibration in the range of frequencies that match those of light, waves are produced that *are* light! Maxwell discovered that light is simply electromagnetic waves in the range of frequencies to which the eye is sensitive.

Because of electromagnetic induction, the energy of elevated rivers has been harnessed, turned to electricity, and transported to distant cities. The advent of motors, generators, and transformers occurred at about the time the American Civil War was being fought. From a long view of human history, there can be little doubt that events such as the American Civil War will pale into provincial insignificance in comparison with the more significant event of the 19th century: the discovery and implementation of the electromagnetic laws.

[7]On the eve of his discovery, story has it that Maxwell had a date with a young woman he was later to marry. While walking in a garden, his date remarked about the beauty and wonder of the stars. Maxwell asked how she would feel to know that she was walking with the only person in the world who knew what starlight really was. For it was true. At that time, James Clerk Maxwell was the only person in the world to know that light of any kind is energy carried in waves of electric and magnetic fields that continually regenerate each other.

SUMMARY OF TERMS

Electromagnetic induction The induction of voltage when a magnetic field changes with time. If the magnetic field within a closed loop changes in any way, a voltage is induced in the loop:

$$\text{Voltage induced} \sim \text{area of loop} \times \frac{\Delta \text{ magnetic field}}{\Delta \text{ time}}$$

This is a statement of Faraday's law. (If multiple loops are connected together in a coil, the voltage induced is multiplied by the number of loops.) The induction of voltage is actually the result of a more fundamental phenomenon: generally, the induction of an electric *field*.

Faraday's law An electric field is created in any region of space in which a magnetic field is changing with time. The magnitude of the induced electric field is proportional to the rate at which the magnetic field changes. The direction of the induced field is at right angles to the changing magnetic field.

Generator An electromagnetic induction device that produces electric current by rotating a coil within a stationary magnetic field. A generator converts mechanical energy to electrical energy.

Transformer A device for transferring electric power from one coil of wire to another, by means of electromagnetic induction, for the purpose of transforming one value of voltage to another.

Maxwell's counterpart to Faraday's law A magnetic field is created in any region of space in which an electric field is changing with time. The magnitude of the induced magnetic field is proportional to the rate at which the electric field changes. The direction of the induced magnetic field is at right angles to the changing electric field.

REVIEW QUESTIONS

Electromagnetic Induction

1. Exactly what did Michael Faraday and Joseph Henry discover?
2. What must change in order for electromagnetic induction to occur?

Faraday's Law

3. In addition to induced voltage, on what does the current produced by electromagnetic induction depend?
4. What are the three ways in which voltage can be induced in a wire?

Generators and Alternating Current

5. How does the frequency of induced voltage relate to how frequently a magnet is plunged in and out of a coil of wire?
6. What is the basic *similarity* between a generator and an electric motor? What is the basic *difference* between them?
7. Where in the rotation cycle of a simple generator is the induced voltage at a maximum?
8. Why does a generator produce alternating current?

Power Production

9. Who discovered electromagnetic induction, and who put it to practical use?
10. What is an armature?
11. What commonly supplies the energy input to a turbine?
12. What are the principal differences between an *MHD generator* and a *conventional generator*?
13. Does an MHD generator employ Faraday's law of induction?
14. Electric energy can certainly be carried along wires, but can it be carried across empty space? If so, how?
15. Why does a transformer require ac?
16. What name is given to the rate at which energy is transferred?
17. What is the principal advantage of ac over dc?

Self-Induction

18. When the magnetic field changes in a coil of wire, voltage in each loop of the coil is induced. Will voltage be induced in a loop if the source of the magnetic field is the coil itself?

Power Transmission

19. What is the purpose of transmitting power at high voltages over long distances?
20. Does the transmission of electric energy require electrical conductors between the source and receiver? Cite an example to defend your answer.

Field Induction

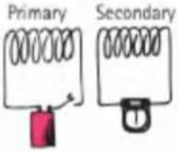
21. What is induced by the rapid alternation of a *magnetic field*?
22. What is induced by the rapid alternation of an *electric field*?

PROJECT

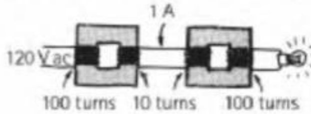
1. Drop a small magnet through a vertical plastic pipe, noting its speed of fall. Then do the same with a copper pipe. Explain why the magnet falls much slower in the copper pipe.
2. Write a letter to Grandma and tell her the answer to what has been a mystery for centuries—what light is. Tell her how light is related to electricity and magnetism.

EXERCISES

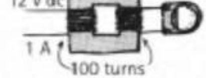
1. Why does the word *change* occur so frequently in this chapter?
2. A common pickup for an electric guitar consists of a coil of wire around a small permanent magnet, as described in Figure 25.5. Why will this type of pickup fail with nylon strings?
3. Why does an iron core increase the magnetic induction of a coil of wire?
4. Why are the armature and field windings of an electric motor usually wound on an iron core?
5. Why is a generator armature harder to rotate when it is connected to a circuit and supplying electric current?
6. Why does a motor also tend to act as a generator?
7. Will a cyclist coast farther if the lamp connected to the generator on his bicycle is turned off? Explain.
8. When an automobile moves over a wide, closed loop of wire embedded in a road surface, is the magnetic field of Earth within the loop altered? Is a pulse of current produced? Can you cite a practical application for this at a traffic intersection?
9. At the security area, people walk through a large coil of wire and through a weak ac magnetic field. What is the result of a small piece of metal on a person that slightly alters the magnetic field in the coil?
10. A piece of plastic tape coated with iron oxide is magnetized more in some parts than in others. When the tape is moved past a small coil of wire, what happens in the coil? What is a practical application of this?
11. Joseph Henry's wife donated part of her silk wedding gown to cover the wires of Joseph's electromagnets. What was the purpose of the silk covering?
12. A certain simple earthquake detector consists of a little box firmly anchored to Earth. Suspended inside the box is a massive magnet that is surrounded by stationary coils of wire fastened to the box. Explain how this device works, applying two important principles of physics—one studied in Chapter 2 and the other in this chapter.
13. How do the direction of the magnetic force and its effects differ between the motor effect and the generator effect, as shown in Figure 25.7?
14. When you turn the shaft of an electric motor by hand, what occurs in the interior coils of wire?
15. Your friend says that if you crank the shaft of a dc motor manually, the motor becomes a dc generator. Do you agree or disagree?
16. Does the voltage output increase when a generator is made to spin faster? Defend your answer.
17. If you place a metal ring in a region in which a magnetic field is rapidly alternating, the ring may become hot to your touch. Why?
18. An electric saw operating at normal speed draws a relatively small current. But if a piece of wood being sawed jams and the motor shaft is prevented from turning, the current dramatically increases and the motor overheats. Why?
19. A magician places an aluminum ring on a table with a hidden electromagnet underneath. When the magician says "abracadabra" (and pushes a switch that starts current flowing through the coil under the table), the ring jumps into the air. Explain his "trick."
20. In the chapter-opening photograph, Jean Curtis asks her class why the copper ring levitates about the iron core of the electromagnet. What is the explanation, and does it involve ac or dc?
21. How could a lightbulb near an electromagnet, but not touching it, be lit? Is ac or dc required? Defend your answer.
22. A length of wire is bent into a closed loop and a magnet is plunged into it, inducing a voltage and, consequently, a current in the wire. A second length of wire, twice as long, is bent into two loops of wire, and a magnet is similarly plunged into it. Twice the voltage is induced, but the current is the same as that produced in the single loop. Why?
23. Two separate but similar coils of wire are mounted close to each other, as shown. The first coil is connected to a battery and has a direct current flowing through it. The second coil is connected to a galvanometer.



    a. How does the galvanometer respond when the switch in the first circuit is closed?
    b. After being closed, how does the meter respond when the current is steady?
    c. How does the meter respond when the switch is opened?
24. Why will more voltage be induced with the apparatus shown above if an iron core is inserted in the coils?
25. Why will a transformer not work if you are using dc?
26. How does the current in the secondary of a transformer compare with the current in the primary when the secondary voltage is twice the primary voltage?
27. In what sense can a transformer be considered an electrical lever? What does it multiply? What does it *not* multiply?
28. What is the principal difference between a step-up transformer and a step-down transformer?
29. Why can a hum usually be heard when a transformer is operating?
30. Why doesn't a transformer work with direct current? Why is ac required?
31. Why is it important that the core of a transformer pass through both coils?
32. Are the primary and secondary coils in a transformer physically linked, or is there space between the two? Explain.
33. In the circuit shown, how many volts are impressed across the lightbulb and how many amps flow through it?



34. In the circuit shown, how many volts are impressed across the meter and how many amps flow through it?

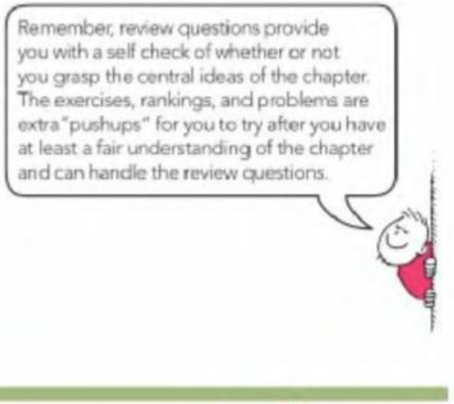


35. How would you answer the previous question if the input were 12 V ac?
36. Your friend says that according to Ohm's law, high voltage produces high current. Then your friend asks, "So how can power be transmitted at high voltage and *low* current in a power line?" What is your illuminating response?

37. Can an efficient transformer step up energy? Defend your answer.
38. If a bar magnet is thrown into a coil of high-resistance wire, it will slow down. Why?
39. Your physics instructor drops a magnet through a long vertical copper pipe and it moves slowly compared with the drop of a nonmagnetized object. Provide an explanation.
40. This exercise is similar to the previous one. Why will a bar magnet fall slower and reach terminal velocity in a vertical copper or aluminum tube but not in a cardboard tube?
41. Although copper and aluminum are not magnetic, why is a sheet of either metal more difficult to pass between the pole pieces of a magnet than a sheet of cardboard?
42. A metal bar, pivoted at one end, oscillates freely in the absence of a magnetic field. But when it oscillates between the poles of a magnet, its oscillations are quickly damped. Why? (Such magnetic damping is used in a number of practical devices.)
43. The metal wing of an airplane acts like a "wire" flying through Earth's magnetic field. A voltage is induced between the wing tips, and a current flows along the wing, but only for a short time. Why does the current stop even though the airplane continues flying through Earth's magnetic field?
44. What is wrong with this scheme? To generate electricity without fuel, arrange a motor to operate a generator that will produce electricity that is stepped up with transformers so that the generator can operate the motor and simultaneously furnish electricity for other uses.
45. We know that the source of a sound wave is a vibrating object. What is the source of an electromagnetic wave?
46. With no magnets in the vicinity, why will current flow in a large coil of wire waved around in the air?
47. What does an incident radio wave do to the electrons in a receiving antenna?
48. How do you suppose the frequency of an electromagnetic wave compares with the frequency of the electrons it sets into oscillation in a receiving antenna?
49. A friend says that changing electric and magnetic fields generate one another and that this gives rise to visible light when the frequency of change matches the frequencies of light. Do you agree? Explain.
50. Would electromagnetic waves exist if changing magnetic fields could produce electric fields, but changing electric fields could not, in turn, produce magnetic fields? Explain.

PROBLEMS

1. The primary coil of a step-up transformer draws 100 W. How much power is provided by the secondary coil?
2. An ideal transformer has 50 turns in its primary and 250 turns in its secondary. 12 V ac is connected to the primary.
   a. Find the volts ac available at the secondary.
   b. Show that a 10-Ω device connected to the secondary draws a current of 6 A.
   c. How much power is supplied to the primary?
3. A model electric train requires 6 V to operate. If the primary coil of its transformer has 240 windings, how many windings should the secondary have if the primary is connected to a 120-V household circuit?
4. Neon signs require about 12,000 V for their operation. What should be the ratio of the number of loops in the secondary to the number of loops in the primary for a neon-sign transformer that operates from 120-V lines?
• 5. 100 kW (10^5 W) of power is delivered to the other side of a city by a pair of power lines between which the voltage is 12,000 V.
   a. How much current is carried in the lines?
   b. Each of the two lines has a resistance of 10 Ω. What is the voltage difference between the two ends of each line? (Think carefully. This voltage is not that between the two lines.)
   c. What power is wasted as heat in both lines together (distinct from power delivered to customers)? How does this compare with the power being delivered?



CHAPTER 25 ONLINE RESOURCES

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- 25.6, 25.7

Videos
- Faraday's Law
- Application of E&M Induction

Quizzes

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PART FIVE MULTIPLE-CHOICE PRACTICE EXAM

Choose the BEST answer to the following:

1. The electrical force of attraction between an electron and a proton is greater on the
   (a) proton. (b) electron. (c) Neither; both are the same.
2. When you brush your hair and scrape electrons from your hair, the charge of your hair becomes
   (a) positive. (b) negative. (c) Both of these. (d) Neither of these.
3. According to Coulomb, a pair of charged particles placed twice as close to each other experience a force
   (a) twice as strong. (b) 4 times as strong. (c) 1/2 as strong. (d) 1/4 as strong.
4. When you buy a pipe in a hardware store, the water isn't included. When you buy copper wire, electrons
   (a) must be supplied by you.
   (b) are included in the wire.
   (c) may fall out; hence, insulation.
   (d) None of these.
5. Immediately after two separated charged particles are released from rest, both increase in *speed*. The sign of charge of the particles is therefore
   (a) the same. (b) opposite. (c) Either of these. (d) Need more information.
6. Immediately after two separated charged particles are released from rest, both increase in *acceleration*. The sign of charge of the particles is therefore
   (a) the same. (b) opposite. (c) Either of these. (d) Need more information.
7. The electric field between a pair of oppositely charged parallel plates
   (a) gets weaker with distance inside the plates.
   (b) follows the inverse-square law.
   (c) Both of these.
   (d) Neither of these.
8. A capacitor can store
   (a) charge. (b) energy. (c) Both of these. (d) Neither of these.
9. The electric field inside the dome of a Van de Graaff generator is zero when the dome is
   (a) charged. (b) uncharged. (c) Either of these. (d) Neither of these.
10. The potential energy of a compressed spring and the potential energy of a charged object both depend on
    (a) the work done on them. (b) motion. (c) Both of these. (d) Neither of these.
11. To receive an electric shock there must be a
    (a) current in one direction.
    (b) presence of moisture.
    (c) high voltage and low body resistance.
    (d) voltage difference across part or all of your body.
12. A 10-Ω resistor carries 10 A. The voltage across the resistor is
    (a) 0. (b) more than 0 but less than 10 V. (c) 10 V. (d) more than 10 V.
13. If the current in the filament of a lamp is 3 A, the current in the connecting wire is
    (a) less than 3 A. (b) 3 A. (c) more than 3 A. (d) Not enough information to say.
14. The difference between dc and ac in electrical circuits is that in dc, charges flow
    (a) steadily in one direction. (b) in one direction. (c) to and fro. (d) All of these.
15. As more lamps are connected to a series circuit, the current in the power source
    (a) increases. (b) decreases. (c) remains the same. (d) None of these.
16. In a series circuit, if the current in one lamp is 2 A, the current in the lamp next to it is
    (a) half, 1 A.
    (b) 2 A.
    (c) Depends on which lamp is closer to the battery.
    (d) Not enough information to say.
17. As more lamps are connected in parallel in a circuit, the current in the power source
    (a) increases. (b) decreases. (c) remains the same. (d) Not enough information to say.
18. In a circuit of two lamps in parallel, if the current in one lamp is 2 A, the current in the other lamp is
    (a) about 1 A.
    (b) 2 A.
    (c) Depends on which lamp is closer to the battery.
    (d) Not enough information to say.
19. An electron can be speeded up by
    (a) an electric field. (b) a magnetic field. (c) Both of these. (d) Neither of these.
20. The magnetic field lines about a current-carrying wire form
    (a) circles. (b) radial lines. (c) eddy currents. (d) energy loops.
21. A magnetic force can act on an electron even when it
    (a) is at rest. (b) moves parallel to magnetic field lines. (c) Both of these. (d) Neither of these.
22. A magnetic force acting on a beam of electrons can change its
    (a) direction. (b) energy. (c) Both of these. (d) Neither of these.
23. A galvanometer can be calibrated to read electric
    (a) current. (b) voltage. (c) Either of these. (d) Neither of these.
24. A motor and a generator are
    (a) similar devices. (b) very different devices. (c) forms of transformers. (d) energy sources.
25. The metal detectors people walk through at airports operate via
    (a) Ohm's law. (b) Faraday's law. (c) Coulomb's law. (d) Newton's laws.
26. If you change the magnetic field in a closed loop of wire, what is created in the loop is a(n)
    (a) current. (b) voltage. (c) electric field. (d) All of these.
27. A voltage will be induced in a wire loop when the magnetic field within that loop
    (a) changes.
    (b) aligns with the electric field.
    (c) is at right angles to the electric field.
    (d) converts to magnetic energy.
28. A step-up transformer in an electrical circuit can step up
    (a) voltage. (b) energy. (c) Both of these. (d) Neither of these.
29. Compared with power input, the power output of an ideal transformer is
    (a) greater. (b) less. (c) the same. (d) Any of these.
30. Electricity and magnetism connect to form
    (a) mass. (b) energy. (c) ultra-high-frequency sound. (d) light.

After you have made thoughtful choices, and discussed them with your friends, find the answers on page 681.

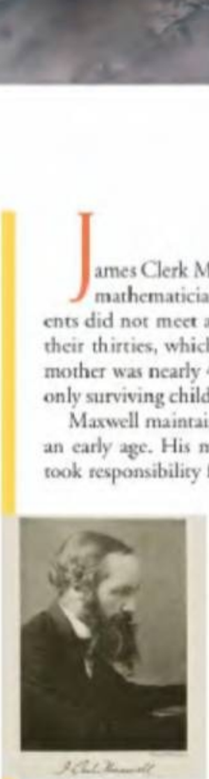
Part Six
Light

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.

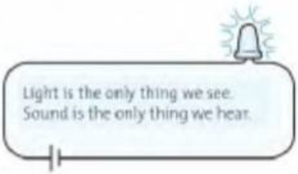
At age 18, Maxwell contributed two papers to the Royal Society of Edinburgh. Although the work was impressive, as with his schoolboy paper on oval curves, he was considered too young to stand at the rostrum and make the presentation himself. Maxwell's papers were instead delivered by his tutor.

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.

FIGURE 26.1

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

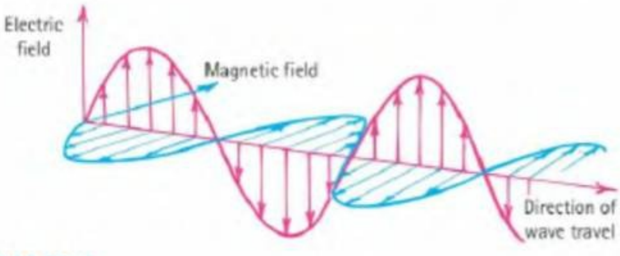


FIGURE 26.2

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

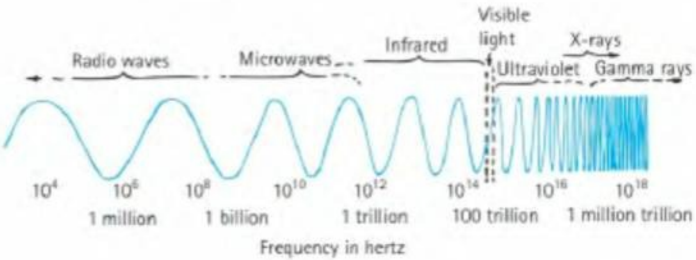

FIGURE 26.3

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.

[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.

[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.

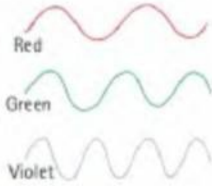

FIGURE 26.4

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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Video
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.

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.

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

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.

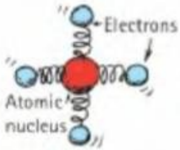

FIGURE 26.6
The spring model of light. The electrons of atoms in glass have certain natural frequencies of vibration and behave as if they were connected to the atomic nucleus by springs.

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

[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 $0.75c$. In glass, light travels at about $0.67c$, depending on the type of glass. In a diamond, light travels at less than half its speed in a vacuum, only $0.41c$. 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.

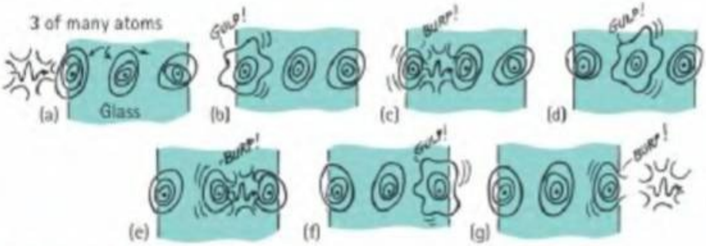

FIGURE 26.7

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.

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.

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.

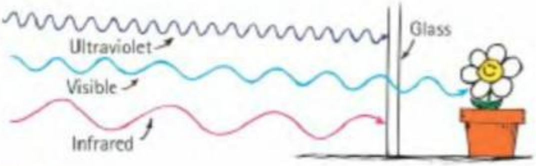

FIGURE 26.9

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

[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

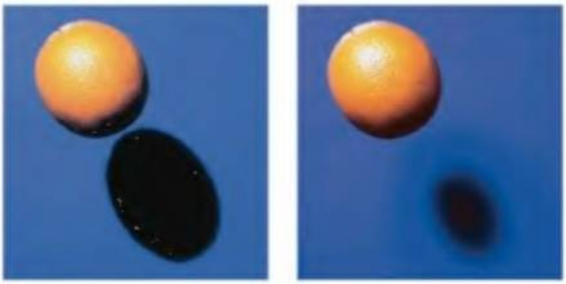

FIGURE 26.11

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

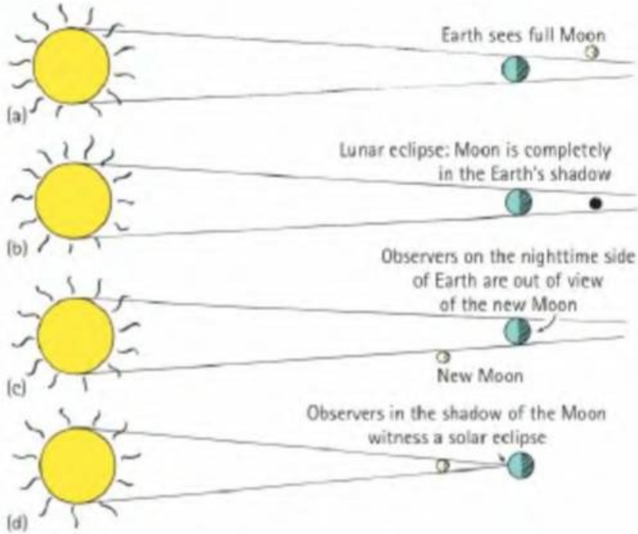

FIGURE 26.13

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.

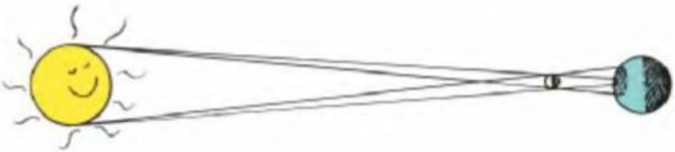

FIGURE 26.14

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.

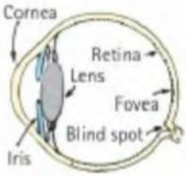

FIGURE 26.15
The human eye.

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!

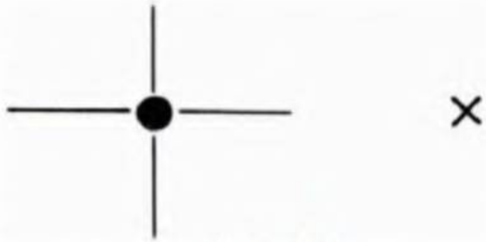

FIGURE 26.16
The blind-spot experiment. Close your left eye and look with your right eye at the round dot. Adjust your distance and find the blind spot that erases the X. Switch eyes and look at the X and the dot disappears. Does your brain fill in crossed lines where the dot was?

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.

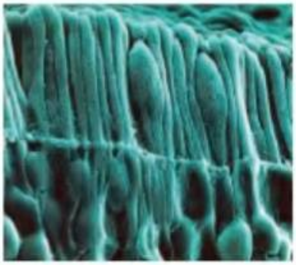

FIGURE 26.17
Magnified view of the rods and cones in the human eye.

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

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- 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.

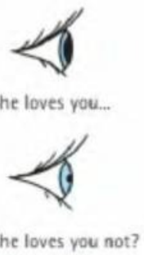

FIGURE 26.19

The size of your pupils depends on your mood.

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*.)

[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

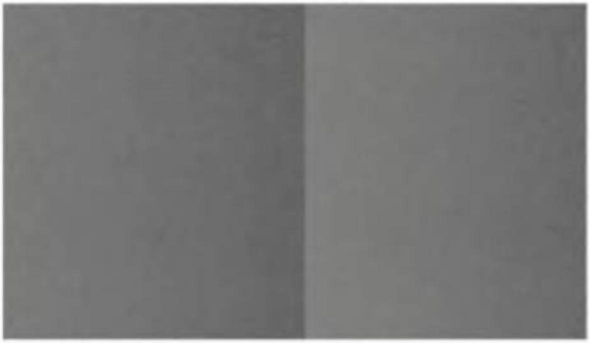

FIGURE 26.20

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

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.

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.

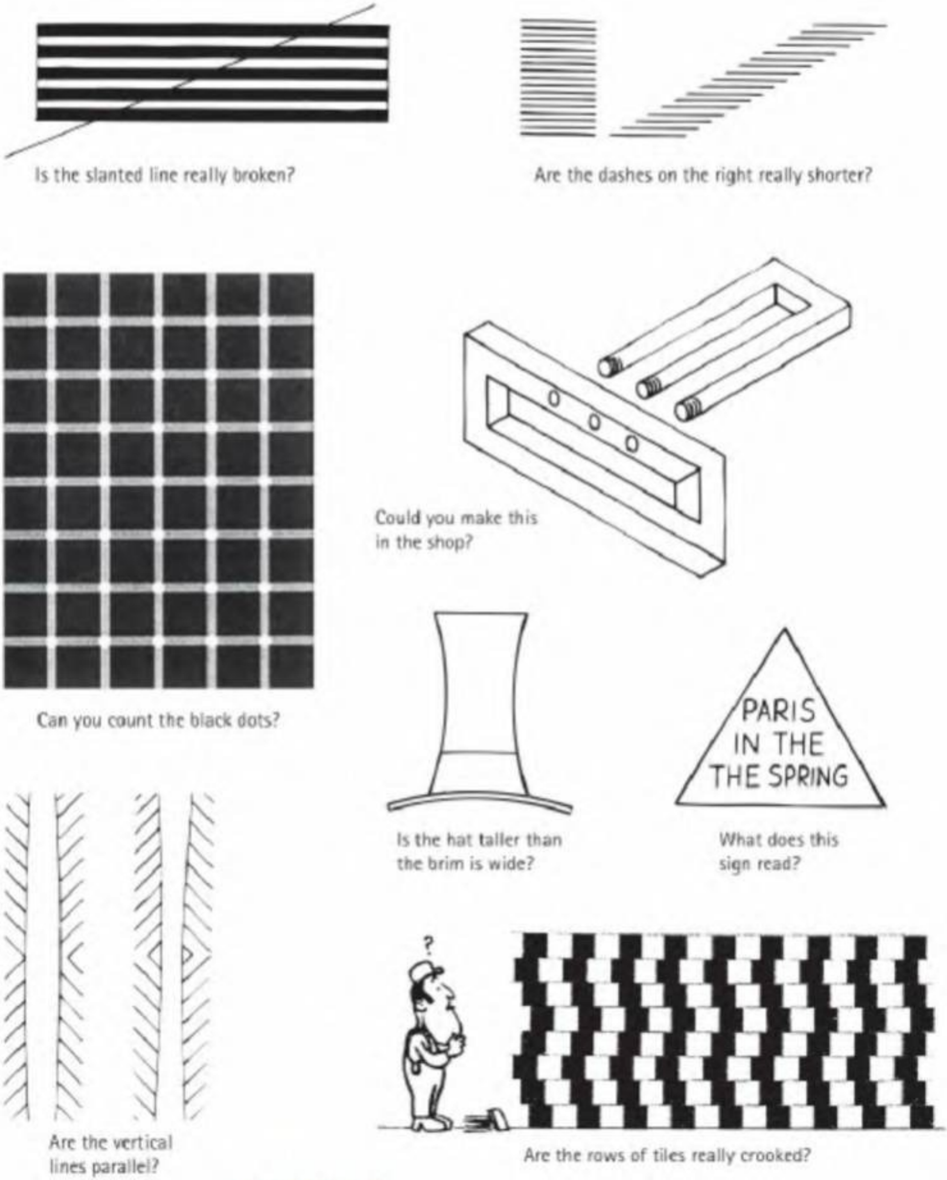

FIGURE 26.22
Optical illusions.

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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- Eclipses

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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.

PhysicsPlace.com
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.

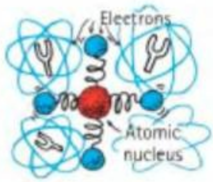


FIGURE 27.2
The outer electrons in an atom vibrate and resonate just as weights on springs would do. As a result, atoms and molecules behave somewhat like optical tuning forks.

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;

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

the atoms of the stem absorb all light except green, which they reflect. An object that reflects light of all the visible frequencies, such as the white part of this page does, is the same color as the light that shines upon it. If a material absorbs all the light that shines upon it, it reflects none and is seen as black.

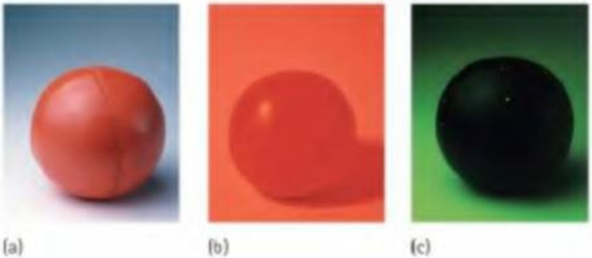


FIGURE 27.3
(a) Red ball seen under white light. The red color is due to the ball reflecting only the red part of the illuminating light. The rest of the light is absorbed by the surface. (b) Red ball seen under red light. (c) Red ball seen under green light. The ball appears black because the surface absorbs green light—there is no source of red light for it to reflect.

FIGURE 27.4
Most of the bunny's fur reflects light of all frequencies and appears white in sunlight. Its dark fur absorbs all of the radiant energy in incident sunlight and therefore appears black.

Interestingly, the petals of most yellow flowers, such as daffodils, reflect red and green as well as yellow. Yellow daffodils reflect a broad band of frequencies. The reflected colors of most objects are not pure single-frequency colors, but are composed of a spread of frequencies.

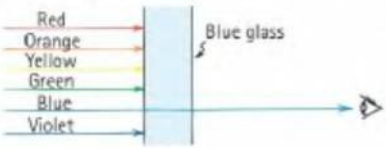
An object can reflect only those frequencies present in the illuminating light. The appearance of a colored object, therefore, depends on the kind of light that illuminates it. An incandescent lamp, for instance, emits more light in the lower than in the higher frequencies, enhancing any reds viewed in this light. In a fabric having only a trace of red, the red is more apparent under an incandescent lamp than it is under a fluorescent lamp. Fluorescent lamps are richer in the higher frequencies, and so blues are enhanced under them. Usually we define an object's "true" color as the color it has in daylight. So, when you're shopping for clothing or accessories, the color you see in artificial light may be quite different from its true color (Figure 27.5).

FIGURE 27.5
Color depends on the light source.

Selective Transmission

The color of a transparent object depends on the color of the light it transmits. A piece of glass contains dyes or *pigments*—fine particles that selectively absorb light of certain frequencies and selectively transmit others. A red piece of glass appears red because it absorbs all the colors that compose white light, except red, which it *transmits*. Similarly, a blue piece of glass appears blue because it absorbs light of the other colors that illuminate it and transmits primarily blue light. From an atomic point of view, electrons in the pigment atoms selectively absorb illuminating light of certain frequencies. Light of other frequencies is reemitted from molecule to molecule in the glass. The energy of the absorbed light increases the kinetic energy of the molecules, and the glass is warmed. Ordinary window glass is colorless because it transmits light of all visible frequencies equally well.

FIGURE 27.6
Only energy having the frequency of blue light is transmitted; energy of the other frequencies is absorbed and warms the glass.



CHECK POINT

1. When red light shines on a red rose, why do the leaves become warmer than the petals?
2. When green light shines on a rose, why do the petals look black?
3. If you hold any small source of white light between you and a piece of red glass, you'll see two reflections from the glass: one from the front surface and one from the back surface. What color is each reflection?

Check Your Answers

1. The leaves absorb the energy of red light, rather than reflect it, and so become warmer.
2. The petals absorb rather than reflect the green light. Because green is the only color illuminating the rose and because green contains no red to be reflected, the rose reflects no color and appears black.
3. The reflection from the front surface is white because the light doesn't go far enough into the colored glass to allow absorption of nonred light. Only red light reaches the back surface because the pigments in the glass absorb all the other colors, and so the back reflection is red.

Mixing Colored Light

The fact that white light from the Sun is a composite of all the visible frequencies is easily demonstrated, as Newton first did nearly four centuries ago, by passing sunlight through a prism and observing the rainbow-colored spectrum. The intensity of light from the Sun varies with frequency, being most intense in the yellow-green part of the spectrum. It is interesting to note that our eyes have evolved to have maximum sensitivity in this range. That's why more fire engines these days are painted yellow-green, particularly at airports, where visibility is vital. Our sensitivity to yellow-green light also explains why we see better at night under the illumination of yellow sodium-vapor lamps than under tungsten-filament lamps of the same brightness.

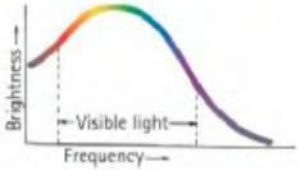


FIGURE 27.7
The radiation curve of sunlight is a graph of brightness versus frequency. Sunlight is brightest in the yellow-green region, in the middle of the visible range.

The graphical distribution of brightness versus frequency is called the *radiation curve* of sunlight (Figure 27.7). Most whites produced from reflected sunlight share this frequency distribution.

All the colors combined make white. Interestingly, the perception of white also results from the combination of only red, green, and blue light. We can understand this by dividing the solar radiation curve into three regions, as in Figure 27.8. Three types of cone-shaped receptors in our eyes perceive color. Light in the lowest third of the spectral distribution stimulates the cones sensitive to low frequencies and appears red; light in the middle third stimulates the cones sensitive to middle frequencies and appears green; light in the highest third stimulates the cones sensitive to the higher frequencies and appears blue. When all three types of cones are stimulated equally, we see white.

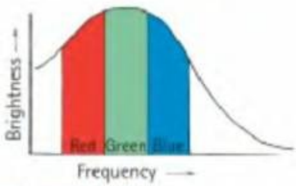


FIGURE 27.8
Radiation curve of sunlight divided into three regions—red, green, and blue (RGB). These are the additive primary colors.

Project red, green, and blue lights on a screen. Where they all overlap, white is produced. Where two of the three colors overlap, another color is produced (Figure 27.9). In the language of physicists, colored lights that overlap are said to *add* to each other. So we say that red, green, and blue light *add to produce white light,* and that any two of these colors of light add to produce another color. Various amounts of red, green, and blue, the colors to which each of our three types of cones are sensitive, produce any color in the spectrum. For this reason, red, green, and blue are called the **additive primary colors.** This color system, known by the initials RGB, is used in computer monitors and television sets. Dots of red, green, and blue create

Adding different combinations of pure rainbow colors can produce other colors like shocking pink, brown, or many of the colors of nature.

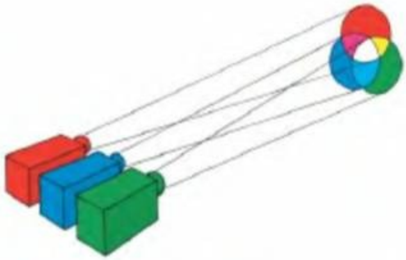


FIGURE 27.9

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.

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Videos

Yellow-Green Peak of Sunlight

Colored Shadows

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.

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

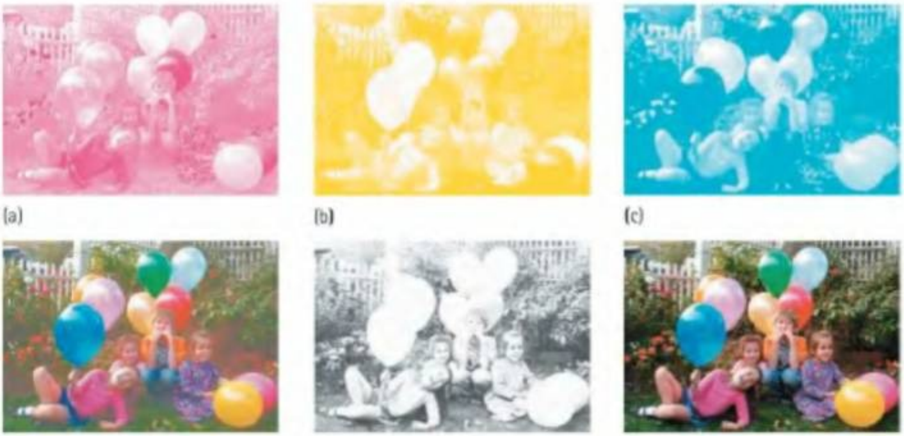
1. From Figure 27.9, find the complements of cyan, of yellow, and of red.
2. Red + blue = ____
3. White − red = ____
4. White − blue = ____

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).

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.)

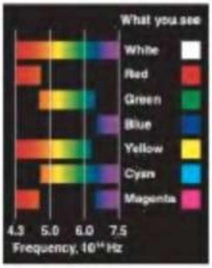


FIGURE 27.14

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

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]

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*.

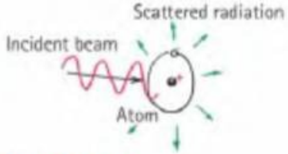


FIGURE 27.15

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.

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.

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.

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 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.

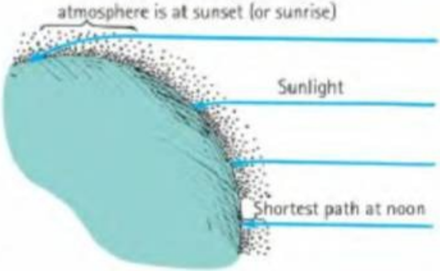


FIGURE 27.18
INTERACTIVE FIGURE
A sunbeam must travel through more of the atmosphere at sunset than at noon. As a result, more blue is scattered from the beam at sunset than at noon. By the time a beam of initially white light reaches the ground, only light of the lower frequencies survives to produce 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.[5]

FIGURE 27.19
The sunset sky is red because of the absence of high-frequency light that has been scattered beyond the horizon.

[5]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.

[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

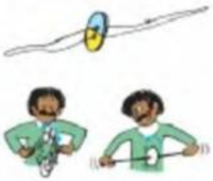
25. What is the evidence for a variety of droplet sizes in a cloud?
26. What is the effect on the color of a cloud when it contains an abundance of large droplets?

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

PhysicsPlace.com

Interactive Figures

- 27.9, 27.10, 27.18

Tutorial

- Color

Videos

- Yellow-Green Peak of Sunlight
- Colored Shadows
- Why the Sky Is Blue and Why the Sunset Is Red

Quizzes

Flashcards

Links

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.

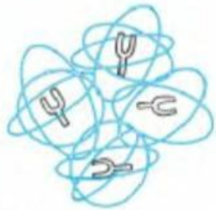


FIGURE 28.1
Light interacts with atoms as sound interacts with tuning forks.

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.

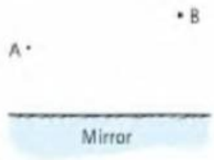


FIGURE 28.2

FIGURE 28.3

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.

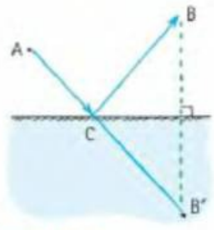


FIGURE 28.4

[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).

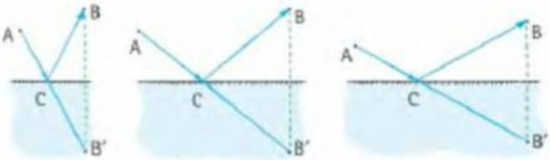


FIGURE 28.5
Reflection.

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.)

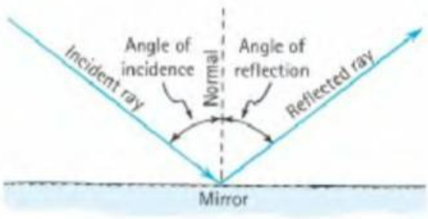


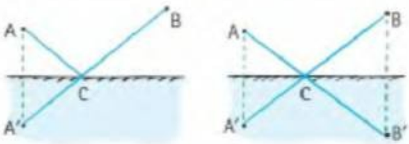
FIGURE 28.6
INTERACTIVE FIGURE
The law of reflection.

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*).

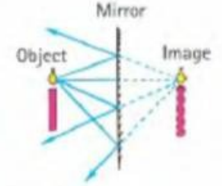


FIGURE 28.7

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.

PhysicsPlace.com
Video
Image Formation in a Mirror

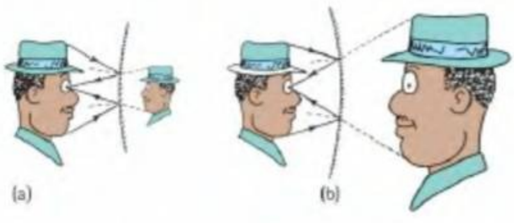


FIGURE 28.9

(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.

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.

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.

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

FIGURE 28.13
Refraction.

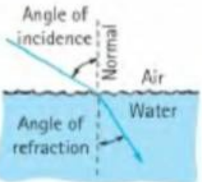


FIGURE 28.14
INTERACTIVE FIGURE
Refraction.

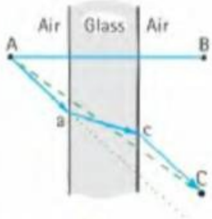


FIGURE 28.15
Refraction through glass. Although dashed line AC is the shortest path, light takes a slightly longer path through the air from A to a, then a shorter path through the glass to c, and then to C. The emerging light is displaced but parallel to the incident light.

[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.

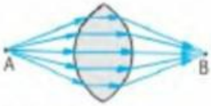


FIGURE 28.18
A converging lens.

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).

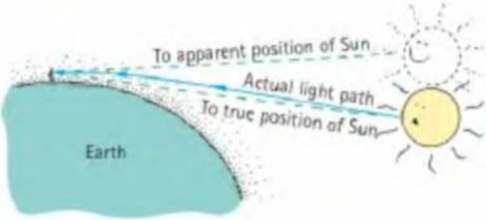


FIGURE 28.19
Because of atmospheric refraction, when the Sun is near the horizon, it appears to be higher in the sky.

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.

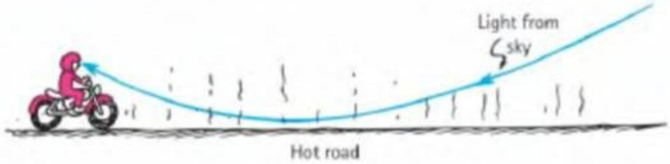


FIGURE 28.21
Light from the sky picks up speed in the air near the ground because that air is warmer and less dense than the air above. When the light grazes the surface and bends upward, the observer sees a mirage.

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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Video
Model of Refraction

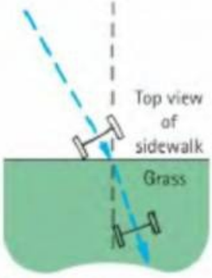


FIGURE 28.23
The direction of the rolling wheels changes when one wheel slows down before the other one does.

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]

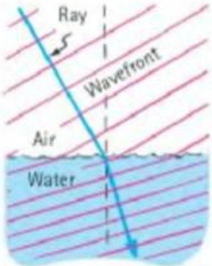
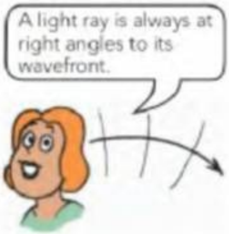


FIGURE 28.24
The direction of the light waves changes when one part of each wave slows down before the other part.



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.

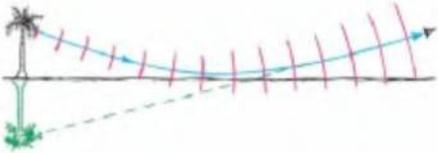


FIGURE 28.25
A wave explanation of a mirage. Wavefronts of light travel faster in the hot air near the ground and bend upward.

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.

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

[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.

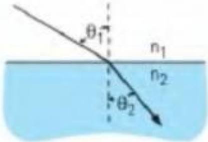


FIGURE 28.27
Because of refraction, a submerged object seems to be nearer to the surface than it actually is.

FIGURE 28.28
Because of refraction, the full root-beer mug appears to hold more root beer than it actually does.

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.

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.

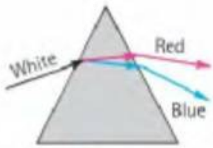


FIGURE 28.29
Dispersion by a prism makes the components of white light visible.

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

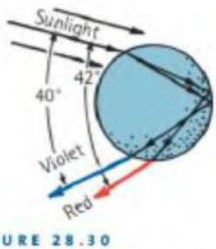


FIGURE 28.30
Dispersion of sunlight by a single raindrop.

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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°.

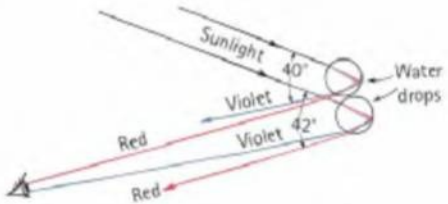


FIGURE 28.31
Sunlight incident on two sample raindrops, as shown, emerges from them as dispersed light. The observer sees the red light from the upper drop and the violet light from the lower drop. Millions of drops produce the whole spectrum of visible light.

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.

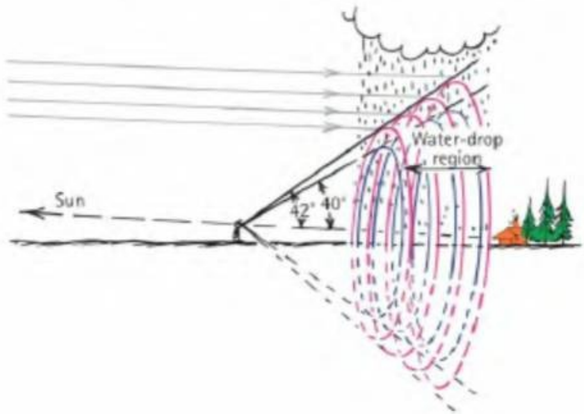


FIGURE 28.32
When your eye is located between the Sun (not shown off to the left) and a water drop region, the rainbow you see is the edge of a three-dimensional cone that extends through the water drop region. (Innumerable layers of drops form innumerable two-dimensional arcs like the four suggested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

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 28.33
Only raindrops along the dashed line disperse red light to the observer at a 42° angle; hence, the light forms a bow.

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.

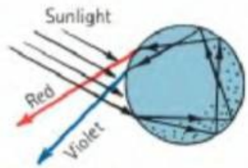


FIGURE 28.35
Double reflection in a drop produces a secondary bow.

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

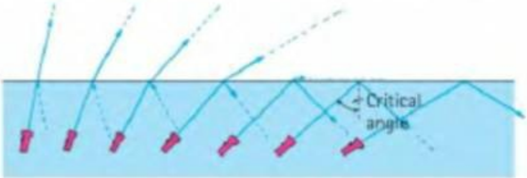


FIGURE 28.36

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.

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.

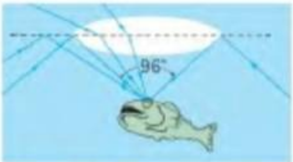


FIGURE 28.37

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 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.

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.

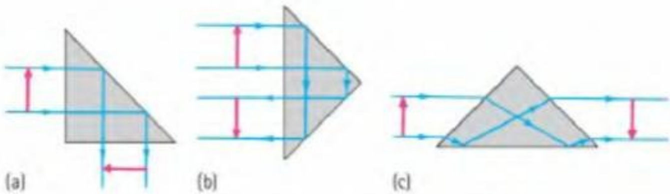


FIGURE 28.38

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.

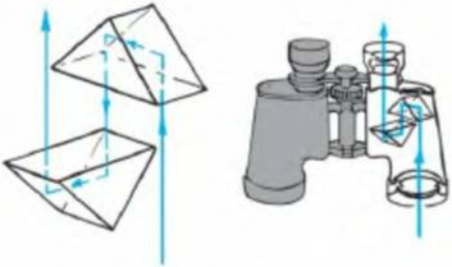


FIGURE 28.39
Total internal reflection in a pair of prisms, common in binoculars.

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."

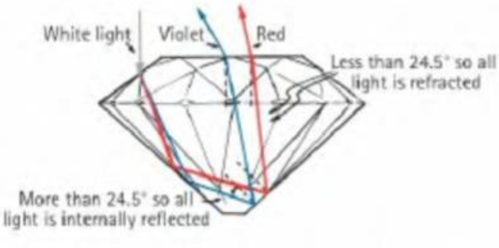


FIGURE 28.40
Paths of light in a diamond. Rays that strike the inner surface at angles greater than the critical angle are internally reflected and exit via refraction at the top surface.

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

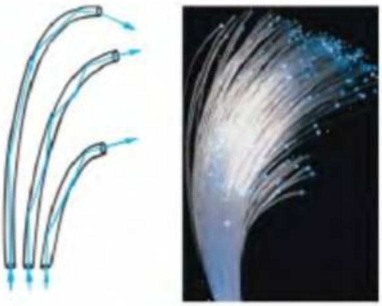


FIGURE 28.41
The light is "piped" from below by a succession of total internal reflections until it emerges at the top ends.

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.

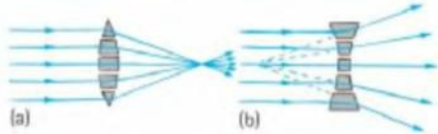


FIGURE 28.42

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.

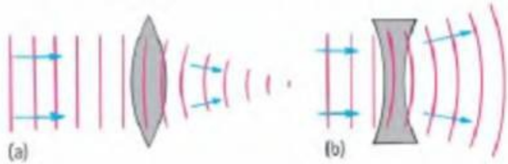


FIGURE 28.43

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

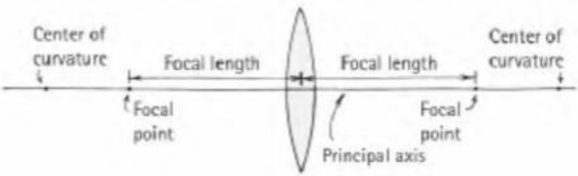


FIGURE 28.44

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

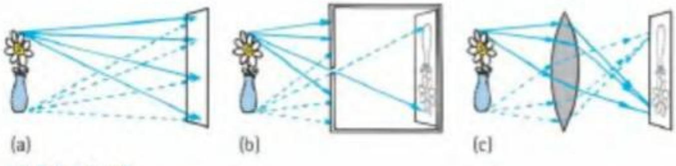


FIGURE 28.46

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.

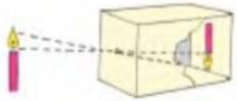
[5]A quantitative way of relating object distances with image distances is given by the thin-lens equation

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

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.

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 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*.

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.

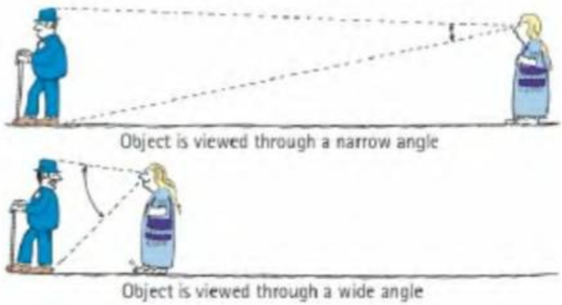


FIGURE 28.47
Viewing.

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.

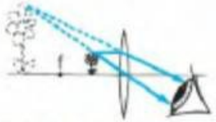


FIGURE 28.48
When an object is near a converging lens (inside its focal point f), the lens acts as a magnifying glass to produce a virtual image. The image appears larger and farther from the lens than the object.

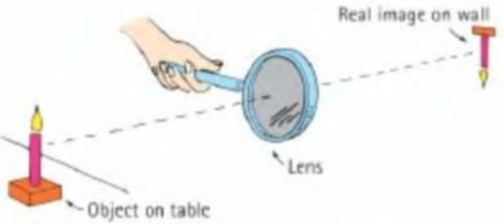


FIGURE 28.49
When an object is far from a converging lens (beyond its focal point), a real upside-down image is formed.

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.)

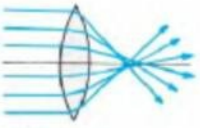


FIGURE 28.51
Spherical aberration.

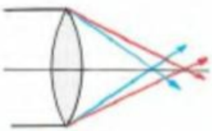


FIGURE 28.52
Chromatic aberration.

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?

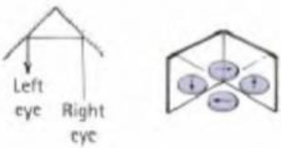
Lens Defects

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?

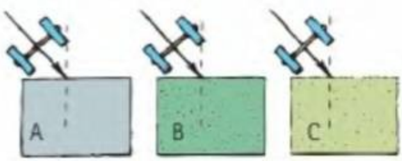
5. Determine the magnifying power of a lens by focusing on the lines of a ruled piece of paper. Count the spaces between the lines that fit into one magnified space and you have the magnifying power of the lens. You can do the same with binoculars and a distant brick wall. Hold the binoculars so that 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?)

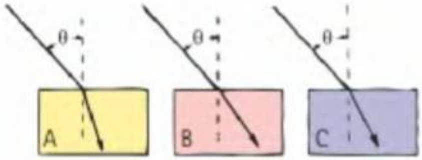
RANKING

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.

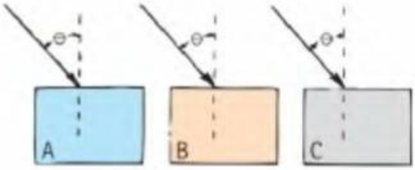
2. Wheels from a toy cart are rolled from a concrete sidewalk onto the following surfaces: A, a paved driveway; B, a grass lawn; C, close-cropped grass on a golf-course putting green. Due to slowing, each set of wheels bends at the boundary and is deflected from its initial straight-line course. Rank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

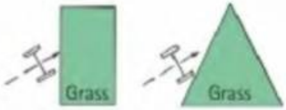
20. Why does reflected light from the Sun or Moon appear as a column in the body of water as shown? How would the reflected light appear if the water surface were perfectly smooth?

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.

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.

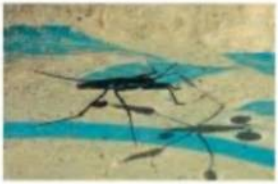
31. When a fish in a pond looks upward at an angle of 45°, does it see the sky above the water's surface or a reflection from the water–air boundary of the bottom of the pond? Defend your answer.

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?

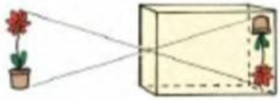
33. If you were to send a beam of laser light to a space station above the atmosphere and just above the horizon, would you aim the laser above, below, or at the visible space station? Defend your answer.

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

29 Light Waves

1 Robert Greenler shows interference colors with a *big* soap bubble. 2 This photo is a highly valued one for physics teachers Marshall Ellenstein and Helen Yan, who were in the Cal Tech parking lot discussing the Feynman diagrams on Feynman's van when Richard Feynman came by—and agreed to this pose. 3 New Zealander Jennie McKelvie shows wave behavior with a ripple tank.

After *Conceptual Physics* was first published in 1971, I met Marshall Ellenstein at a physics conference in Chicago. He was one of the first teachers to adopt the book and said it was the book that he intended writing. Marshall asked if I'd come to his home in Chicago for dinner with him and his wife. He also asked if I'd visit his classes in the high school where he taught. I agreed to both requests and we have been close friends ever since.

Marshall, now retired, was among Chicago's very finest physics teachers. In addition to his passion for teaching physics, he's an accomplished magician and a prize winner in both jitterbug dancing and bridge playing. In his teaching he believes that physics is too exciting and relevant to everyday life not to be part of the educational mainstream. Because he possessed all the qualities that make for a great teacher, his physics classes were overflowing with students eager to learn. A term project at the time I visited was having each student produce a scrapbook of ten photographs that showed physics in daily life. The punch line, given well into the school term after all photos were submitted, was that *any* photograph shows physics—that physics is *everywhere*. Even a blank all-white photo shows the reflection of whatever color of light is incident upon it. Physics wasn't something tucked away in books or on lab shelves with Marshall's students.

Marshall never wrote his textbook on physics. Instead, he pumped ideas to me continuously over the years. Hence the many "thanks to Marshall Ellenstein" at the bottoms of Practice Book pages and Next-Time Questions. Marshall edited video footage of my classroom lectures, which are featured in the Videos listings at the ends of chapters throughout this book. Less conspicuous are his many ideas within the textbook paragraphs and figures. In this chapter, for example, Marshall suggested the section on three-dimensional viewing and provided the computer-generated stereogram in Figure 29.41. He urged me to treat holograms and helped me to tailor topics all throughout the book. Like many teachers, Marshall began physics with the study of light rather than mechanics, his experience telling him that light was a better hook for gaining initial student interest. We begin this chapter as Marshall did with his courses, with the wave nature of light.

FIGURE 29.1
Water waves form concentric circles.

Huygens' Principle

Throw a rock in a quiet pool, and waves appear along the surface of the water. Strike a tuning fork, and waves of sound spread in all directions. Light a match, and waves of light similarly expand in all directions. In 1678 a Dutch physicist, Christian Huygens, studied wave behavior and proposed that the wavefronts of light waves spreading out from a point source can be regarded as the overlapped crests of tiny secondary waves (Figure 29.2)—that wavefronts are made up of tinier wavefronts. This idea is called **Huygens' principle.**

Every point of a wavefront may be considered the source of secondary wavelets that spread out in all directions with a speed equal to the speed of propagation of the waves.

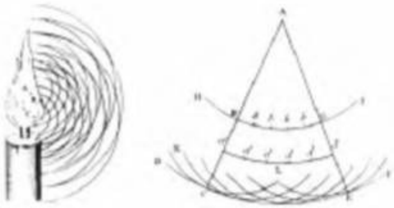


FIGURE 29.2
These drawings are from Huygens' book *Treatise on Light.* Light from A expands in wavefronts, every point of which behaves as if it were a new source of waves. Secondary wavelets starting at *b,b,b,b* form a new wavefront (*d,d,d,d*); secondary wavelets starting at *d,d,d,d* form still another new wavefront (DCEF).

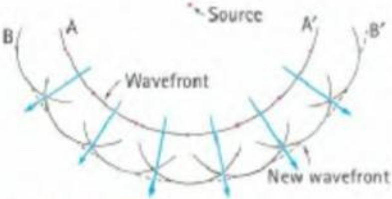


FIGURE 29.3
INTERACTIVE FIGURE
Huygens' principle applied to a spherical wavefront.

Consider the spherical wave front in Figure 29.3. We can see that if all points along the wavefront AA′ are sources of new wavelets, a short time later the new overlapping wavelets will form a new surface, BB′, which can be regarded as the envelope of all the wavelets. In the figure we show only a few of the infinite number of wavelets from a few secondary point sources along AA′ that combine to produce the smooth envelope BB′. As the wave spreads, a segment appears less curved. Very far from the original source, the waves nearly form a plane—as do waves from the Sun, for example. A Huygens wavelet construction for plane wavefronts is shown in Figure 29.4. We see the laws of reflection and refraction illustrated via Huygens' principle in Figure 29.5.

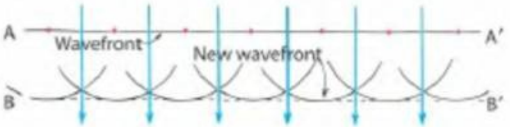


FIGURE 29.4
INTERACTIVE FIGURE
Huygens' principle applied to a plane wavefront.

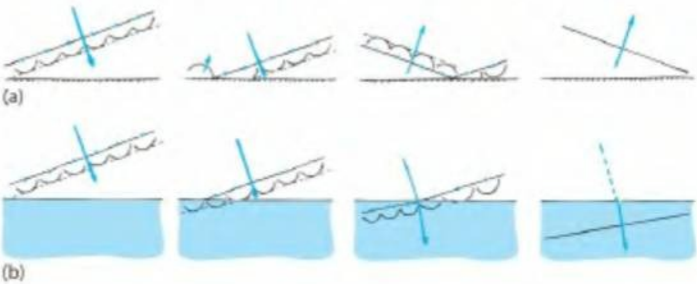


FIGURE 29.5
Huygens' principle applied to (a) reflection and (b) refraction. Notice that rays and wavefronts are perpendicular to each other.

Plane waves can be generated in water by successively dipping a horizontally held straightedge, such as a meterstick, into the surface (Figure 29.6). The photographs in Figure 29.7 are top views of a ripple tank in which plane waves are incident upon openings of various sizes (the straightedge is not shown). In (a), where the opening is wide, we see the plane waves continue through the opening without change—except at the corners, where the waves are bent into the shadow region, as predicted by Huygens' principle. As the width of the opening is narrowed, as in (b), less and less of the incident wave is transmitted, and the spreading of waves into the shadow region becomes more pronounced. When the opening is small compared with the wavelength of the incident wave, as in (c), the truth of Huygens' idea that every part of a wavefront can be regarded as a source of new wavelets becomes quite apparent. As the waves are incident upon the narrow opening, the water sloshing up and down in the opening is easily seen to act as a "point" source of the new waves that fan out on the other side of the barrier. We say that the waves are *diffracted* as they spread into the shadow region.

FIGURE 29.6

The oscillating meterstick makes plane waves in the tank of water. Water oscillating in the opening acts as a source of waves. Water diffracts through the opening.

Diffraction

In the previous chapter, we learned that light can be bent from its ordinary straight-line path by reflection and by refraction, and now we learn another way in which light bends. Any bending of light by means other than reflection and refraction is called *diffraction*. **Diffraction** is the bending of light as it passes the edge of an object, creating a fuzzy edge. It also occurs when a wave passes through an aperture. The diffraction of plane water waves shown in Figure 29.7 occurs for all kinds of waves, including light waves.

FIGURE 29.7

Plane waves passing through openings of various sizes. The smaller the opening, the greater the bending of the waves at the edges—in other words, the greater the diffraction.

When light passes through an opening that is large compared with the wavelength of light, it casts a shadow such as the one shown in Figure 29.8a. We see a rather sharp boundary between the light and dark area of the shadow. But if we pass light through a thin razor slit in a piece of opaque cardboard, we see that the light diffracts (Figure 29.8b). The sharp boundary between the light and dark area disappears, and the light spreads out like a fan to produce a bright area that fades into darkness without sharp edges. The light is diffracted.

If someone in another room calls you, the sound seems to be coming from the doorway (unless you have very thin walls).

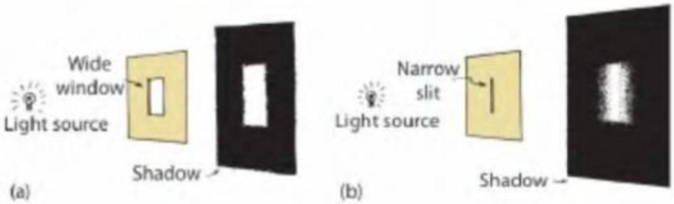


FIGURE 29.8

INTERACTIVE FIGURE

(a) Light casts a sharp shadow with some fuzziness at its edges when the opening is large compared with the wavelength of the light.
(b) When the opening is very narrow, diffraction is more apparent and the shadow is fuzzier.

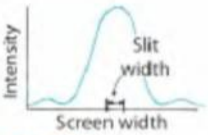


FIGURE 29.9

Graphic interpretation of diffracted light through a single thin slit.

A graph of the intensity distribution for diffracted light through a single thin slit appears in Figure 29.9. Because of diffraction, there is a gradual increase in light intensity rather than an abrupt change from dark to light. A photodetector sweeping across the screen would sense a gradual change from no light to maximum light. (Actually, there are slight fringes of intensity to either side of the main pattern; we will see shortly that these are evidence of interference that is more pronounced with a double slit or multiple slits.)

Diffraction is not confined to narrow slits or to openings in general but can be seen for all shadows. On close examination, even the sharpest shadow is blurred slightly at the edge. When the light is of a single color (monochromatic), diffraction can produce *diffraction fringes* at the edge of the shadow, as in Figure 29.10. In white light, the fringes merge together to create a fuzzy blur at the edge of a shadow.

FIGURE 29.10

Diffraction fringes are evident in the shadows of monochromatic (single-frequency) laser light. These fringes would be filled in by multitudes of other fringes if the source were white light.

The amount of diffraction depends on the wavelength of the wave compared with the size of the obstruction that casts the shadow. Longer waves diffract more. They're better at filling in shadows, which is why the sounds of foghorns are low-frequency long waves—to fill in any "blind spots." Likewise for radio waves of the standard AM broadcast band, which are very long compared with the size of most objects in their path. The wavelengths of AM radio waves range from 180 to 550 meters, and the waves readily bend around buildings and other objects that might otherwise obstruct them. A long-wavelength radio wave doesn't "see" a relatively small building in its path, but a short-wavelength radio wave does. The radio waves of the FM band range from 2.8 to 3.4 meters and don't bend very well around buildings. This is one of the reasons that FM reception is often poor in localities where AM comes in loud and clear. In the case of radio reception, we don't wish to "see" objects in the path of radio waves, so diffraction is not a bad thing.

Diffraction is not so nice for viewing very small objects with a microscope. If the size of an object is about the same as the wavelength of light, diffraction blurs the image. If the object is smaller than the wavelength of light, no structure can be seen. The entire image is lost due to diffraction. No amount of magnification or perfection of microscope design can defeat this fundamental diffraction limit.

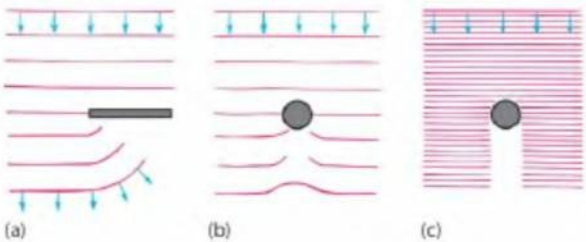


FIGURE 29.11

(a) Waves tend to spread into the shadow region.
(b) When the wavelength is about the size of the object, the shadow is soon filled in.
(c) When the wavelength is short relative to the object's size, a sharper shadow is cast.

To minimize this problem, microscopists can illuminate tiny objects with electron beams rather than with light. Relative to light waves, electron beams have extremely short wavelengths. *Electron microscopes* take advantage of the fact that all matter has wave properties: A beam of electrons has a wavelength shorter than those of visible light. In an electron microscope, electric and magnetic fields, rather than optical lenses, are used to focus and magnify images.

The fact that smaller details can be seen better with shorter wavelengths is neatly employed by the dolphin in scanning its environment with ultrasound. The echoes of long-wavelength sound give the dolphin an overall image of objects in its surroundings. To examine more detail, the dolphin emits sound of shorter wavelengths. As discussed in Chapter 20, the dolphin has always done naturally what physicians are now able to do with ultrasonic imaging devices.

CHECK POINT

Why does a microscopist use blue light rather than white light to illuminate objects being viewed?

Check Your Answer

There is less diffraction with shorter-wavelength blue light, and so the microscopist sees more detail (just as a dolphin beautifully investigates fine detail in its environment by the echoes of ultra-short wavelengths of sound).

Diffraction occurs when a wave passes through an aperture or by the edge of an object.

Superposition and Interference

When two waves interact, the amplitude of the resulting wave is the sum of the amplitudes of the two individual waves. This is called the **principle of superposition.** This phenomenon is generally described as **interference** (as discussed in Chapters 19 and 20). Constructive and destructive interference are reviewed in Figure 29.12. We see that the superposition of a pair of identical waves in phase with each other produces a wave of the same frequency but twice the amplitude. If the waves are exactly one-half wavelength out of phase, their superposition results in complete cancellation. If they are out of phase by other amounts, partial cancellation occurs.

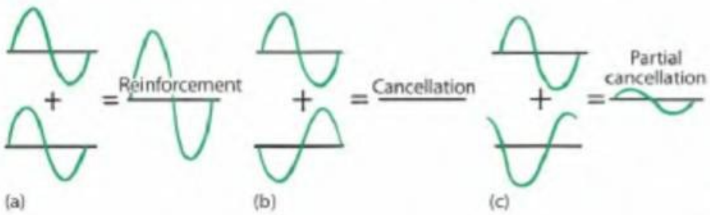


FIGURE 29.12
Wave interference.

The interference of water waves is a common sight, as shown in Figure 29.13. In some places, crests overlap crests; in other places, crests overlap troughs of other waves.

FIGURE 29.13
Interference of water waves.

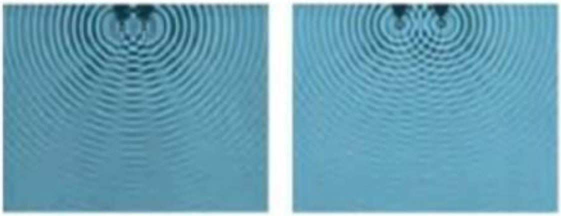


FIGURE 29.14
Interference patterns of overlapping waves from two vibrating sources.

Under more carefully controlled conditions, interesting patterns are produced by a pair of wave sources placed side by side (Figure 29.14). Drops of water are allowed to fall at a controlled frequency into shallow tanks of water (ripple tanks similar to Jennie's in the chapter opener) while their patterns are photographed from above. Note that areas of constructive and destructive interference extend as far as the right-side edges of the ripple tanks, where the number of these regions and their size depend on the distance between the wave sources and on the wavelength (or frequency) of the waves. Interference is not restricted to easily seen water waves but is a property of all waves.

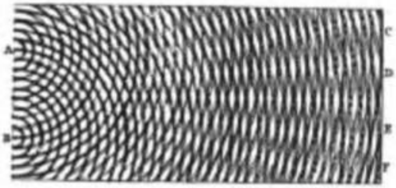


FIGURE 29.15
Thomas Young's original drawing of a two-source interference pattern. The dark circles represent wave crests; the white spaces between the crests represent troughs. Constructive interference occurs where crests overlap crests or troughs overlap troughs. Letters C, D, E, and F mark regions of destructive interference.

In 1801, the wave nature of light was convincingly demonstrated when the British physicist and physician Thomas Young performed his now famous interference experiment.[1] Young found that light directed through two closely spaced pinholes recombines to produce fringes of brightness and darkness on a screen behind. The bright fringes form when a crest from the light wave through one hole and a crest from the light wave through the other hole arrive at the screen at the same time. The dark fringes form when a crest from one wave and a trough from the other arrive at the same time. Figure 29.15 shows Young's drawing of the pattern of superimposed waves from the two sources. When his experiment is done with two closely spaced slits instead of pinholes, the fringe patterns are straight lines (Figure 29.17).

We see in Figure 29.18 how the series of bright and dark lines results from the different path lengths from the slits to the screen.[2] For the central bright fringe, the paths from the two slits are the same length and so the waves arrive in phase and reinforce each other. The dark fringes on either side of the central fringe result from one path being longer (or shorter) by one-half wavelength, so that the waves arrive half a wavelength out of phase. The other sets of dark fringes occur where the paths differ by odd multiples of one-half wavelength: 3/2, 5/2, and so on.

In performing this double-slit experiment, suppose we cover one of the slits so that light passes through only a single slit. Then light will fan out and illuminate the screen to form a simple diffraction pattern, as discussed earlier (Figures 29.8b and 29.9). If we cover the other slit and allow light to pass only through the slit just

FIGURE 29.16
Bright fringes occur when waves from both slits arrive in phase; dark areas result from the overlapping of waves that are out of phase.

[1]Thomas Young read fluently at the age of 2; by 4, he had read the Bible twice; by 14, he knew eight languages. In his adult life, he was a physician and scientist, contributing to an understanding of fluids, work and energy, and the elastic properties of materials. He was the first person to make progress in deciphering Egyptian hieroglyphics. No doubt about it—Thomas Young was a bright guy!

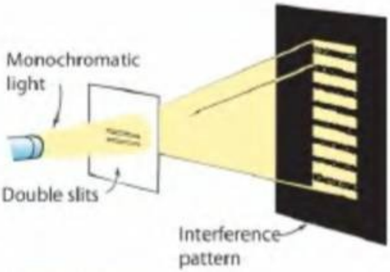


FIGURE 29.17

INTERACTIVE FIGURE

When monochromatic light passes through two closely spaced slits, a striped interference pattern is produced.

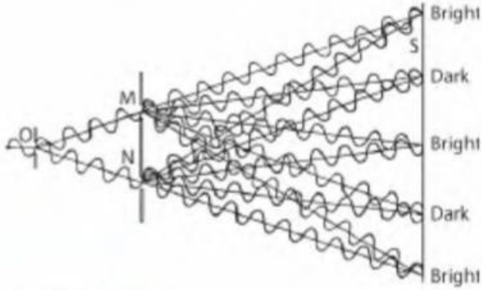


FIGURE 29.18

INTERACTIVE FIGURE

Light from O passes through slits M and N and produces an interference pattern on the screen S.

uncovered, we get the same illumination on the screen, only displaced somewhat because of the difference in slit location. If we didn't know better, we might expect that with both slits open, the pattern would simply be the sum of the single-slit diffraction patterns, as suggested in Figure 29.19a. But this doesn't happen. Instead, the pattern formed is one of alternating light and dark bands, as shown in Figure 29.19b. We have an interference pattern. Interference of light waves does not, by the way, create or destroy light energy; it merely redistributes it.

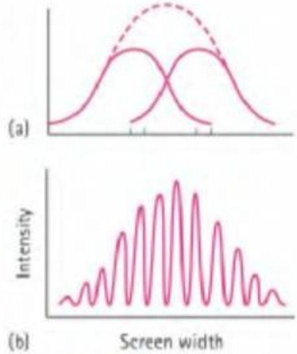


FIGURE 29.19

The light that diffracts through each of the double slits does not form a superposition of intensities as suggested in (a). The intensity pattern, because of interference, is as shown in (b).

CHECK POINT

1. If the double slits were illuminated with monochromatic (single-frequency) red light, would the fringes be more widely or more closely spaced than if they were illuminated with monochromatic blue light?
2. Why is it important that monochromatic light be used?

Check Your Answers

1. More widely spaced. Can you see in Figure 29.18 that a slightly longer—and therefore a slightly more displaced—path from entrance slit to screen would result for the longer waves of red light?
2. If light of various wavelengths were diffracted by the slits, dark fringes for one wavelength would be filled in with bright fringes for another, resulting in no distinct fringe pattern. If you haven't seen this, be sure to ask your instructor to demonstrate it.

Interference patterns are not limited to single and double slits. A multitude of closely spaced slits makes up a *diffraction grating*. These devices, like prisms, disperse white light into colors. Whereas a prism separates the colors of light by refraction, a diffraction grating separates colors by interference. These are used in

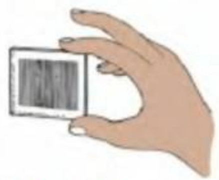


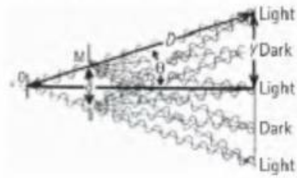
FIGURE 29.20

A diffraction grating may be used in place of a prism in a spectrometer.

[2]In lab, you may determine the wavelength of light using measurements based on Figure 29.18. The equation for the first off-center interference maximum from two or more slits is

$$\lambda = d \sin \theta$$

where λ is the wavelength of light being diffracted, d is the distance between adjacent slits, and θ is the angle between lines to the central fringe of light and the first off-center constructive interference fringe. From the diagram, $\sin \theta$ is the ratio of distance y to distance D, where y is the distance on the screen between the central fringe of light and the first constructive-interference fringe on either side. D is the distance from the fringe to the slits (which, in practice, is much greater than shown here).



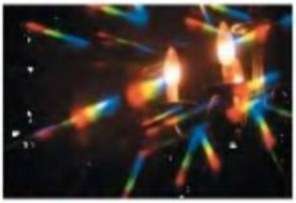


FIGURE 29.21
Lamps of a chandelier seen through diffraction-grating party glasses.

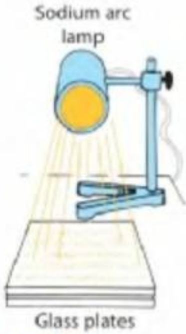


FIGURE 29.22
Interference fringes produced when monochromatic light is reflected from two plates of glass with an air wedge between them.

devices called *spectrometers*, which we will discuss in the next chapter. Diffraction gratings are ruled with tiny grooves and spread white light into bands of color. They are common in some kinds of costume jewelry and in "party glasses" (Figure 29.21). Tiny grooves in the feathers of some birds disperse beautiful colors. Colors by diffraction are especially vivid on the reflective surfaces of DVDs.

SINGLE-COLOR THIN-FILM INTERFERENCE

Another way interference fringes can be produced is by the reflection of light from the top and bottom surfaces of a thin film. A simple demonstration can be set up with a monochromatic light source and a couple of pieces of glass. A sodium-vapor lamp provides a good source of monochromatic light. The two pieces of glass are placed one atop the other, as shown in Figure 29.22. A very thin piece of paper is placed between the plates at one edge to provide a very thin wedge-shaped film of air between the plates. If the eye is in a position to see the reflected image of the lamp, the image will not be continuous but will be made up of dark and bright bands.

The cause of these bands is the interference between the waves reflected from the glass on the top and bottom surfaces of the air wedge, as shown in the exaggerated view in Figure 29.23. The light reflecting from point P comes to the eye by two different paths. In one of these paths, the light is reflected from the top of the air wedge; in the other path, it is reflected from the lower side. If the eye is focused on point P, both rays reach the same place on the retina of the eye. But these rays have traveled different distances and may meet in phase or out of phase, depending on the thickness of the air wedge—that is, on how much farther one ray has traveled than the other. When we examine the entire surface of the glass, we see alternate dark and bright regions—the dark portions, where the air thickness is just right to produce destructive interference, and the bright portions, where the air wedge is just the proper amount thinner or thicker to result in the reinforcement of light. So the dark and bright bands are caused by the interference of light waves reflected from the two sides of the thin film.[3]

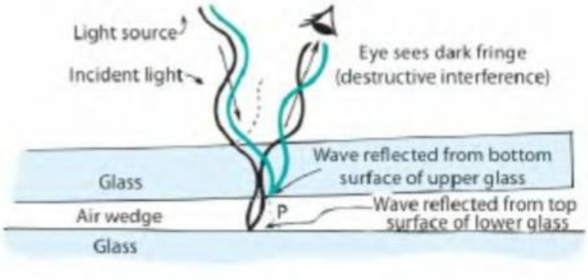


FIGURE 29.23
Reflection from the upper and lower surfaces of a "thin film of air."

[3]Phase shifts at some reflecting surfaces also contribute to interference. For simplicity and brevity, our concern with this topic will be limited to this footnote. In short, when light in a medium is reflected at the surface of a second medium in which the speed of light is less (when there is a greater index of refraction), there is a 180° phase shift (that is, half a wavelength). However, no phase shift occurs when the second medium is one that transmits light at a higher speed (and has a lower index of refraction). In our air-wedge example, no phase shift occurs for reflection at the upper glass–air surface, and a 180° shift does occur at the lower air–glass surface. So, at the apex of the air wedge where the thickness approaches zero, the phase shift produces cancellation, and the wedge is dark. Likewise with a soap film so thin that its thickness is appreciably smaller than the wavelength of light. This is why parts of a film that are extremely thin appear black. Waves of all frequencies are canceled.

If the surfaces of the glass plates are perfectly flat, the bands are uniform. But if the surfaces are not perfectly flat, the bands are distorted. The interference of light provides an extremely sensitive method for testing the flatness of surfaces. Surfaces that produce uniform fringes are said to be optically flat—this means that surface irregularities are small relative to the wavelength of visible light (Figure 29.24).

When a lens that is flat on top and has slight convex curvature on the bottom is placed on an optically flat plate of glass and illuminated from above with monochromatic light, a series of light and dark rings is produced. This pattern is known as *Newton's rings* (Figure 29.25). These light and dark rings are the same kinds of fringes observed with plane surfaces. This is a useful testing technique in polishing precision lenses.

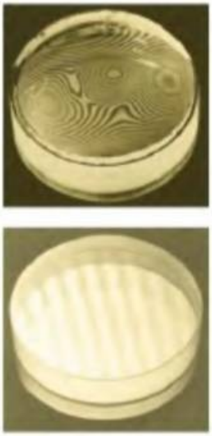


FIGURE 29.24
Optical flats used for testing the flatness of surfaces.

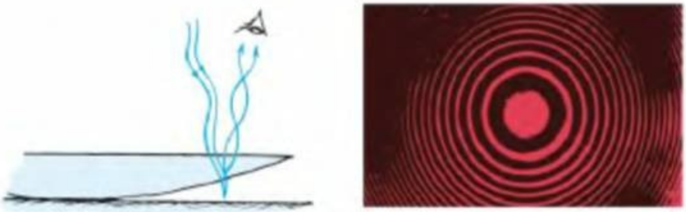


FIGURE 29.25
Newton's rings.

CHECK POINT

How would the spacings between Newton's rings differ when illuminated by red light and by blue light?

Check Your Answer

The rings would be more widely spaced for longer-wavelength red light than for the shorter waves of blue light. Do you see the geometrical reason for this?

INTERFERENCE COLORS BY REFLECTION FROM THIN FILMS

We have all noticed the beautiful spectrum of colors reflected from a soap bubble or from gasoline on a wet street. These colors are produced by the *interference* of light waves. This phenomenon is often called *iridescence* and is observed in thin transparent films.

Soap-bubble colors result from the interference of reflected light from the inside and outside surfaces of the soap film. When a color is canceled, what you see is its complementary color.

A soap bubble appears iridescent in white light when the thickness of the soap film is about the same as the wavelength of light. Light waves reflected from the outer and inner surfaces of the film travel different distances. When illuminated by white light, the film may be just the right thickness at one place to cause the destructive interference of, say, yellow light. When yellow light is subtracted from white light, the mixture left will appear as the complementary color of yellow, which is blue. At another place, where the film is thinner, a different color may be canceled by interference, and the light seen will be its complementary color.

The same thing happens to gasoline on a wet street (Figure 29.26). Light reflects from both the upper gasoline surface and the lower gasoline–water surface. If the thickness of the gasoline is such that it cancels blue, as the figure suggests, then the gasoline surface appears yellow to the eye. This is because the blue is subtracted from the white, leaving the complementary color, yellow. The different colors, then, correspond to different thicknesses of the thin film, providing a vivid "contour map" of microscopic differences in surface "elevations." Over a wider field of view, different colors can be seen, even if the thickness of the gasoline film is uniform.

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Video
Soap Bubble Interference

This is due to the apparent thickness of the film: Light reaching the eye from different parts of the surface is reflected at different angles and traverses different thicknesses. If the light is incident at a grazing angle, for example, the ray transmitted to the gasoline's lower surface travels a longer distance. Longer waves are canceled in this case, and different colors appear.

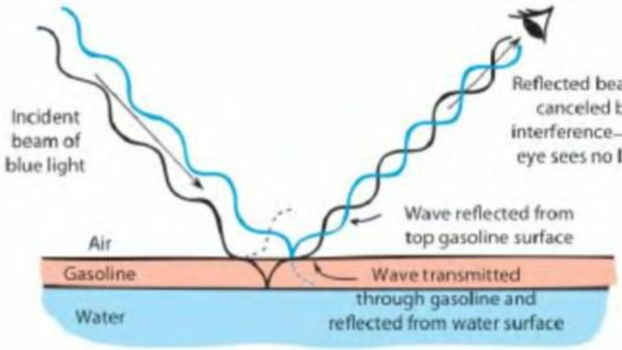

FIGURE 29.26
The thin film of gasoline is just the right thickness to cancel the reflections of blue light from the top and bottom surfaces. If the film were thinner, perhaps shorter-wavelength violet would be canceled. (One wave is drawn in black to show how it is out of phase with the blue wave upon reflection.)

Dishes washed in soapy water and poorly rinsed have a thin film of soap on them. Hold such a dish up to a light source so that *interference colors* can be seen. Then turn the dish to a new position, keeping your eye on the same part of the dish, and the color will change. Light reflecting from the bottom surface of the transparent soap film is canceling light reflecting from the top surface of the soap film. Light waves of different wavelengths are canceled for different angles. Interference colors are best seen in soap bubbles (Figure 29.27). You'll notice that these colors are predominantly cyan, magenta, and yellow, due to the subtraction of primary red, green, and blue.

FIGURE 29.27
The magenta seen in Emily's soap bubbles is due to cancellation of green light. What primary color is canceled to produce cyan?

Interference provides a way to measure the wavelength of light and other electromagnetic radiation. It also makes it possible to measure extremely small distances with great accuracy. Instruments called *interferometers*, which use the principle of interference, are the most accurate instruments known for measuring small distances.

Practicing Physics

Do this physics experiment at your kitchen sink. Dip a dark-colored coffee cup (dark colors make the best background for viewing interference colors) in dishwashing detergent and then hold it sideways and look at the reflected light from the soap film that covers its mouth. Swirling colors appear as the soap flows down to form a wedge that grows thicker at the bottom. The top becomes thinner, so thin that it appears black. This tells you that its thickness is less than one-fourth the wavelength of the shortest waves of visible light. Whatever its wavelength, light reflecting from the inner surface reverses phase, rejoins light reflecting from the outer surface, and cancels. The film soon becomes so thin it pops.

CHECK POINT

In the left column are the colors of certain objects. In the right column are various ways in which colors are produced. Match the right column to the left.

1. yellow daffodil	a. interference
2. blue sky	b. selective reflection
3. rainbow	c. refraction
4. soap bubble	d. scattering

Check Your Answers

1. b; 2. d; 3. c; 4. a

Polarization

Interference and diffraction provide the best evidence that light is wavelike. As we learned in Chapter 19, waves can be either longitudinal or transverse. Sound waves are longitudinal, which means the vibratory motion is *along* the direction of wave travel. But when we shake a taut rope, the vibratory motion traveling along the rope is perpendicular, or *transverse,* to the rope. Both longitudinal and transverse waves exhibit interference and diffraction effects. Are light waves, then, longitudinal or transverse?

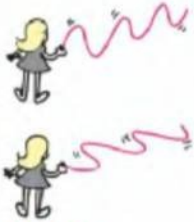

FIGURE 29.28

A vertically plane-polarized wave and a horizontally plane-polarized wave.

Polarization of the light waves demonstrates that they are transverse. Polarization can be understood when we shake a taut rope as in Figure 29.28. A transverse wave travels along the rope in one plane. We say that such a wave is *plane-polarized,*[4] meaning the waves traveling along the rope are confined to a single plane. If we shake the rope up and down, we produce a vertically plane-polarized wave. If we shake it from side to side, we produce a horizontally plane-polarized wave.

A single vibrating electron can emit an electromagnetic wave that is plane-polarized. The plane of polarization will match the vibrational direction of the electron. A vertically accelerating electron, then, emits light that is vertically polarized, while a horizontally accelerating electron emits light that is horizontally polarized (Figure 29.29).

FIGURE 29.29

(a) A vertically plane-polarized wave from a charge vibrating vertically. (b) A horizontally plane-polarized wave from a charge vibrating horizontally.

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Video

Polarized Light and 3-D Viewing

A common light source—such as an incandescent lamp, a fluorescent lamp, or a candle flame—emits light that is unpolarized. This is because there is no preferred vibrational direction for the accelerating electrons emitting the light. The planes of vibration might be as numerous as the accelerating electrons producing them. A few planes are represented in Figure 29.30a. We can represent all these planes by radial lines (Figure 29.30b) or, more simply, by vectors in two mutually perpendicular directions (Figure 29.30c), as if we had resolved all the vectors of Figure 29.30b into horizontal and vertical components. This simpler schematic represents unpolarized light. Polarized light would be represented by a single vector.

[4]Light may also be circularly polarized and elliptically polarized, which are combinations of transverse polarizations. But we will not study these cases.

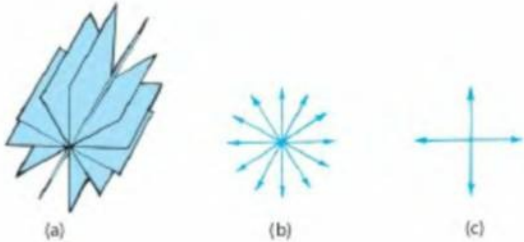

FIGURE 29.30
Representations of plane-polarized waves. The three representations show the electric part of the electromagnetic wave.

FIGURE 29.31
One component of the incident unpolarized light is absorbed, resulting in emerging polarized light.

All transparent crystals of a noncubic natural shape have the property of transmitting light of one polarization differently from light of another polarization. Certain crystals[5] not only divide unpolarized light into two internal beams polarized at right angles to each other but also strongly absorb one beam while transmitting the other (Figure 29.31). Tourmaline is one such common crystal, but, unfortunately, the transmitted light is colored. Herapathite, however, does the job without discoloration. Microscopic crystals of herapathite are embedded between cellulose sheets in uniform alignment and are used in making Polaroid filters. Some Polaroid sheets consist of certain aligned molecules rather than tiny crystals.[6]

If you look at unpolarized light through a Polaroid filter, you can rotate the filter in any direction and the light will appear unchanged. But if you are looking at polarized light and you rotate the filter, you can progressively cut off more and more of the light until it is entirely blocked out. An ideal Polaroid will transmit 50% of incident unpolarized light. That 50% is, of course, polarized. When two Polaroids are arranged so that their polarization axes are aligned, light will be transmitted through both (Figure 29.32a). If their axes are at right angles to each other (in this case we say the filters are *crossed*), no light penetrates the pair. (Actually, some light of the shorter wavelengths does get through, but not to any significant degree.) When Polaroids are used in pairs like this, the first one is called the *polarizer* and the second one is called the *analyzer*.[7]

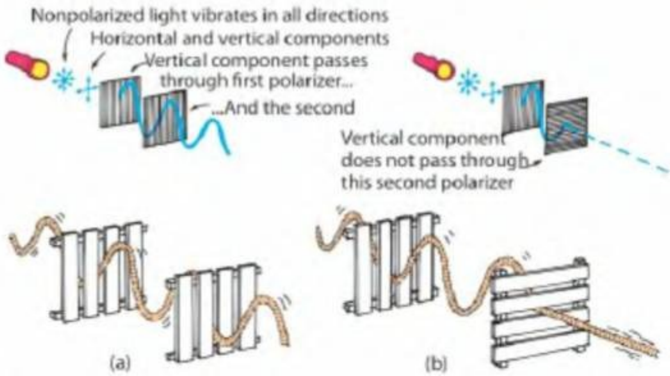

FIGURE 29.32
A rope analogy illustrates the effect of crossed Polaroids.

[5]Called *dichroic*.

[6]The molecules are polymeric iodine in a sheet of polyvinyl alcohol or polyvinylene.

[7]In a common Polaroid filter, long-chain molecules are oriented with their axis perpendicular to the polarizing axis, and preferentially *absorb* (rather then transmit) light polarized along their length, much like an antenna absorbs radio waves. Such filters are in contrast to the rope-through-the-fence analogy of Figure 29.32. For either type of filter, the point to learn is that the transmitted and absorbed wave components are at right angles to each other.

Much of the light reflected from nonmetallic surfaces is polarized. The glare from glass or water is a good example. Except for perpendicular incidence, the reflected ray contains more vibrations parallel to the reflecting surface, whereas the transmitted beam contains more vibrations at right angles to the vibrations of reflected light (Figure 29.34). This is analogous to skipping flat rocks off the surface of a pond.

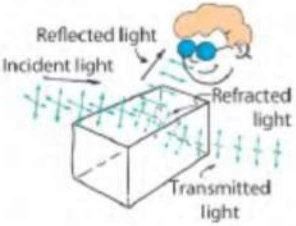

FIGURE 29.34
Most glare from nonmetallic surfaces is polarized. Note how components of incident light parallel to the surface are reflected and how components perpendicular to the surface pass through the surface into the medium.

FIGURE 29.33
Polaroid sunglasses block out horizontally vibrating light. When the lenses overlap at right angles, no light gets through.

When the rocks hit with their faces parallel to the surface, they easily reflect; but if they hit with their faces tilted to the surface, they "refract" into the water. The glare from reflecting surfaces can be appreciably diminished with the use of Polaroid sunglasses. The polarization axes of the lenses are vertical because most glare reflects from horizontal surfaces.

FIGURE 29.35
Light is transmitted when the axes of the Polaroids are aligned (a), but absorbed when Ludmila rotates one so that the axes are at right angles to each other (b). When she inserts a third Polaroid at an angle between the crossed Polaroids, light is again transmitted (c). Why? (For the answer—after you have given this some thought—see Appendix D, "More About Vectors.")

Polarization occurs only for transverse waves. In fact, it is an important way of determining whether a wave is transverse or longitudinal.

CHECK POINT

Which pair of glasses is best suited for automobile drivers? (The polarization axes are shown by the straight lines.)

Check Your Answer

Glasses (a) are best suited because the vertical axis blocks horizontally polarized light, which constitutes most of the glare from horizontal surfaces. Glasses (c) are suited for viewing 3-D movies.

THREE-DIMENSIONAL VIEWING

Vision in three dimensions depends primarily on the fact that both eyes give their impressions simultaneously (or nearly so), each eye viewing the scene from a slightly different angle. To convince yourself that each eye sees a different view, hold an upright finger at arm's length and see how it appears to shift position from left to right in front of the background as you alternately close each eye. The drawings of Figure 29.36 illustrate a stereo view of the crystal structure of ice.

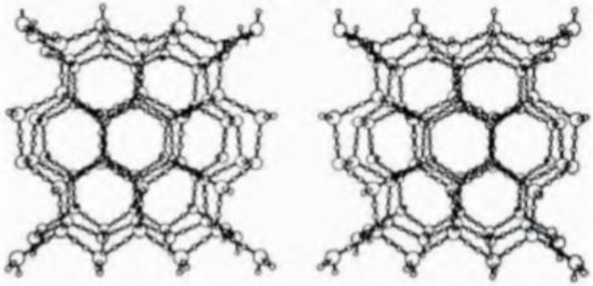

FIGURE 29.36

The crystal structure of ice in stereo. You'll see depth when your brain combines the views of your left eye looking at the left figure and your right eye looking at the right figure. To accomplish this, focus your eyes for distant viewing before looking at this page. Without changing your focus, look at the page, and each figure will appear double. Then adjust your focus so that the two inside images overlap to form a central composite image. Practice makes perfect. (If you instead *cross* your eyes to overlap the figures, near and far are reversed!)

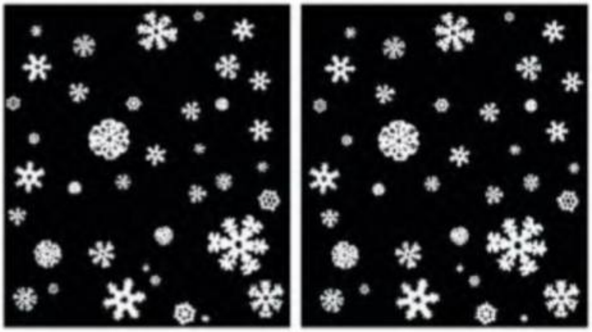

FIGURE 29.37

A stereo view of snowflakes. View these in the same way as Figure 29.36.

The handheld stereoscopic viewer familiar to your grandparents (Figure 29.38) simulates the effect of depth. In this device, there are two photographic transparencies (or slides) taken from slightly different positions. When they are viewed at the same time, the arrangement is such that the left eye sees the scene as photographed from the left, and the right eye sees it as photographed from the right. As a result, the objects in the scene sink into relief in correct perspective, giving apparent depth to the picture. The device is constructed so that each eye sees only the proper view. There is no chance for one eye to see both views. If you remove the slides from the hand viewer and project each view on a screen by slide projector (so that the views are superimposed), a blurry picture results.

This is because each eye sees both views simultaneously. This is where Polaroid filters come in. If you place the Polaroids in front of the projectors so that they are at right angles to each other, and you view the polarized image with polarized glasses of the same orientation, each eye will see the proper view as with the stereoscopic viewer (Figure 29.38). You then will see an image in three dimensions.

FIGURE 29.38

A stereoscopic viewer.

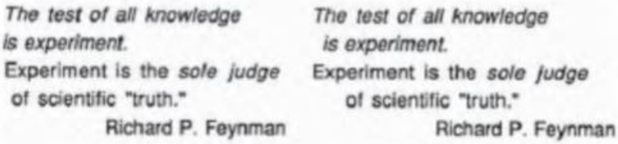

FIGURE 29.39

With your eyes focused for distant viewing, the second and fourth lines appear to be farther away; if you cross your eyes, the second and fourth lines appear closer.

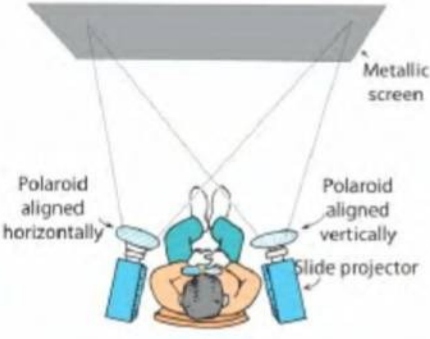

FIGURE 29.40

A 3-D show using Polaroids. The left eye sees only polarized light from the left projector, the right eye sees only polarized light from the right projector, and both views merge in the brain to produce depth.

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- Cosmic microwave background (CMB) fills all of space and comes at us from every direction. It is an echo of the Big Bang that got our universe started nearly 14 billion years ago. Recent findings show this radiation to be ever so slightly polarized and with slight variations of polarization from one direction to another. Polarization observations help to provide a clear and detailed look at the early cosmos.

Depth is also seen in computer-generated stereograms, as in Figure 29.41. Here the slightly different patterns are not obvious in a casual view. Use the procedure for viewing the previous stereo figures. Once you've mastered the viewing technique, head for the local mall and check the variety of stereograms in posters and books.

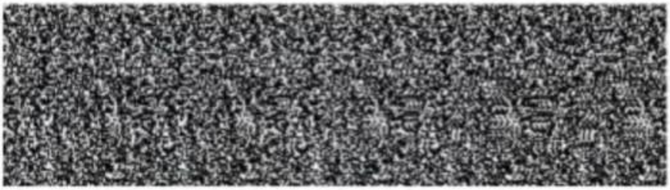

FIGURE 29.41

A computer-generated stereogram.

Holography

Perhaps the most exciting illustration of interference is the **hologram,** a two-dimensional photographic plate illuminated with laser light that allows you to see a faithful reproduction of a scene in three dimensions. The hologram was invented and named by Dennis Gabor in 1947, 10 years before lasers were invented. *Holo* in Greek means "whole," and *gram* in Greek means "message" or "information." A hologram contains the whole message or entire picture. With proper illumination, the image is so realistic that you can actually look around the corners of objects in the image and see the sides.

In ordinary photography, a lens is used to form an image. Light reflected from each point on the object is directed by the lens only to a corresponding point on the film or photoreceptor. In the case of holography, however, no image-forming lens is used. Instead, each point of the object being "photographed" reflects light to the *entire* photographic plate, so every part of the plate is exposed with light reflected from every part of the object. It is important that the light used to make a hologram be of a single frequency and all parts exactly in phase: It must be *coherent.* If, for

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- Watch for autostereoscopy, 3-D without Polaroid glasses. The system relies on lenticular lenses that project a slightly different image to each eye, creating the illusion of depth.

example, white light were used, the diffraction fringes for one frequency would be washed out by those of other frequencies. Only a laser can easily produce such light. (We will treat lasers in detail in the next chapter.) Holograms are made with laser light but can be seen with regular light, as attested to by the hologram on your credit card or on some kinds of money.

Light is truly fascinating—especially when it is diffracted into interference fringes in a hologram. Look for detailed information about holograms on the web.

SUMMARY OF TERMS

Huygens' principle Every point on a wavefront can be regarded as a new source of wavelets, which combine to produce the next wavefront, whose points are sources of further wavelets, and so on.

Diffraction The bending of light that passes near the edge of an object or through a narrow slit, causing the light to spread.

Superposition The overlapping and combining of waves.

Interference The result of superposing different waves, usually of the same wavelength. Constructive interference results from crest-to-crest reinforcement; destructive interference results from crest-to-trough cancellation. The interference of selected wavelengths of light produces colors known as *interference colors*.

Polarization The alignment of the transverse electric vibrations of electromagnetic radiation. Such waves of aligned vibrations are said to be *polarized*.

Hologram A two-dimensional microscopic interference pattern that shows three-dimensional optical images.

REVIEW QUESTIONS

Huygens' Principle

1. According to Huygens, how does every point on a wavefront behave?
2. Will plane waves incident upon a small opening in a barrier fan out on the other side or continue as plane waves?

Diffraction

3. Is diffraction more pronounced through a small opening or through a large opening?
4. For an opening of a given size, is diffraction more pronounced for a longer wavelength or for a shorter wavelength?
5. Which is more easily diffracted around buildings, AM or FM radio waves? Why?

Superposition and Interference

6. Is interference restricted to only some types of waves or does it occur for all types of waves?
7. What exactly did Thomas Young demonstrate in his famous experiment with light?

Single-Color Thin-Film Interference

8. What accounts for the light and dark bands produced when monochromatic light reflects from a glass pane atop another glass pane?
9. What is meant by saying a surface is *optically flat*?
10. What is the cause of Newton's rings?

Interference Colors by Reflection from Thin Films

11. What produces iridescence?
12. What causes the spectrum of colors seen in gasoline splotches on a wet street? Why are these not seen on a dry street?
13. What accounts for the different colors in either a soap bubble or a layer of gasoline on water?
14. Why are interference colors primarily cyan, magenta, and yellow?

Polarization

15. What phenomenon distinguishes longitudinal waves from transverse waves?
16. How does the direction of polarization of light compare with the direction of vibration of the electron that produces it?
17. Why will light pass through a pair of Polaroids when the axes are aligned but not when the axes are at right angles to each other?
18. How much ordinary light will an ideal Polaroid transmit?
19. When *ordinary* light is incident at an oblique angle upon water, what can you say about the *reflected* light?

Three-Dimensional Viewing

20. Why would depth not be perceived if you viewed duplicates of ordinary slides in a stereo viewer (Figure 29.39), rather than the pairs of slides taken with a stereo camera?
21. What role do polarization filters play in a 3-D movie?

Holography

22. How does a hologram differ from a conventional photograph?

PROJECTS

1. With a razor blade, cut a slit in a card and look at a light source through it. You can vary the size of the opening by bending the card slightly. See the interference fringes? Try it with two closely spaced slits.
2. Next time you're in the bathtub, froth up the soapsuds and notice the colors of highlights from the illuminating light overhead on each tiny bubble. Notice that different bubbles reflect different colors, due to the different thicknesses of soap film. If a friend is bathing with you, compare the different colors that each of you see reflected from the same bubbles. You'll see that they're different—for what you see depends on your point of view!
3. When wearing Polaroid sunglasses, look at the glare from a nonmetallic surface, such as a road or body of water. Tip your head from side to side and see how the glare intensity changes as you vary the magnitude of the electric vector component aligned with the polarization axis of the glasses. Also notice the polarization of different parts of the sky when you hold the sunglasses in your hand and rotate them.
4. Place a source of white light on a table in front of you. Then place a sheet of Polaroid in front of the source, a bottle of corn syrup in front of the sheet, and a second sheet of Polaroid in front of the bottle. Look through the Polaroid sheets that sandwich the syrup and view spectacular colors as you rotate one of the sheets.

EXERCISES

1. Why can sunlight that illuminates Earth be approximated by plane waves, whereas the light from a nearby lamp cannot?
2. In our everyday environment, diffraction is much more evident for sound waves than for light waves. Why is this so?
3. Why do *radio waves* diffract around buildings, while *light waves* do not?
4. How are interference fringes of light analogous to the varying intensity that you hear as you walk past a pair of speakers emitting the same sound?
5. By how much should a pair of light rays from a common source differ in distance traveled to produce destructive interference?
6. Light illuminates two closely spaced thin slits and produces an interference pattern on a screen behind. For which color of light—yellow or green—will the distance between the fringes be greater?
7. A double-slit arrangement produces interference fringes for yellow sodium light. To produce narrower-spaced fringes, should red light or blue light be used?
8. When white light diffracts upon passing through a thin slit, as in Figure 29.8b, different color components diffract by different amounts so that a rainbow of colors appears at the edge of the pattern. Which color is diffracted through the greatest angle? Which color through the smallest angle?
9. Which will give wider-spaced fringes in a double-slit experiment, red light or violet light? (Let Figure 29.18 guide your thinking.)
10. Which will give wider-spaced fringes, a double-slit experiment in air or in water? (Let Figure 29.18 guide your thinking.)
11. If the path-length difference between two identical and coherent beams is two wavelengths when they arrive on a screen, will they produce a dark or a bright spot?
12. Which will produce more widely spaced fringes of light when passed through a diffraction grating—light from a red laser or light from a green laser?
13. When the reflected path from one surface of a thin film is one full wavelength different in length from the reflected path from the other surface and no phase change occurs, will the result be destructive interference or constructive interference?
14. When the reflected path from one surface of a thin film is one-half wavelength different in length from the reflected path from the other surface and no phase change occurs, will the result be destructive interference or constructive interference?
15. Suppose you place a diffraction grating in front of a camera lens and take a picture of illuminated streetlights. What will you expect to see in your photograph?
16. What happens to the distance between interference fringes if the separation between two slits is increased?
17. Why is Young's experiment more effective with slits than with the pinholes he first used?
18. In which of these is color formed by refraction—flower petals, rainbow, soap bubbles? By selective reflection? By thin-film interference?
19. The colors of peacocks and hummingbirds are the result not of pigments but of ridges in the surface layers of their feathers. By what physical principle do these ridges produce colors?
20. The colored wings of many butterflies are due to pigmentation, but in others, such as the Morpho butterfly, the colors do not result from any pigmentation. When the wing is viewed from different angles, the colors change. How are these colors produced?
21. Why do the iridescent colors seen in some seashells (such as abalone shells) change as the shells are viewed from various positions?
22. When dishes are not properly rinsed after washing, different colors are reflected from their surfaces. Explain.
23. Why are interference colors more apparent for thin films than for thick films?
24. Will the light from two very close stars produce an interference pattern? Explain.
25. If you notice the interference patterns of a thin film of oil or gasoline on water, you'll note that the colors form complete rings. How are these rings similar to the lines of equal elevation on a contour map?

26. Because of wave interference, a film of oil on water in sunlight is seen to be yellow to observers directly above in an airplane. What color of light transmits through the oil (that would be seen by a scuba diver directly below)?
27. For the Hubble Space Telescope, which light—red, green, blue, or ultraviolet—is better for seeing fine detail of distant astronomical objects?
28. Polarized light is a part of nature, but polarized sound is not. Why?
29. The digital displays of watches and other devices are normally polarized. What related problem can occur when wearing Polaroid sunglasses?
30. Why will an ideal Polaroid filter transmit 50% of incident nonpolarized light?
31. Why may an ideal Polaroid filter transmit anything from zero to 100% of incident polarized light?
32. What percentage of light is transmitted by two ideal Polaroids, one on top of the other with their polarization axes aligned? With their axes at right angles to each other?
33. How can you determine the polarization axis for a single sheet of Polaroid (especially if you're at the edge of a lake)?
34. Why do Polaroid sunglasses reduce glare, whereas nonpolarized sunglasses simply cut down the total amount of light reaching the eyes?
35. To remove the glare of light from a polished floor, should the axis of a Polaroid filter be horizontal or vertical?
36. Most of the glare from nonmetallic surfaces is polarized, the axis of polarization being parallel to that of the reflecting surface. Would you expect the polarization axis of Polaroid sunglasses to be horizontal or vertical? Why?
37. How can a single sheet of Polaroid film be used to show that the sky is partially polarized? (Interestingly enough, unlike humans, bees and many insects can discern polarized light and use this ability for navigation.)
38. Light will not pass through a pair of Polaroid sheets when they are aligned perpendicularly. However, if a third Polaroid is sandwiched between the two with its alignment halfway between the alignments of the other two (that is, with its axis making a 45° angle with each of the other two alignment axes), some light does get through. Why?
39. Why did practical holography have to await the advent of the laser?
40. Which of these is most central to holography—interference, selective reflection, refraction, or all of these?

CHAPTER 29 ONLINE RESOURCES

PhysicsPlace.com

Interactive Figures

- 29.3, 29.4, 29.8, 29.17, 29.18

Videos

- Soap Bubble Interference
- Polarized Light and 3-D Viewing

Quizzes

Flashcards

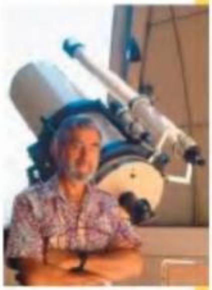
Links

30 Light Emission

1 George Curtis separates light from an argon source into its component frequencies with a spectroscope. 2 The aurora borealis (northern lights) and aurora australis (southern lights) are produced by charged particles thrown off from the Sun, which make impact with and excite atoms and molecules high in the sky. 3 Evan Jones points to an extensive use of light-emitting diodes (LEDs) in a billboard near his college. 4 The LEDs are arranged in sets of the three additive primaries: red, green, and blue. All colors of the rainbow are activated by turning on various combinations of LEDs.

Walter Steiger is a stargazer. His interest in stars centers on the light they emit and how they do so. I met Walter when I first visited the University of Hawaii at Manoa in the mid-1970s. At that time, he was chairman of the physics department. I was impressed to meet the pioneer of astronomy in Hawaii, for he was the first scientist to install an interim solar observatory at nearby Makapuu Point, and later a permanent facility atop Haleakala in Maui. His pioneering work led to the development of the first telescope atop Mauna Kea on the Big Island, which is now home to some of the leading telescopes on planet Earth.

After retirement from the Manoa campus, Walter served as the manager of the Science Center of the B. P. Bishop Museum in Honolulu until 1986. He then moved to Hilo and served 5 years as the site manager of the Caltech Submillimeter Observatory on Mauna Kea. Since 1993, he has lectured on physics and astronomy at the University of Hawaii at Hilo. I also lectured in physics there and we have been close friends since. Walter's many interests include photography, in which he has won various awards. For a time, he and I enjoyed making pottery together—justifiably winning *no* prizes.



Humans know about as much about the atmospheres of stars as they do about the atmosphere of Earth. That's because the light emitted by stars, and everything else, tells us what atoms make up the emitters. This chapter examines the emission of light, which is fascinating to astronomers, physicists, and, I hope, you too.

FIGURE 30.1
Simplified view of electrons orbiting in discrete shells about the nucleus of an atom.

Light Emission

If energy is pumped into a metal antenna in such a way that it causes free electrons to vibrate to and fro a few hundred thousand times per second, a radio wave is emitted. If the free electrons could be made to vibrate to and fro on the order of a million billion times per second, a visible light wave would be emitted. But light is not produced from metallic antennae, nor is it exclusively produced by atomic antennae via oscillations of electrons in atoms, as discussed in previous chapters. In this chapter, we discuss the physics of light sources—of light *emission*.

The details of light emission from atoms involve the transitions of electrons from higher to lower energy states within the atom. This emission process can be understood in terms of the familiar planetary model of the atom that we discussed in Chapter 11. Just as each element is characterized by the number of electrons that occupy the shells surrounding its atomic nucleus, each element also possesses its own characteristic pattern of electron shells, or energy states. These states are found only at certain energies; we say they are *discrete*. We call these discrete states *quantum states*, and we'll return to them in detail in the next two chapters. For now, we'll concern ourselves only with their role in light emission.

Excitation

Everything in nature is connected. Even islands are connected underneath.

An electron farther from the nucleus has a greater electric potential energy with respect to the nucleus than an electron nearer the nucleus. We say that the more distant electron is in a higher energy state, or, equivalently, at a higher energy level. In a sense, this is similar to the energy of a spring door or a pile driver. The wider the door is pulled open, the greater its spring potential energy; the higher the ram of a pile driver is raised, the greater its gravitational potential energy.

When an electron is in any way raised to a higher energy level, the atom is said to be *excited*. The electron's higher position is only momentary: Like the pushed-open spring door, it soon returns to its lowest energy state. The atom loses its temporarily acquired energy when the electron returns to a lower level and emits radiant energy. The atom has undergone the process of **excitation** and *de-excitation*.

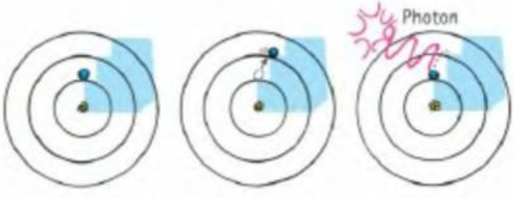


FIGURE 30.2
INTERACTIVE FIGURE
When an electron in an atom is boosted to a higher orbit, the atom is excited. When the electron returns to its original orbit, the atom de-excites and emits a photon of light.

Just as each electrically neutral element has its own number of electrons, each element also has its own characteristic set of energy levels. Electrons dropping from higher to lower energy levels in an excited atom emit with each jump a throbbing pulse of electromagnetic radiation called a *photon*, the frequency of which is related to the energy transition of the jump. We think of this photon as a localized corpuscle of pure energy—a "particle" of light—which is ejected from the atom. The frequency of the photon is directly proportional to its energy. In shorthand notation,

$$E \sim f$$

When the proportionality constant h is introduced, this becomes the exact equation

$$E = hf$$

where h is Planck's constant (more about this in the next chapter). A photon in a beam of red light, for example, carries an amount of energy that corresponds to its frequency. Another photon of twice the frequency has twice as much energy and is found in the ultraviolet part of the spectrum. If many atoms in a material are excited, many photons with many frequencies are emitted that correspond to the many different levels excited. These frequencies correspond to characteristic colors of light from each chemical element.

The light emitted in the glass tubes of advertising signs is a familiar consequence of excitation. The different colors in the signs correspond to the excitation of different gases, although it is common to refer to any of these as "neon." Only the red light is that of neon. At the ends of the glass tube that contains the neon gas are electrodes. Electrons are boiled off these electrodes and are jostled back and forth at high speeds by a high ac voltage. Millions of high-speed electrons vibrate back and forth inside the glass tube and smash into millions of target atoms, boosting orbital electrons into higher energy levels by an amount of energy equal to the decrease in kinetic energy of the bombarding electron. This energy is then radiated as the characteristic red light of neon when the electrons fall back to their stable orbits (to their ground states). The process occurs and recurs many times, as neon atoms continually undergo a cycle of excitation and de-excitation. The overall result of this process is the transformation of electrical energy into radiant energy.

The colors of various flames are due to excitation. Different atoms in the flame emit colors characteristic of their energy-level spacings. Common table salt placed in a flame, for example, produces the characteristic yellow of sodium. Every element, excited in a flame or otherwise, emits its own characteristic color or colors.

Street lamps provide another example. City streets are illuminated with light emitted by gases such as mercury vapor. The light from these lamps is rich in blues and violets and therefore is a different "white" than the light from previous incandescent lamps. Most street lamps use the glow of sodium gas, which consumes less energy. Sodium vapor lamps have an orange-yellow tint. See if your instructor has a spare prism or diffraction grating you can borrow. Look through the prism or grating at the light from street lamps and see the discreteness of the colors, which indicates the discreteness of the atomic levels. Note the different colors of mercury and sodium lamps.

FIGURE 30.3
Excitation and de-excitation.

Excitation is illustrated in the aurora borealis and australis (as pictured in the chapter opener). High-speed charged particles that originate in the solar wind strike atoms and molecules in the upper atmosphere. They emit light exactly as occurs in a neon tube. The different colors in the aurora correspond to the excitation of different gases—oxygen atoms produce a greenish-white color, nitrogen molecules produce red-violet, and nitrogen ions produce a blue-violet color. Auroral emissions are not restricted to visible light; they also include infrared, ultraviolet, and X-ray radiation.

The excitation/de-excitation process can be accurately described only by quantum mechanics. An attempt to view the process in terms of classical physics runs into contradictions. Classically, an accelerating electric charge produces electromagnetic radiation. Does this explain light emission by excited atoms? An electron does accelerate in a transition from a higher to a lower energy level. Just as the innermost planets of the solar system have greater orbital speeds than those in the outermost orbits, the electrons in the innermost orbits of the atom have greater speeds. An electron gains speed in dropping to lower energy levels. Fine—the accelerating electron radiates a photon! But not so fine—the electron is continually undergoing acceleration (centripetal acceleration) in any orbit, whether or not it changes energy levels. According to classical physics, it should continually radiate energy. But it doesn't. All attempts to explain the emission of light by an excited atom in terms of a classical

Exciting an atom is like trying to kick a ball out of a ditch. Many short kicks won't do the job, because the ball keeps falling back. A kick of just the right amount of energy is enough to get the ball out of the ditch. Likewise with the excitation of atoms.

model have been unsuccessful. We shall simply say that light is emitted when an electron in an atom makes a "quantum jump" from a higher to a lower energy level and that the energy and frequency of the emitted photon are described by $E = hf$.

CHECK POINT

Suppose a friend suggests that, for a first-rate operation, the gaseous neon atoms in a neon tube should be periodically replaced with fresh atoms because the energy of the atoms tends to be used up with continued excitation, producing dimmer and dimmer light. What do you say to this?

Check Your Answer

The neon atoms don't release any energy that is not given to them by the electric current in the tube and therefore don't get "used up." Any single atom may be excited and re-excited without limit. If the light is, in fact, becoming dimmer and dimmer, it is probably because a leak exists. Otherwise, there is no advantage whatsoever to changing the gas in the tube, because a "fresh" atom is indistinguishable from a "used" one. Both are ageless and older than the solar system.

Emission Spectra

Every element has its own characteristic pattern of electron energy levels and therefore emits light with its own characteristic pattern of frequencies, its **emission spectrum,** when excited. This pattern can be seen when light is passed through a prism—or, better, when it is first passed through a thin slit and then focused through a prism onto a viewing screen behind. Such an arrangement of slit, focusing lenses, and prism (or diffraction grating) is called a **spectroscope,** one of the most useful instruments of modern science (Figure 30.4).

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Tutorial
Light and Spectroscopy

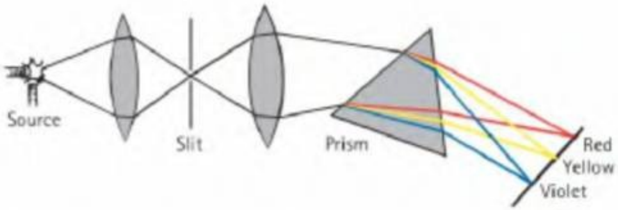

FIGURE 30.4
A simple spectroscope. Images of the illuminated slit are cast on a screen and make up a pattern of lines. The spectral pattern is characteristic of the light used to illuminate the slit.

Each component color is focused at a definite position, according to its frequency, and forms an image of the slit on the screen, photographic film, or appropriate detector. The different-colored images of the slit are called *spectral lines.* Some typical spectral patterns labeled by wavelengths are shown in Figure 30.5. It is customary to refer to colors in terms of their wavelengths rather than their frequencies. A given frequency corresponds to a definite wavelength.[1]

If the light given off by a sodium-vapor lamp is analyzed in a spectroscope, a single yellow line predominates—a single image of the slit. If we narrow the width of the slit, we find that this line is really composed of two very close lines. These lines correspond

[1]Recall, from Chapter 19, that $v = f\lambda$, where v is the wave speed, f is the wave frequency, and λ (lambda) is the wavelength. For light, v is the constant c, so we see from $c = f\lambda$ the relationship between frequency and wavelength—namely, $f = \frac{c}{\lambda}$ and $\lambda = \frac{c}{f}$.

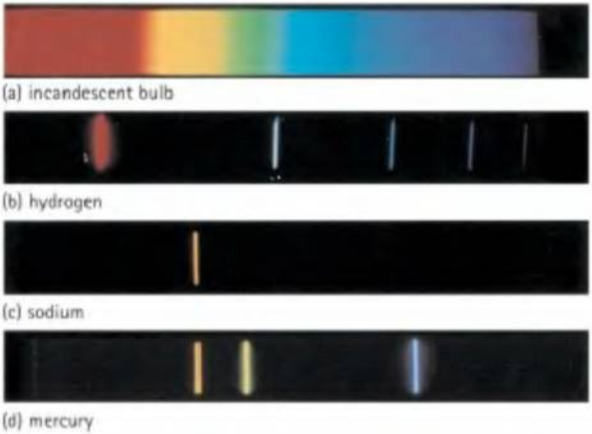

FIGURE 30.5

INTERACTIVE FIGURE

(a) An incandescent bulb has a continuous spectrum. Each of the three elements (b) hydrogen, (c) sodium, and (d) mercury has a different line spectrum.

to the two predominant frequencies of light emitted by excited sodium atoms. The rest of the spectrum looks dark. (Actually, there are many other lines, often too dim to be seen with the naked eye.) The same happens with all glowing vapors. The light from a mercury-vapor lamp shows a pair of bright yellow lines close together (but in different positions from those of sodium), a very intense green line, and several blue and violet lines. A neon tube produces a more complicated pattern of lines. We find that the light emitted by each element in the vapor phase produces its own characteristic pattern of lines. These lines correspond to the electron transitions between atomic energy levels and are as characteristic of each element as are the fingerprints of people. The spectroscope, therefore, is widely used in chemical analysis.

The next time you see evidence of atomic excitation, perhaps the green flame produced when a piece of copper is placed in a fire, squint your eyes and see if you can imagine electrons jumping from one energy level to another in a pattern characteristic of the atom being excited—a pattern that displays a color unique to that atom. That's what's happening!

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- Because every chemical element has its own *unique* set of energy levels, each element also has its own *distinctive pattern* of spectral absorption (and emission) lines—the *spectral "fingerprint"* that astronomers use to identify various chemical elements in astronomical objects.

CHECK POINT

Spectral patterns are not shapeless smears of light but, instead, consist of fine and distinct straight lines. Why is this so?

Check Your Answer

The spectral lines are simply images of the slit, which is itself a thin, straight opening through which light is admitted before being spread by the prism (or diffraction grating). When the slit is adjusted to make its most narrow opening, closely spaced lines can be resolved (distinguished from one another). A wider slit admits more light, which permits easier detection of dimmer radiant energy. But width is at the expense of resolution when closely spaced lines blur together.

Incandescence

Light that is produced as a result of high temperature has the property of **incandescence** (from a Latin word meaning "to grow hot"). It can have a reddish tint, as from the heating element of a toaster, or a bluish tint, as from a particularly hot star. Or it can be white, as from the familiar incandescent lamp. What sets incandescent light apart from the light of a neon tube or mercury vapor lamp is that it contains an infinite number of frequencies, spread smoothly across the spectrum. Does this mean that an infinite number of energy levels characterizes the tungsten atoms making up the filament of the incandescent lamp? The answer is no; if the filament were vaporized and then excited, the tungsten gas would emit light with a finite number of frequencies and produce an overall bluish color. Light emitted by atoms far from one another in the gaseous phase is quite different from the light emitted by the same atoms closely packed in the solid phase. This is analogous to the differences in sound from an isolated ringing bell and from a box crammed with ringing bells (Figure 30.6). In a gas, the atoms are far apart. Electrons undergo transitions between energy levels within the atom quite unaffected by the presence of neighboring atoms. But when the atoms are closely packed, as in a solid, electrons of the outer orbits make transitions not only within the energy levels of their "parent" atoms but also between the levels of neighboring atoms. They bounce around over dimensions larger than a single atom, resulting in an infinite variety of transitions—hence the infinite number of radiant-energy frequencies.

FIGURE 30.6

The sound of an isolated bell rings with a clear and distinct frequency, whereas the sound emanating from a box of bells crowded together is discordant. Likewise with the difference between the light emitted from atoms in the gaseous state and that from atoms in the solid state.

As might be expected, incandescent light depends on temperature, because it is a form of thermal radiation. A plot of radiated energy over a wide range of frequencies for two different temperatures is shown in Figure 30.7. (Recall that we treated the radiation curve for sunlight back in Chapter 27 and discussed blackbody radiation in Chapter 16.) As the solid is heated further, more high-energy transitions occur, and higher-frequency radiation is emitted. The curve comprises a continuous spectrum. In the brightest part of the spectrum, the predominant frequency of emitted radiation, the *peak frequency*, is directly proportional to the absolute temperature of the emitter:

$$\bar{f} \sim T$$

We use the bar above the f to indicate the peak frequency, for radiations of many frequencies are emitted from the incandescent source. If the temperature of an object (in kelvins) is doubled, the peak frequency of emitted radiation is doubled. The electromagnetic waves of violet light have nearly twice the frequency of red light waves. A violet-hot star, therefore, has nearly twice the surface temperature of a red-hot star.[2] The temperature of incandescent bodies, whether they be stars or blast-furnace interiors, can be determined by measuring the peak frequency (or color) of the radiant energy they emit.

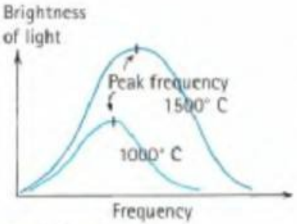


FIGURE 30.7

INTERACTIVE FIGURE

Radiation curves for an incandescent solid.

CHECK POINT

From the radiation curves shown in Figure 30.7, which emits the higher average frequency of radiant energy—the 1000°C source or the 1500°C source? Which emits more radiant energy?

Check Your Answers

The 1500°C radiating source emits the higher average frequencies, as noted by the extension of the curve to the right. The 1500°C source is brighter and also emits more radiant energy, as noted by its greater vertical displacement.

[2]If you study this topic further, then as mentioned in footnote 3 of Chapter 16, you will find that the time rate at which an object radiates energy (the radiated power) is proportional to the fourth power of its Kelvin temperature. So a doubling of temperature corresponds to a doubling of the frequency of radiant energy but a sixteenfold increase in the rate of emission of radiant energy.

Absorption Spectra

When we view white light from an incandescent source with a spectroscope, we see a continuous spectrum over the whole rainbow of colors. If a gas is placed between the source and the spectroscope, however, careful inspection will show that the spectrum is not quite continuous. This is an **absorption spectrum,** and there are dark lines distributed throughout it; these dark lines against a rainbow-colored background are like emission lines in reverse. These are *absorption lines.*

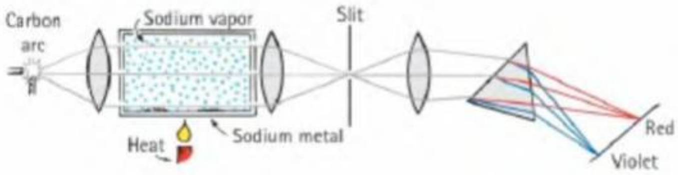


FIGURE 30.8
INTERACTIVE FIGURE
Experimental arrangement for demonstrating the absorption spectrum of a gas.

Atoms absorb light as well as emit light. An atom will most strongly absorb light having the frequencies to which it is tuned—some of the same frequencies it emits. When a beam of white light passes through a gas, the atoms of the gas absorb light of selected frequencies from the beam. This absorbed light is reradiated, but in *all* directions instead of only in the direction of the incident beam. When the light remaining in the beam spreads out into a spectrum, the frequencies that were absorbed appear as dark lines in the otherwise continuous spectrum. The positions of these dark lines correspond exactly to the positions of lines in an emission spectrum of the same gas (Figure 30.9).

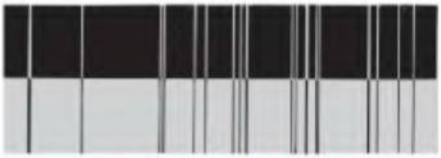


FIGURE 30.9
Emission and absorption spectra.

Although the Sun is a source of incandescent light, the spectrum it produces, upon close examination, is not continuous. There are many absorption lines, called *Fraunhofer lines* in honor of the Bavarian optician and physicist Joseph von Fraunhofer, who first observed and mapped them accurately. Similar lines are found in the spectra produced by the stars. These lines indicate that the Sun and stars are each surrounded by an atmosphere of cooler gases that absorb some of the frequencies of light coming from the main body. Analysis of these lines reveals the chemical composition of the atmospheres of such sources. We find from these analyses that the stellar elements are the same elements that exist on Earth. An interesting sidelight is that, in 1868, spectroscopic analysis of sunlight showed some spectral lines different from any known on Earth. These lines identified a new element, which was named *helium,* after Helios, the Greek god of the Sun. Helium was discovered in the Sun before it was discovered on Earth. How about that!

We can determine the speed of stars by studying the spectra they emit. Just as a moving sound source produces a Doppler shift in its pitch (Chapter 19), a moving light source produces a Doppler shift in its light frequency. The frequency (not the speed!) of light emitted by an approaching source is higher, while the frequency of light from a receding source is lower, than the frequency of light from a stationary source. The corresponding spectral lines are displaced toward the red end of the spectrum for receding sources. Since the universe is expanding, almost all the galaxies show a red shift in their spectra.

We shall see, in Chapter 31, how the spectra of elements enable us to determine atomic structure.

The Andromeda galaxy is approaching us, emitting light toward Earth that is blue-shifted.

CHECK POINT

Distinguish between *emission spectra*, *continuous spectra*, and *absorption spectra*.

Check Your Answer

Emission spectra are produced by thin gases in which the atoms do not experience many collisions. Continuous spectra result when atoms continually collide, which is why solids, liquids, or dense gases emit light at all the visible frequencies when heated. Absorption spectra occur when light passes through a dilute gas and atoms in the gas absorb at characteristic frequencies. Because the re-emitted light is unlikely to be emitted in the same direction as the absorbed photons, dark lines (absence of light) occur in the spectrum.

Fluorescence

Thermal agitation and bombardment by particles, such as high-speed electrons, are not the only means of imparting excitation energy to an atom. An atom may be excited by absorbing a photon of light. From the relationship $E = hf$, we see that high-frequency light, such as ultraviolet, which lies beyond the visible spectrum, delivers more energy per photon than lower-frequency light. Many substances undergo excitation when illuminated with ultraviolet light.

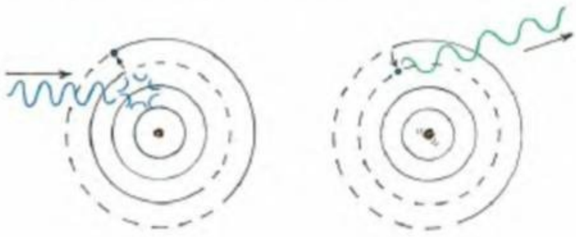


FIGURE 30.10

INTERACTIVE FIGURE

In fluorescence, the energy of the absorbed ultraviolet photon boosts the electron in an atom to a higher energy state. When the electron then returns to an intermediate state, the photon emitted is less energetic and therefore of a lower frequency than the ultraviolet photon.

Many materials that are excited by ultraviolet light emit visible light upon de-excitation. The action of these materials is called **fluorescence.** In these materials, a photon of ultraviolet light excites the atom, boosting an electron to a higher energy state. In this upward quantum jump, the atom is likely to leapfrog over several intermediate energy states. So when the atom de-excites, it may make smaller jumps, emitting photons with less energy.

This excitation and de-excitation process is like leaping up a small staircase in a single bound, and then descending one or two steps at a time rather than leaping all the way down in a single bound. Photons of lower frequencies are emitted. Hence, ultraviolet light shining on the material causes it to glow an overall red, yellow, or

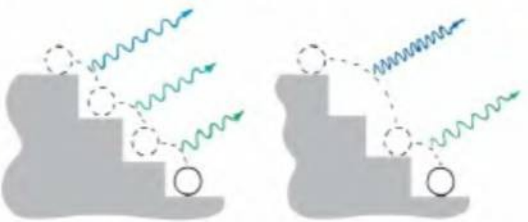


FIGURE 30.11

An excited atom may de-excite in several combinations of jumps.

whatever color is characteristic of the material. Fluorescent dyes are used in paints and fabrics to make them glow when bombarded with ultraviolet photons in sunlight. They can be spectacular when illuminated with an ultraviolet lamp.

Detergents that make the claim of cleaning your clothes "whiter than white" use the principle of fluorescence. Such detergents contain a fluorescent dye that converts the ultraviolet light in sunlight into blue visible light, so clothes washed in this way appear to reflect more blue light than they otherwise would. This makes the clothes appear whiter.[3]

The next time you visit a natural-science museum, go to the geology section and take in the exhibit of minerals illuminated with ultraviolet light (Figure 30.13). You'll notice that different minerals radiate various colors. This is to be expected because different minerals are composed of various elements, which, in turn, have a variety of sets of electron energy levels. Seeing the radiating minerals is a beautiful visual experience, which is even more fascinating when integrated with your knowledge of nature's submicroscopic happenings. High-energy ultraviolet photons strike the minerals, causing the excitation of atoms in the mineral structure. The frequencies of light that you see correspond to the tiny energy-level spacings as the energy cascades down. Every excited atom emits its characteristic frequencies, with no two different minerals emitting light of exactly the same color. Beauty is in both the eye and the mind of the beholder.

FIGURE 30.12
Crayons fluorescing in various colors under ultraviolet light.

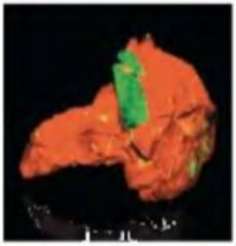


FIGURE 30.13
The rock contains the fluorescing minerals calcite and willemite, which, under ultraviolet light, are clearly seen as red and green, respectively.

CHECK POINT

Why would it be impossible for a fluorescent material to emit ultraviolet light when illuminated by infrared light?

Check Your Answer

Photon energy output would be greater than photon energy input, which would violate the law of conservation of energy.

Phosphorescence

When excited, certain crystals as well as some large organic molecules remain in a state of excitation for a prolonged period of time. Unlike what occurs in fluorescent materials, their electrons are boosted into higher orbits and become "stuck." As a result, there is a time delay between the processes of excitation and de-excitation. Materials that exhibit this peculiar property are said to have **phosphorescence.**

The element phosphorus is used in a variety of luminous materials, even toothbrushes, that are made to glow in the dark. Atoms or molecules in these materials are excited by incident visible light. Rather than de-exciting immediately, as fluorescent materials do, many of the atoms remain in a *metastable state*—a prolonged state of excitation—sometimes as long as several hours, although most de-excite rather quickly. If the source of excitation is removed—for instance, if the lights are put out—an afterglow occurs while millions of atoms spontaneously undergo gradual de-excitation. The afterglow of some phosphorescent light switches in the home may last more than an hour. Likewise for luminous clock dials, which are excited by visible light. Some older clock dials glow indefinitely in the dark, not because of a long time delay between excitation and de-excitation, but because they contain radium or some other radioactive material that continuously supplies energy to keep the excitation process

fyi

- To make counterfeiting more difficult, many governments, including the U.S. government, use fluorescence. See this yourself by exposing any new-style U.S. currency to UV light. Near one end, a line will appear that cannot be seen with visible light. This fluorescent thread can be seen on the front and back of the bill.

[3]Interestingly enough, the same detergents marketed in Mexico and some other countries are adjusted for a rosier, warmer effect.

going. Such dials are no longer common because of the potential harm of the radioactive material to the user, especially if in a wristwatch or pocket watch.[4]

Many living creatures—from bacteria to fireflies and larger animals, such as jellyfish—chemically excite molecules in their bodies that emit light. We say that such living things are *bioluminescent.* Under some conditions, certain fish become luminescent when they swim but remain dark when stationary. Schools of these fish hang motionless and are not seen, but when they are alarmed, they streak the depths with sudden light, creating a sort of deep-sea fireworks. The mechanism of bioluminescence is not well understood and is currently being researched.

CHECK POINT

Distinguish between fluorescence and phosphorescence in terms of time.

Check Your Answer

Fluorescent materials emit light immediately after being excited. For phosphorescent materials there is a time delay between excitation and de-excitation.

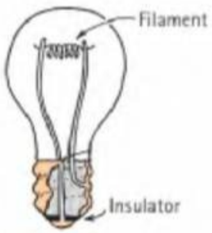


FIGURE 30.14
Simplified version of an incandescent bulb. A voltage source provides surges of energy to electrons in the high-resistance filament. A relatively small portion of this energy is converted to light.

fyi

- Although the incandescent bulb was not invented by Thomas Edison, he was the first to build one that outperformed other versions of the time and went on to invent an entire integrated system of electric lighting.

Lamps

INCANDESCENT LAMP

The common incandescent lamp consists of a glass enclosure with a filament of tungsten wire inside, through which an electric current is passed (Figure 30.14). The current typically heats the filament to 2000 K to 3300 K, well below tungsten's melting point of 3695 K. The hot filament emits a continuous spectrum, mostly in the infrared, with visible light as the smaller and useful part. The glass enclosure prevents oxygen in air from reaching the hot filament, which otherwise would be destroyed by rapid oxidation. Eventually, the filament fails anyway because of its gradual evaporation, which leads finally to a break in the filament and to the bulb "burning out."

Typically, argon is the gas inside the enclosure. If a small amount of a halogen element such as iodine is added to the interior, the evaporation of the tungsten is slowed and the bulb lasts longer. The action of the halogen requires that the whole bulb be hotter (don't touch a glowing halogen lamp!), so it is made smaller and usually encased in heat-resistant quartz. The halogen lamp may also be somewhat more efficient than the conventional incandescent lamp.

The efficiency of incandescent lightbulbs as visible light emitters is typically less than 10%. Hence, they are gradually being replaced by lamps that convert a greater percentage of electrical energy into visible light.

FLUORESCENT LAMP

The common fluorescent lamp consists of a cylindrical glass tube with electrodes at each end (Figure 30.15). In the lamp, as in the tube of a neon sign, electrons

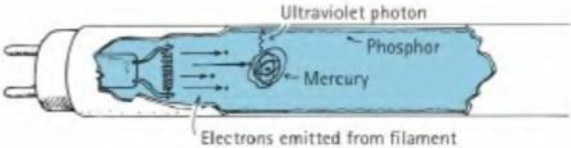


FIGURE 30.15
A fluorescent tube. Ultraviolet (UV) light is emitted by gas in the tube excited by an alternating electric current. The UV light, in turn, excites phosphors on the inner surface of the glass tube, which emit white light.

[4]A radioactive form of hydrogen called *tritium*, however, can serve to keep watch dials illuminated harmlessly. This is because its radiation doesn't have enough energy to penetrate the metal or plastic of the watch case.

are boiled from one of the electrodes and forced to vibrate to and fro at high speeds within the tube by the ac voltage. The tube is filled with very-low-pressure mercury vapor added to argon. Mercury atoms are excited by the impact of the high-speed electrons. Much of the emitted light is in the ultraviolet region. This is the primary excitation process. The secondary process occurs when the ultraviolet light strikes *phosphors*, a powdery material on the inner surface of the tube. The phosphors are excited by the absorption of the ultraviolet photons and fluoresce, emitting a multitude of lower-frequency photons that combine to produce white light. Different phosphors can be used to produce different colors or "textures" of light.

FIGURE 30.16
This pair of 23-W CFLs emit as much light as a pair of 100-W incandescent lightbulbs operating at the same voltage.

COMPACT FLUORESCENT LAMP (CFL)

Miniaturize a fluorescent tube, wrap it into a coil, and outfit it with the same kind of plug a common incandescent lamp has, and you have a compact fluorescent lamp (CFL). Like the traditional tube-type fluorescent lamps, CFLs are more efficient than incandescent lamps, putting out about 4 times more light for the same power input. They fit into conventional lamp sockets and have lifetimes more than 10 times that of incandescent bulbs. As mentioned above and in Chapter 23, incandescent lamps are being replaced with more efficient lighting.

Like the tubular lamp, there are two main parts in a CFL: the gas-filled tube (mercury vapor mixed with argon) and the magnetic or electronic ballast. Whereas the ballasts used in early fluorescent tubes were magnetic, electronic ballasts are now much more common and don't flicker as the earlier ones did. The ballast provides the initial kick to start an arc discharge, boosts operating frequency via its transistors, and stabilizes current. Phosphors on the interior of the lamp can be chosen to produce not only different hues of white light but also colored light: yellow for outdoor lighting that does not attract insects; or long-wave ultraviolet for special effects.

A downside to the CFL is its mercury content, which poses environmental disposal problems. A more attractive alternative for lighting is the up-and-coming LED.

LIGHT-EMITTING DIODE (LED)

When a diode collects light and produces electricity it's a solar cell. When the input is electricity and the output light, it's an LED. Just another nice symmetry in physics!

A diode is a two-terminal electronic device that permits a flow of charge in only one direction. Recall from Chapter 23 our brief discussion of a diode in converting ac to dc in electric circuits. Diodes serve a variety of functions, including regulation of voltage in circuits, signal amplification, measuring illumination, and converting light to electricity as photocells. One kind of diode design is the reverse of a photocell, in that an impressed voltage stimulates the emission of light! This is a light-emitting diode, LED. The first LEDs developed in the 1960s produced the red light common in instrument panels of the time. They let you know whether your DVD player is off or on. LEDs that emit a full range of colors were developed in the 1990s. Today, LEDs have advanced beyond indicator displays of electronic appliances and are common in traffic lights, automobile brake lights, airport runway lighting, warning lights on TV transmission towers, and even billboards. LEDs are compact, efficient, require no filament, are long-lasting (about 100 times longer than incandescent bulbs), and contain no harmful mercury.

FIGURE 30.17
Evan holds two LEDs. The larger one, a GeoBulb (www.ccrane.com), uses less than 8 W and is the first direct replacement for a same-size incandescent 60-W bulb. The smaller LED, common in flashlights, emits 15 times as much light per watt as an incandescent bulb.

In one common LED design, a layer of a semiconductor that contains free electrons is deposited onto the surface of another semiconductor that contains energy "holes" that can accept the free electrons. An electrical barrier at the boundary of these two materials blocks electron flow (Figure 30.18a). But when an external voltage is applied, the barrier is overcome and energetic electrons cross over and "drop" into energy "holes." In a way similar to de-excitation, dropped electrons lose potential energy that is converted into quanta of light—photons (Fig. 30.18b). Just as a bowling ball rolling off of a table makes a loud "kerplunk" when it hits the floor, the analogous "kerplunk" of electrons in an LED is the emission of light. The drop in electron energy is converted to light.

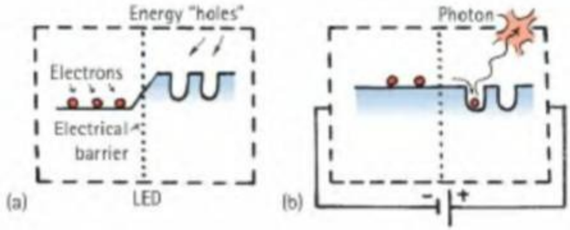


FIGURE 30.18
(a) An LED chip consists of two semiconductors, one with loose electrons, the other with "holes." (b) When a voltage is applied, electrons cross the barrier, occupy the holes, and emit light. The 0.25-mm square chip is surrounded by a transparent epoxy dome (not shown) of about 2 to 10 mm in diameter.

fyi

- One type of diode, the organic light emitting diode (OLED), is thin, lightweight, bright, and easy to manufacture. OLEDs may become important in the production of large flexible displays, wall decorations, and even illuminated clothing! This possibility gives new meaning to the phrase, "blue jeans!"

The elements used in the manufacture of an LED determine the depth of the energy "holes" and hence the color of the emitted photons. A greater energy drop releases light closer to blue; a lesser energy drop releases light toward the red. The huge commercial LED display in the billboard shown in the opening photographs of this chapter is composed of arrays of LEDs in sets of three. Each LED in a set can produce a single color: red, green, or blue. As with the displays of TV screens, each LED is activated to produce the desired mix of red, green, and blue. The full range of colors follows the color-mixing rules of Chapter 27. Then there are white-light LEDs that employ phosphors.

Lasers

The phenomena of excitation, fluorescence, and phosphorescence underlie the operation of a most intriguing instrument, the **laser** (light amplification by stimulated emission of radiation).[5] Although the first laser was invented in 1958, the concept of stimulated emission was predicted by Albert Einstein in 1917. To understand how a laser operates, we must first discuss *coherent light.*

Light emitted by a common lamp is incoherent; that is, photons of many frequencies and in many phases of vibration are emitted. The light is as incoherent as the footsteps on an auditorium floor when a mob of people are chaotically rushing about. Incoherent light is chaotic. A beam of incoherent light spreads out after a short distance, becoming wider and wider and less intense with increased distance.

FIGURE 30.19
Incoherent white light contains waves of many frequencies (and of many wavelengths) that are out of phase with one another.

[5] A word constructed from the initials of a phrase is called an *acronym.*

Even if the beam is filtered so that it consists of single-frequency waves (monochromatic light), it is still incoherent, because the waves are out of phase with one another.

FIGURE 30.20
Light of a single frequency and wavelength still contains a mixture of phases.

A beam of photons having the same frequency, phase, and direction—that is, a beam of photons that are identical copies of one another—is said to be *coherent*. A laser emits a beam of coherent light that spreads and weakens very little.[6]

FIGURE 30.21
Coherent light. All the waves are identical, in phase, and in the same direction.

Every laser has a source of atoms called an active medium, which can be a gas, liquid, or solid (the first laser was a ruby crystal). The atoms in the medium are excited to metastable states by an external source of energy. When most of the atoms in the medium are excited, a single photon from an atom that undergoes de-excitation can start a chain reaction. This photon strikes another atom, stimulating it into emission, and so on, producing coherent light. Most of this light is initially moving in random directions. Light traveling along the laser axis, however, is reflected from mirrors coated to reflect light of the desired wavelength selectively. One mirror is totally reflecting, while the other is partially reflecting. The reflected waves reinforce each other after each round-trip reflection between the mirrors, thereby setting up a to-and-fro resonance condition wherein the light builds up to an appreciable intensity. The light that escapes through the more transparent-mirrored end makes up the laser beam. In addition to gas and crystal lasers, other types have joined the laser family: glass, chemical, liquid, and semiconductor lasers. Present models produce beams ranging from infrared through ultraviolet. Some models can be tuned to various frequency ranges.

A laser is not a source of energy. It is simply a converter of energy that takes advantage of the process of stimulated emission to concentrate a certain fraction of its energy (commonly 1%) into radiant energy of a single frequency moving in a single direction. Like all devices, a laser can put out no more energy than is put into it.

A laser beam is not seen unless it scatters off something in the air. Like sunbeams or moonbeams, what you see are the particles in the scattering medium, not the beam itself. When the beam strikes a diffuse surface, part of it is scattered toward your eye as a dot.

Lasers have found wide use in surgery. Lasers are also used in cutting and welding procedures, mainly where small parts are involved. They cut cleanly. Laser beams weld wires into microcircuits and repair damaged wires inside glass tubes. They are used in reading CDs and DVDs, and they create holograms. One day, they may trigger controlled fusion power. A huge application is in communications. Whereas radio wavelengths span hundreds of meters and television waves span many centimeters, wavelengths of laser light are measured in millionths of a centimeter. Correspondingly, laser-light frequencies are vastly greater than radio or television

[6] The narrowness of a laser beam is evident when you see a lecturer produce a tiny red spot on a screen using a laser "pointer." Light from an intense laser pointed at the Moon has been reflected and detected back on Earth, revealing the Earth–Moon distance to an inch or so.

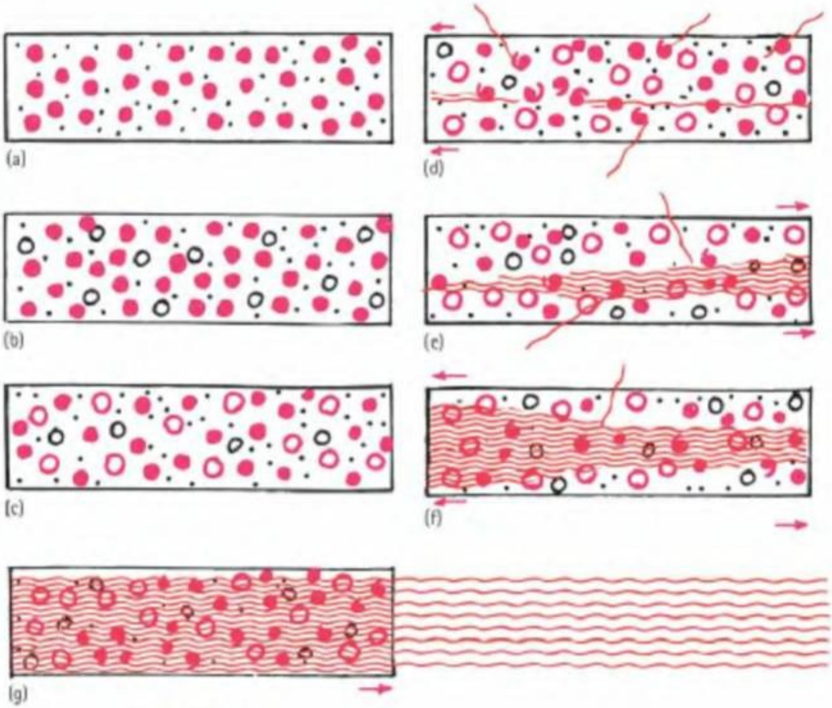


FIGURE 30.22

Laser action in a helium–neon laser.

(a) The laser consists of a narrow Pyrex tube that contains a low-pressure gas mixture consisting of 85% helium (small black dots) and 15% neon (large colored dots).

(b) When a high-voltage current zaps through the tube, it excites both helium and neon atoms to their usual higher states, and they immediately undergo de-excitation, except for one state in the helium that is characterized by a prolonged delay before de-excitation—a *metastable state.* Since this state is relatively stable, a sizable population of excited helium atoms (black open circles) is built up. These atoms wander about in the tube and act as an energy source for neon, which has an otherwise hard-to-come-by metastable state very close to the energy of the excited helium.

(c) When excited helium atoms collide with neon atoms in their lowest energy state (ground state), the helium gives up its energy to the neon, which is boosted to its metastable state (red open circles). The process continues, and the population of excited neon atoms soon outnumbers neon atoms in a lower-energy excited state. This inverted population is, in effect, waiting to radiate its energy.

(d) Some neon atoms eventually de-excite and radiate red photons in the tube. When this radiant energy passes other excited neon atoms, the latter are stimulated into emitting photons exactly in phase with the radiant energy that stimulated the emission. Photons pass out of the tube in irregular directions, giving it a red glow.

(e) Photons moving parallel to the axis of the tube are reflected from specially coated parallel mirrors at the ends of the tube. The reflected photons stimulate the emission of photons from other neon atoms, thereby producing an avalanche of photons having the same frequency, phase, and direction.

(f) The photons flash to and fro between the mirrors, becoming amplified with each pass.

(g) Some photons "leak" out of one of the mirrors, which is only partially reflecting. These make up the laser beam.

frequencies. As a result, laser light can transmit an enormous number of messages bunched into a very narrow band of frequencies. Communications can be carried in a laser beam directed through space, through the atmosphere, or through optical fibers (light pipes) that can be bent like cables.

The laser is at work at supermarket checkout counters, where code-reading machines scan the universal product code (UPC) symbol printed on packages and on the back cover of this book. Laser light is reflected from the bars and spaces and converted to an electric signal as the symbol is scanned. The signal rises to a high value when reflected from a bright space and falls to a low value when reflected from a dark bar. The information on the thickness and spacing of the bars is "digitized" (converted into the 1s and 0s of binary code) and processed by a computer.

Environmental scientists use lasers to measure and detect pollutants in exhaust gases. Different gases absorb light at characteristic wavelengths and leave their "fingerprints" on a reflected beam of laser light. The specific wavelength and amount of light absorbed are analyzed by a computer, which produces an immediate tabulation of the pollutants.

Lasers have ushered in a whole new technology, the promise of which we continually tap. The future for laser applications seems unlimited.

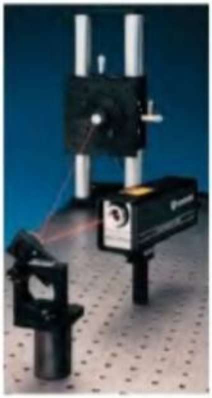


FIGURE 30.23
A helium–neon laser.

SUMMARY OF TERMS

Excitation The process of boosting one or more electrons in an atom or molecule from a lower to a higher energy level. An atom in an excited state will usually decay (de-excite) rapidly to a lower state by the emission of a photon. The energy of the photon is proportional to its frequency: $E = hf$.

Emission spectrum The distribution of wavelengths in the light from a luminous source.

Spectroscope An optical instrument that separates light into its constituent wavelengths in the form of spectral lines.

Incandescence The state of glowing while at a high temperature, caused by electrons bouncing around over dimensions larger than the size of an atom, emitting radiant energy in the process. The peak frequency of radiant energy is proportional to the absolute temperature of the heated substance:

$$\bar{f} \sim T$$

Absorption spectrum A continuous spectrum, like that of white light, interrupted by dark lines or bands that result from the absorption of light of certain frequencies by a substance through which the radiant energy passes.

Fluorescence The property of certain substances to absorb radiation of one frequency and to re-emit radiation of lower frequency. It occurs when an atom is boosted up to an excited state and loses its energy in two or more downward jumps to a lower energy state.

Phosphorescence A type of light emission that is the same as fluorescence except for a delay between excitation and de-excitation, which provides an afterglow. The delay is caused by atoms being excited to energy states that do not decay rapidly. The afterglow may last from fractions of a second to hours or even days, depending on the type of material, temperature, and other factors.

Laser (light amplification by stimulated emission of radiation) An optical instrument that produces a beam of coherent monochromatic light.

REVIEW QUESTIONS

Light Emission

1. If electrons are made to vibrate to and fro at a few hundred thousand hertz, radio waves are emitted. What class of waves is emitted when electrons are made to vibrate to and fro at a few million billion hertz?
2. What does it mean to say an energy state is *discrete?*

Excitation

3. Relative to the atomic nucleus, which has more potential energy, electrons in inner electron shells or electrons in outer electron shells?
4. In a neon tube, what occurs immediately after an atom is excited?
5. What is the relationship between the *difference in energy* between energy levels and the *energy of the photon* that is emitted by a transition between those levels?
6. How is the *energy* of a photon related to its vibrational frequency?
7. Which has the higher *frequency*, red or blue light? Which has the greater *energy* per photon, red or blue light?
8. Can a neon atom in a glass tube be excited more than once? Explain.
9. What do the various colors displayed in the flame of a burning log represent?
10. Which puts out the greater percentage of its energy as light, an incandescent lamp or a mercury-vapor lamp?

Emission Spectra

11. What is a *spectroscope,* and what does it accomplish?

Incandescence

12. When a gas glows, discrete colors are emitted. When a solid glows, the colors are smudged. Why?
13. How is the peak frequency of emitted light related to the temperature of its incandescent source?

Absorption Spectra

14. How does an absorption spectrum differ in appearance from an emission spectrum?
15. What are Fraunhofer lines?
16. How can astrophysicists tell whether a star is receding or approaching Earth?

Fluorescence

17. Why is ultraviolet light, but not infrared light, effective in making certain materials fluoresce?

Phosphorescence

18. Distinguish between *fluorescence* and *phosphorescence.*
19. What is a *metastable state?*

Lamps

20. Why is argon, instead of air, used inside an incandescent bulb?
21. Distinguish between the primary and secondary excitation processes that occur in a fluorescent lamp.
22. How does the lifetime of a typical CFL compare with that of an incandescent bulb?
23. How does the lifetime of a typical LED compare with that of an incandescent bulb?

Lasers

24. Distinguish between *monochromatic light* and *coherent light.*
25. How does the avalanche of photons in a laser beam differ from the hordes of photons emitted by an incandescent lamp?

PROJECTS

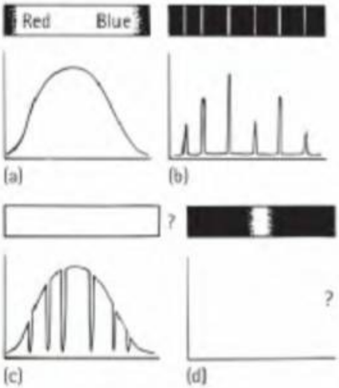
1. Write a letter to Grandma to explain how light is emitted from lamps, flames, and lasers. Tell her why fluorescent dyes and paints are so impressively vivid when illuminated with an ultraviolet lamp. Go on to tell her about the higher efficiencies of CFLs and LEDs.
2. Borrow a diffraction grating from your physics instructor. The common kind looks like a photographic slide, and light passing through it or reflecting from it is diffracted into its component colors by thousands of finely ruled lines. Look through the grating at the light from a sodium-vapor street lamp. If it's a low-pressure lamp, you'll see the nice yellow spectral "line" that dominates sodium light (actually, it's two closely spaced lines). If the street lamp is round, you'll see circles instead of lines; if you look through a slit cut in cardboard or some similar material, you'll see lines. What happens with the now common high-pressure sodium lamps is more interesting. Because of the collisions of excited atoms, you'll see a smeared-out spectrum that is nearly continuous, almost like that of an incandescent lamp. Right at the yellow location, where you'd expect to see the sodium line, is a dark area. This is the sodium absorption band. It is due to the cooler sodium, which surrounds the high-pressure emission region. You should view this a block or so away so that the line, or circle, is small enough to allow the resolution to be maintained. Try this. It is very easy to see!

EXERCISES

1. Why is a gamma-ray photon more energetic than an X-ray photon?
2. Have you ever watched a fire and noticed that the burning of various materials often produces flames of different colors? Why is this so?
3. Green light is emitted when electrons in a substance make a particular energy-level transition. If blue light were instead emitted from the same substance, would it correspond to a greater or lesser change of energy in the atom?
4. Ultraviolet light causes sunburns, whereas visible light, even of greater intensity, does not. Why is this so?
5. If we double the frequency of light, we double the energy of each of its photons. If we instead double the wavelength of light, what happens to the photon energy?
6. Why doesn't a neon sign finally "run out" of atoms to excite and produce dimmer and dimmer light?
7. An investigator wishes spectral lines in a spectrum to be thin crescents. What change in the spectroscope will accomplish this?
8. If light were passed through a round hole instead of a thin slit in a spectroscope, how would the spectral "lines" appear? What is the drawback of a hole in comparison with a slit?
9. If we use a prism or a diffraction grating to compare the red light from a common neon tube and the red light from a helium–neon laser, what striking difference do we see?
10. What is the evidence for the claim that iron exists in the relatively cool outer layer of the Sun?
11. How might the Fraunhofer lines in the spectrum of sunlight that are due to absorption in the Sun's atmosphere be distinguished from those due to absorption by gases in Earth's atmosphere?

12. In what specific way does light from distant stars and galaxies tell astronomers that atoms throughout the universe have the same properties as those on Earth?
13. What difference does an astronomer see between the emission spectrum of an element in a receding star and a spectrum of the same element in the lab? (*Hint:* This relates to information in Chapter 19.)
14. A blue-hot star is about twice as hot as a red-hot star. But the temperatures of the gases in advertising signs are about the same, whether they emit red or blue light. What is your explanation?
15. Which has the greatest energy—a photon of infrared light, of visible light, or of ultraviolet light?
16. Does atomic excitation occur in solids as well as in gases? How does the radiant energy from an incandescent solid differ from the radiant energy emitted by an excited gas?
17. Low-pressure sodium-vapor lamps emit line spectra with well-defined wavelengths, but high-pressure sodium-vapor lamps emit light whose lines are more spread out. Relate this to the continuous smear of wavelengths emitted by solids.
18. A lamp filament is made of tungsten. Why do we get a continuous spectrum rather than a tungsten line spectrum when light from an incandescent lamp is viewed with a spectroscope?
19. How can a hydrogen atom, which has only one electron, have so many spectral lines?
20. Since an absorbing gas re-emits the light it absorbs, why are there dark lines in an absorption spectrum? That is, why doesn't the re-emitted light simply fill in the dark places?
21. If atoms of a substance absorb ultraviolet light and emit red light, what becomes of the "missing" energy?
22. (a) Light from an incandescent source is passed through sodium vapor and then examined with a spectroscope. What is the appearance of the spectrum? (b) The incandescent source is switched off and the sodium is heated until it glows. How does the spectrum of the glowing sodium compare with the previously observed spectrum?
23. Your friend reasons that if ultraviolet light can activate the process of *fluorescence,* infrared light ought to also. Your friend looks to you for approval or disapproval of this idea. What is your position?
24. When ultraviolet light falls on certain dyes, visible light is emitted. Why does this not happen when infrared light falls on these dyes?
25. Why are fabrics that fluoresce when exposed to ultraviolet light so bright in sunlight?
26. Why do different fluorescent minerals emit different colors when illuminated with ultraviolet light?
27. Some doors have spring-and-damper combinations so they close slowly when released. How is this similar to phosphorescence?
28. When a certain material is illuminated with visible light, electrons jump from lower to higher energy states in atoms of the material. When illuminated by ultraviolet light, atoms are ionized as some of them eject electrons. Why do the two kinds of illumination produce such different results?
29. To keep chickens warm in a chicken coop, why would a CFL be a poor choice compared with an incandescent bulb?
30. Why are LEDs the lamps of choice in hard-to-get-to places, such as high ceilings?
31. What color results when a red and a green LED shine together?
32. Cite at least two reasons for predicting that LEDs will emerge as more popular than CFLs.
33. The forerunner to the laser involved microwaves rather than visible light. What does *maser* mean?
34. The first laser consisted of a red ruby rod activated by a photoflash tube that emitted green light. Why would a laser composed of a green crystal rod and a photoflash tube that emits red light not work?
35. A laboratory laser has a power of only 0.8 mW, 8×10^{-4} W. Why does it seem more powerful than light from a 100-W lamp?
36. How do the avalanches of photons in a laser beam differ from the hordes of photons emitted by an incandescent lamp?
37. In the operation of a helium–neon laser, why is it important that the metastable state of helium be relatively long-lived? (What would be the effect of this state de-exciting too rapidly?) (Refer to Figure 30.22.)
38. In the operation of a helium–neon laser, why is it important that the metastable state in the helium atom closely match the energy level of a more-difficult-to-come-by metastable state in neon?
39. A friend speculates that scientists in a certain country have developed a laser that produces far more energy than is put into it and asks for your response. What is your response?
40. A laser cannot produce more energy than is put into it. A laser can, however, produce pulses of light with more power output than the power input required to run the laser. Explain.
41. In the equation $\bar{f} \sim T$, what do the symbols f and T represent?
42. We know that an incandescent lamp filament at 2500 K radiates white light. Does the lamp filament also radiate energy when it is at room temperature?
43. We know that the Sun radiates energy. Does Earth similarly radiate energy? If so, what is different about their radiations?
44. Since every object has some temperature, every object radiates energy. Why, then, can't we see objects in the dark?
45. If we continue heating a piece of initially room-temperature metal in a dark room, it will begin to glow visibly. What will be its first visible color, and why?
46. We can heat a piece of metal to red-hot and then to white-hot. Can we heat it until the metal glows blue-hot?
47. How do the surface temperatures of reddish, bluish, and whitish stars compare?
48. If you see a red-hot star, you can be certain that its peak intensity is in the infrared region. Why is this?
49. If you see a "violet-hot" star, you can be certain its peak intensity is in the ultraviolet range. Why is this?
50. We perceive a "green-hot" star not as green but as white. Why? (*Hint:* Consider the radiation curve back in Figures 27.7 and 27.8, and in Figure 30.7.)

51. Sketch (a) below shows a radiation curve of an incandescent solid and its spectral pattern as produced with a spectroscope. Sketch (b) shows the "radiation curve" of an excited gas and its emission spectral pattern. Sketch (c) shows the curve produced when a cool gas is between an incandescent source and the viewer; the corresponding spectral pattern is left as an exercise for you to construct. Sketch (d) shows the spectral pattern of an incandescent source as seen through a piece of green glass; you are to sketch in the corresponding radiation curve.



52. Consider just four of the energy levels in a certain atom, as shown in the diagram. How many spectral lines will result from all possible transitions among these levels? Which transition corresponds to the highest-frequency light emitted? To the lowest-frequency light emitted?

53. An electron de-excites from the fourth quantum level in the diagram of Exercise 52 to the third and then directly to the ground state. Two photons are emitted. How does the sum of their frequencies compare with the frequency of the single photon that would be emitted by de-excitation from the fourth level directly to the ground state?

54. For the transitions described in the previous exercise, is there any relationship among the wavelengths of the emitted photons?

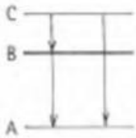
55. Suppose the four energy levels in Exercise 52 were somehow evenly spaced. How many spectral lines would result?

PROBLEM

In the diagram, the energy difference between states A and B is twice the energy difference between states B and C. In a transition (quantum jump) from C to B, an electron emits a photon of wavelength 600 nm.

a. What is the wavelength emitted when the photon jumps from B to A?

b. When it jumps from C to A?



CHAPTER 30 ONLINE RESOURCES

PhysicsPlace.com

Interactive Figures

- 30.2, 30.5, 30.7, 30.8, 30.10

Tutorial

- Light and Spectroscopy

Quizzes

Flashcards

Links

31 Light Quanta

1 Phil Wolf, co-author of *Problem Solving in Conceptual Physics*, demonstrates the photoelectric effect by directing light of different frequencies onto a photocell and measuring the energies of ejected electrons. 2 Busy physicists at a control center at the CERN Super Proton Synchrotron in France, on the Swiss border near Geneva. The control center combines the control rooms of the laboratory's eight accelerators. 3 Anne Cox, co-author of *Physlet Quantum Physics*, aligns an optical tweezer with her students at Eckerd College in Florida.

As a youth in Germany, Max Planck was a gifted musician. He sang, played various instruments, and composed songs and operas. Instead of studying music, however, he chose to study physics, earning his doctorate in1879 when he was 21. At the time, the two great theories of physics being actively pursued were thermodynamics, the study of heat, and electromagnetism, the study of radiation. Little did Planck guess that in trying to blend these two fields, he would usher in a whole new physics of the 20th century—*quantum mechanics*.

In 1900, perplexing questions about the radiation of thermal energy remained unanswered. The way in which the energy of thermal radiation is distributed over different frequencies had been carefully measured, but no one had been able to provide a theory to account for the results. In hopes of providing a theoretical answer, Planck, at the "advanced" age of 42, made a hypothesis that he called "an act of despair." He proposed that when a warm object emits radiant energy, it loses energy not continuously but in discrete amounts, or lumps, which he called *quanta*. Moreover, he postulated that the quantum of energy that is radiated is proportional to the frequency of the radiation. With this theory he could explain how the energy in thermal radiation is distributed over different frequencies. Five years later Einstein (then 26) took the next step, proposing that not only is energy added to light in quantum units but light itself exists as quantum lumps, or "corpuscles," later named photons.

In recognition for introducing the quantum, Planck was awarded the Nobel Prize in Physics in 1918.

Interestingly, Planck himself never accepted the photon idea. In 1912, in a classic put-down, Planck wrote that because of other achievements, Einstein deserved membership in the Prussian Academy of Sciences, despite having gone astray in proposing a corpuscle of light.

Planck had twin daughters, Emma and Grete, and two sons, Karl and Erwin. During the First World War his younger son, Erwin, was taken prisoner by the French in 1914, and his older son, Karl, was killed in action at Verdun. Soon after and two years apart, both daughters died while giving birth. Planck endured these losses stoically.

When Hitler came to power in 1933, Planck at first hoped that Nazism would be a temporary affliction, but eventually he made his distaste for the Nazis plain, and in 1938 he resigned the presidency of the Prussian Academy in protest. In 1944, at the height of World War II, Planck's house in Berlin was completely destroyed by Allied bombing raids. In the same year his son Erwin was implicated in the attempt made on Hitler's life in the famed July 20 plot. Although it is said that Erwin could have been spared had Planck joined the Nazi Party, Planck took a stand and refused to join. Erwin was hanged in early 1945, which devastated his elderly father. Planck died two years later in 1947, at age 89.

Birth of the Quantum Theory

The classical physics that we have so far studied deals with two categories of phenomena: particles and waves. In accord with Newton's laws, "particles" are tiny objects like bullets that have mass and travel through space in straight lines unless a force acts upon them. Likewise, "waves," like those of sound or in the ocean, are phenomena that *extend* in space. When a wave travels through an opening or around a barrier, the wave diffracts and different parts of the wave interfere. Therefore, particles and waves are easy to distinguish from each other. In fact, they have properties that are mutually exclusive. Nonetheless, the question of how to classify light was a mystery for centuries.

One of the early theories about the nature of light is that of Plato, who lived in the 5th and 4th centuries BC. Plato thought that light consisted of streamers emitted by the eye. Euclid, who lived roughly a century later, also held this view. On the other hand, the Pythagoreans believed that light emanated from luminous bodies in the form of very fine particles, while Empedocles, a predecessor of Plato, taught that light is composed of high-speed waves of some sort. For more than 2000 years, the questions remained unanswered. Does light consist of waves or particles?

In 1704, Isaac Newton described light as a stream of particles. He held this view despite his knowledge of what we now call polarization and despite his experiment with light reflecting from glass plates, in which he noticed fringes of brightness and darkness (Newton's rings). He knew that his particles of light had to have certain wave properties too. Christian Huygens, a contemporary of Newton, advocated a wave theory of light.

With all this history as background, Thomas Young, in 1801, performed the "double-slit experiment," which seemed to prove, finally, that light is a wave phenomenon. This view was reinforced in 1862 by Maxwell's prediction that light carries energy in oscillating electric and magnetic fields. Twenty-five years later, Heinrich Hertz used sparking electric circuits to demonstrate the reality of electromagnetic waves (of radio frequency). As mentioned above, Max Planck in 1900 hypothesized that radiant energy was emitted in discrete bundles, each of which he called a **quantum.** According to Planck, the energy in each energy bundle is proportional to the frequency of radiation ($E \sim f$, which we treated in the previous chapter). His hypothesis began a revolution of ideas that has completely changed the way we think about the physical world. Planck's hypothesis was given credence in 1905 when Albert Einstein published a Nobel Prize-winning paper that challenged the wave theory of light by arguing that light interacts with matter, not in continuous waves, as Maxwell envisioned, but in tiny packets of energy as Planck had suggested, which we now call *photons*. Broadly speaking, the body of laws developed from 1900 to the late 1920s that describe all quantum phenomena of the microworld is known as **quantum physics.**

Quantization and Planck's Constant

Quantization, the idea that the natural world is granular rather than continuously smooth, is certainly not a new idea to physics. Matter is quantized: the mass of a bar of gold, for example, is equal to some whole-number multiple of the mass of a single gold atom. Electricity is quantized, as electric charge is always some whole-number multiple of the charge of a single electron.

Quantum physics states that in the microworld of the atom, the amount of energy in any system is quantized—not all values of energy are possible. This is analogous to saying a campfire can only be so hot. It might burn at 450°C or it might burn at 451°C, but can't burn at 450.5°C. Believe it? Well, you shouldn't, for as far as our macroscopic thermometers can measure, a campfire can burn at any temperature as long as it's above the minimum temperature that is required for combustion. But the energy of the campfire, interestingly enough, is the composite energy of a great number and a great variety of elemental units of energy. A simpler example is the energy in a beam of laser light, which is a whole-number multiple of a single lowest value of energy—one quantum. The quanta of light, and of electromagnetic radiation in general, are the photons. (The plural of quantum is *quanta*.)

Recall, from the previous chapter, that the energy of a photon is given by $E = hf$, where h is **Planck's constant** (the single number that results when the energy of a photon is divided by its frequency).[1] We shall see that Planck's constant is a fundamental constant of nature that serves to set a lower limit on the smallness of things. It ranks with the velocity of light and Newton's gravitational constant as a basic constant of nature, and it appears again and again in quantum physics. The equation $E = hf$ gives the smallest amount of energy that can be converted to light with frequency f. The radiation of light is not emitted continuously but is emitted as a stream of photons, with each photon throbbing at a frequency f and carrying an energy hf.

The equation $E = hf$ tells us why microwave radiation can't do the damage to molecules in living cells that ultraviolet light and X-rays can. Electromagnetic radiation interacts with matter only in discrete bundles of photons. So the relatively low frequency of microwaves ensures low energy per photon. Ultraviolet radiation, on the other hand, can deliver about a million times more energy to a molecule because the frequency of ultraviolet radiation is about a million times greater than the frequency of microwaves. X-rays, with even higher frequencies, can deliver even more.

Quantum physics tells us that the physical world is a coarse, grainy place. The "common-sense" world described by classical physics seems smooth and continuous because quantum graininess is on a very small scale compared with the sizes of things in the familiar world. Planck's constant is small in terms of familiar units. But you don't have to enter the quantum world to encounter graininess underlying apparent smoothness. For example, the blending areas of black, white, and gray in the photograph of Max Planck on the opening page of this chapter and other photographs in this book do not look smooth at all when viewed through a magnifying glass. With magnification, you can see that a printed photograph consists of many tiny dots. In a similar way, we live in a world that is a blurred image of the grainy world of atoms.

Light quanta, electrons, and other particles all behave as if they were lumps in some respects and waves in others.

[1] Planck's constant, h, has the numerical value 6.6×10^{34} J·s.

CHECK POINT

1. What does the term *quantum* mean?
2. How much total energy is in a monochromatic beam composed of n photons of frequency f?

Check Your Answers

1. A *quantum* is the smallest elemental unit of a quantity. Radiant energy, for example, is composed of many quanta, each of which is called a *photon*. So the more photons in a beam of light, the more energy in that beam.
2. The energy in a monochromatic beam of light containing n quanta is $E = nhf$.

Photoelectric Effect

In the latter part of the 19th century, several investigators noticed that light was capable of ejecting electrons from various metal surfaces. This is the **photoelectric effect,** for many years used in electric eyes, in the photographer's light meter, and, before digital, in the sound tracks of motion pictures. An extension of the photoelectric effect is today's photovoltaic electric cells and their potential for being a major power source.

An arrangement for observing the photoelectric effect is shown in Figure 31.1. Light shining on the negatively charged, photosensitive metal surface liberates electrons. The liberated electrons are attracted to the positive plate and produce a measurable current. If we instead charge this plate with just enough negative charge that it repels electrons, the current can be stopped. We can then calculate the energies of the ejected electrons from the easily measured potential difference between the plates.

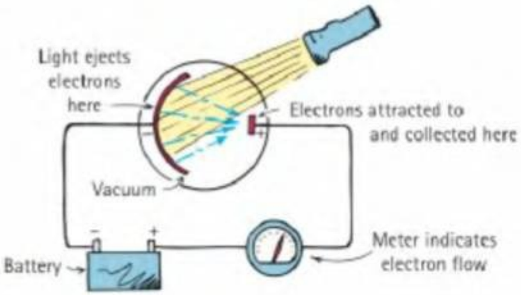


FIGURE 31.1
INTERACTIVE FIGURE

An apparatus used for observing the photoelectric effect. Reversing the polarity and stopping the electron flow provides a way to measure the energy of the electrons.

The photoelectric effect was not particularly surprising to early investigators. The ejection of electrons could be accounted for by classical physics, which pictures the incident light waves building an electron's vibration up to greater and greater amplitudes until it finally breaks loose from the metal surface, just as water molecules break loose from the surface of heated water. It should take considerable time for a weak source of light to give electrons in a metal enough energy to make them boil off the surface. Instead, it was found that electrons are ejected as soon as the light is turned on—but not as many are ejected as with a strong light source. Careful examination of the photoelectric effect led to several observations that were quite contrary to the classical wave picture:

1. The time lag between turning on the light and the ejection of the first electrons was unaffected by the brightness or frequency of the light.

2. The effect was easy to observe with violet or ultraviolet light but not with red light.
3. The rate at which electrons were ejected was proportional to the brightness of the light.
4. The maximum energy of the ejected electrons was unaffected by the brightness of the light. However, there were indications that the electron's energy did depend on the frequency of the light.

The lack of any appreciable time lag was especially difficult to understand in terms of the wave picture. According to the wave theory, an electron in dim light should, after some delay, accumulate sufficient vibrational energy to fly out, while an electron in bright light should be ejected almost immediately. However, this didn't occur. It was not unusual to observe an electron being ejected immediately, even under the dimmest light. The observation that the brightness of light in no way affected the energies of ejected electrons was also perplexing. The stronger electric fields of brighter light did not cause electrons to be ejected at greater speeds. More electrons were ejected in brighter light, but not at greater speeds. A weak beam of ultraviolet light, on the other hand, produced a smaller number of ejected electrons but at much higher speeds. This was most puzzling.

Einstein produced the answer in 1905, the same year he explained Brownian motion and set forth his theory of special relativity. His clue was Planck's quantum theory of radiation. Planck had assumed that the emission of light in quanta was due to restrictions on the vibrating atoms that produced the light. That is, he assumed that energy in *matter* is quantized, but that radiant energy is continuous. Einstein, on the other hand, attributed quantum properties to light itself and viewed radiation as a hail of particles. This particle aspect is emphasized when we speak of photons (by analogy with electrons, protons, and neutrons). One photon is completely absorbed by each electron ejected from the metal. The absorption is an all-or-nothing process and is immediate, so there is no delay as "wave energies" build up.

A light wave has a broad front, and its energy is spread out along this front. For the light wave to eject a single electron from a metal surface, all its energy would somehow have to be concentrated on that one electron. But this is as improbable as an ocean wave hurling a boulder far inland with an energy equal to that of the whole wave. Therefore, instead of thinking of light encountering a surface as a continuous train of waves, the photoelectric effect suggests we conceive of light encountering a surface or any detector as a succession of particles—photons. The number of photons in a light beam affects the brightness of the *whole beam*, whereas the frequency of the light controls the energy of each *individual photon*.

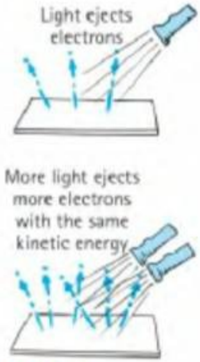


FIGURE 31.2
The photoelectric effect depends on intensity.

Electrons are held in a metal by attractive electrical forces. A minimum energy, called the *work function*, W_0, is required for an electron to leave the surface. A low-frequency photon with energy less than W_0 won't produce electron ejection. Only a photon with energy greater than W_0 results in the photoelectric effect. Thus the energy of the incoming photon will be equal to the outgoing kinetic energy of the electron plus the energy required to get it out of the metal, W_0.

Experimental verification of Einstein's explanation of the photoelectric effect was demonstrated 11 years later by the American physicist Robert Millikan. Interestingly, Millikan spent some 10 years trying to disprove Einstein's theory of the photon only to become convinced of it as a result of his own experiments, which won him a Nobel Prize. Every aspect of Einstein's interpretation was confirmed, including the direct proportionality of photon energy to frequency. It was for this (and not for his theory of relativity) that Einstein received his Nobel Prize. Astoundingly, it was not until 1923 and the discovery of other quantum evidence that physicists generally accepted the reality of the photon.

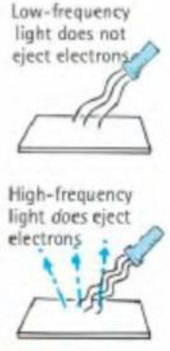


FIGURE 31.3
The photoelectric effect depends on frequency.

The photoelectric effect proves conclusively that light has particle properties. We cannot conceive of the photoelectric effect on the basis of waves. On the other hand, we have seen that the phenomenon of interference demonstrates convincingly that light has wave properties. We cannot conceive of interference in terms of particles. In classical physics this is contradictory. From the point of view of quantum physics, light has properties resembling both. It is "just like a wave" or "just like a particle," depending on the particular experiment. So we think of light as both, as a wave–particle. How about "wavicle"? Quantum physics calls for a new way of thinking.

CHECK POINT

1. Will brighter light eject more electrons from a photosensitive surface than dimmer light of the same frequency?
2. Will high-frequency light eject a greater number of electrons than low-frequency light?

Check Your Answers

1. Yes. The number of ejected electrons depends on the number of incident photons.
2. Not necessarily. The energy (not the number) of ejected electrons depends on the frequency of the illuminating photons. A bright source of blue light, for example, may eject more electrons at a lower energy than a dim violet source.

Wave–Particle Duality

The wave and particle nature of light is evident in the formation of optical images. We understand the photographic image produced by a camera in terms of light waves, which spread from each point of the object, refract as they pass through the lens system, and converge to focus on the light-sensitive recording medium—either photographic film or, in a digital camera, an electronic detector. The path of light from the object through the lens system and to the focal plane can be calculated using methods developed from the wave theory of light.

But now consider carefully the way in which an image is formed on photographic film. The film consists of an emulsion that contains grains of silver halide crystal, each grain containing about 10^{10} silver atoms. Each photon that is absorbed gives up its energy, hf, to a single grain in the emulsion. This energy activates surrounding crystals in the entire grain and is used in development to complete the photochemical process. Many photons activating many grains produce the usual photographic exposure. When a photograph is taken with exceedingly feeble light, we find that the image is built up by individual photons that arrive independently and are seemingly random in their distribution. We see this strikingly illustrated in Figure 31.4, which shows how an exposure progresses photon by photon.

Double-Slit Experiment

Let's return to Thomas Young's double-slit experiment, which we discussed in terms of waves in Chapter 29. Recall that when we pass monochromatic light through a pair of closely spaced thin slits, we produce an interference pattern (Figure 31.5). Now let's consider the experiment in terms of photons. Suppose we dim our light source so that, in effect, only one photon at a time reaches the barrier with the thin slits. If film behind the barrier is exposed to the light for a very short time, the film gets exposed as simulated in Figure 31.6a. Each spot represents the place where the film has been exposed by a photon. If the light is allowed to expose

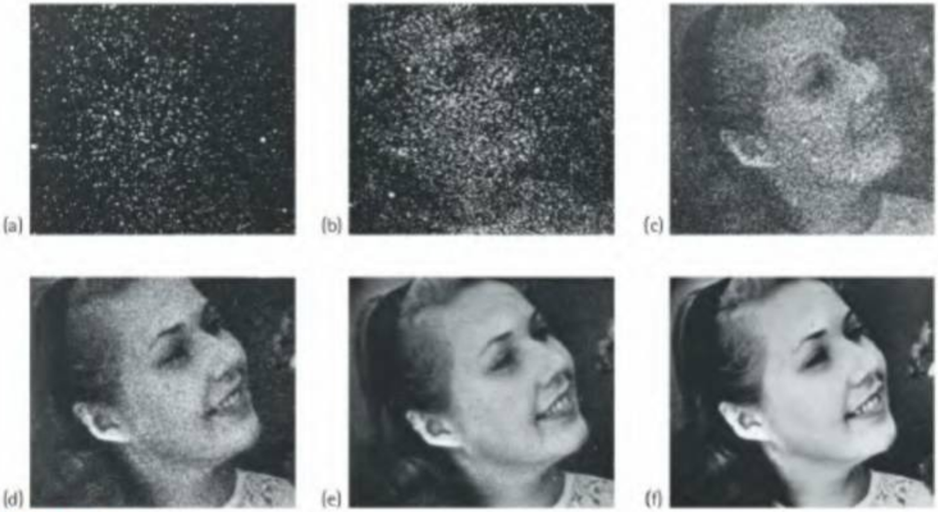


FIGURE 31.4

Stages of film exposure reveal the photon-by-photon production of a photograph. The approximate numbers of photons at each stage are (a) 3×10^3, (b) 1.2×10^4, (c) 9.3×10^4, (d) 7.6×10^5, (e) 3.6×10^6, and (f) 2.8×10^7.

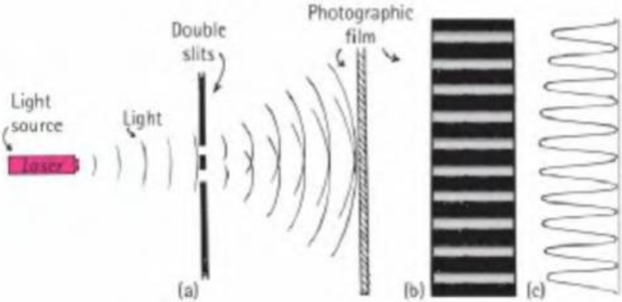


FIGURE 31.5

(a) Arrangement for double-slit experiment. (b) Photograph of interference pattern. (c) Graphic representation of pattern.

the film for a longer time, a pattern of fringes begins to emerge, as in Figures 31.6b and 31.6c. This is quite amazing! Spots on the film are seen to progress, photon by photon, to form the same interference pattern characterized by waves!

If we cover one slit so that photons striking the photographic film can pass only through a single slit, the tiny spots on the film accumulate to form a single-slit

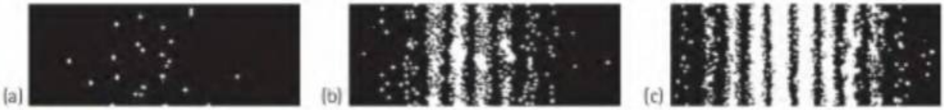


FIGURE 31.6

INTERACTIVE FIGURE

Stages of two-slit interference pattern. The pattern of individually exposed grains progresses from (a) 28 photons to (b) 1000 photons to (c) 10,000 photons. As more photons hit the screen, a pattern of interference fringes appears.

FIGURE 31.7
Single-slit diffraction pattern.

diffraction pattern (Figure 31.7). We find that photons hit the film at places they would not hit if both slits were open! If we think about this classically, we are perplexed and may ask how photons passing through the single slit "know" that the other slit is covered and therefore fan out to produce the wide single-slit diffraction pattern. Or, if both slits are open, how do photons traveling through one slit "know" that the other slit is open and avoid certain regions, proceeding only to areas that will ultimately fill to form the fringed double-slit interference pattern?[2] The modern answer is that the wave nature of light is not some average property that appears only when many photons act together. Each single photon has wave properties as well as particle properties. But the photon displays different aspects at different times. *A photon behaves as a particle when it is being emitted by an atom or absorbed by photographic film or other detectors, and behaves as a wave in traveling from a source to the place where it is detected.* So the photon strikes the film as a particle but travels to its position as a wave that interferes constructively. The fact that light exhibits both wave and particle behavior was one of the interesting surprises of the early 20th century. Even more surprising was the discovery that objects with mass also exhibit a dual wave–particle behavior.

Light travels as a wave and hits like a particle.

Particles as Waves: Electron Diffraction

If a photon of light has both wave and particle properties, why can't a material particle (one with mass) also have both wave and particle properties? This question was posed by the French physicist Louis de Broglie while he was still a graduate student in 1924. His answer constituted his doctoral thesis in physics and later earned him the Nobel Prize in physics. According to de Broglie, every particle of matter is somehow endowed with a wave to guide it as it travels. Under the proper conditions, then, every particle will produce an interference or diffraction pattern. Each body—whether an electron, a proton, an atom, a mouse, you, a planet, a star—has a wavelength that is related to its momentum by

$$\text{Wavelength} = \frac{h}{\text{momentum}}$$

where h is Planck's constant. A body of large mass and ordinary speed has such a small wavelength that interference and diffraction are negligible; rifle bullets fly straight and do not pepper their targets far and wide with detectable interference patches.[3] But, for smaller particles, such as electrons, diffraction can be appreciable.

Louis de Broglie
(1892–1987)

[2]From a pre-quantum point of view, this wave–particle duality is indeed mysterious. This leads some people to believe that quanta have some sort of consciousness, with each photon or electron having "a mind of its own." The mystery, however, is like beauty. It is in the mind of the beholder rather than in nature itself. We conjure models to understand nature and, when inconsistencies arise, we sharpen or change our models. The wave–particle duality of light doesn't fit a model built on classical ideas. An alternate model is that quanta have minds of their own. Another model is quantum physics. In this book, we subscribe to the latter.

[3]A bullet of mass 0.02 kg traveling at 330 m/s, for example, has a de Broglie wavelength of

$$\frac{h}{mv} = \frac{6.6 \times 10^{-34}\,\text{J·s}}{(0.02\text{ kg})(330\text{ m/s})} = 10^{-34}\text{ m}$$

an incredibly small size, a million million million millionth the size of a hydrogen atom. An electron traveling at 2% the speed of light, on the other hand, has a wavelength 10^{-10} m, which is equal to the diameter of the hydrogen atom. Diffraction effects for electrons are measurable, whereas diffraction effects for bullets are not.

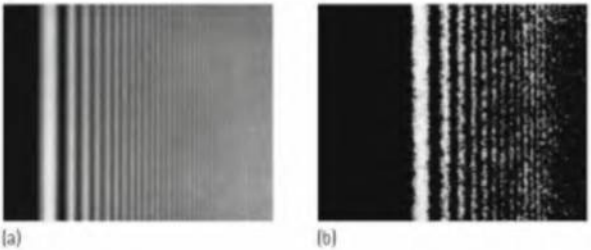


FIGURE 31.8
Fringes produced by the diffraction of (a) light and (b) an electron beam.

Both a beam of electrons and a beam of photons can be diffracted in the same way, as is evident in Figure 31.8. Beams of electrons directed through double slits also exhibit interference patterns. The double-slit experiment discussed in the previous section can be performed with electrons as well as with photons. For electrons, the apparatus is more complex, but the procedure is essentially the same. The intensity of the source can be reduced to direct electrons one at a time through a double-slit arrangement, producing the same remarkable results as with photons. Like photons, electrons strike the screen as particles, but the *pattern* of arrival is wavelike. The angular deflection of electrons to form the interference pattern agrees perfectly with calculations using de Broglie's equation for the wavelength of an electron.

FIGURE 31.9
An electron microscope makes practical use of the wave nature of electrons. The wavelength of electron beams is typically thousands of times shorter than the wavelength of visible light, so the electron microscope is able to distinguish detail not visible with optical microscopes.

In Figure 31.11, we see another example of electron diffraction, using a standard electron microscope. The electron beam of very low current density is directed through an electrostatic biprism that diffracts the beam. A pattern of fringes produced by individual electrons builds up step-by-step and is displayed on a TV monitor. The image is gradually filled by electrons to produce the interference pattern customarily associated with waves. The wave–particle duality is not restricted to photons and electrons. Neutrons, protons, whole atoms, and, to an immeasurable degree, even high-speed rifle bullets exhibit a duality of particle and wave behavior.

FIGURE 31.10
Detail of the head of a female mosquito as seen with a scanning electron microscope at a "low" magnification of 200×.

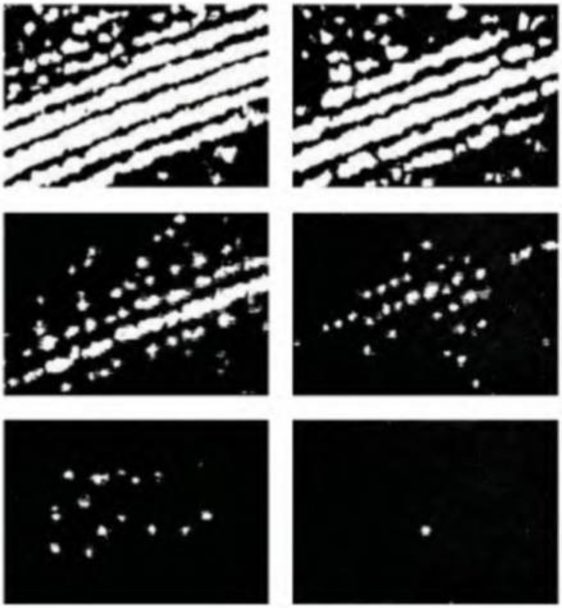
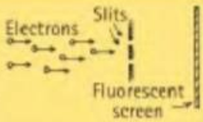


FIGURE 31.11
Electron interference patterns filmed from a TV monitor, showing the diffraction of a very low intensity electron-microscope beam through an electrostatic biprism.

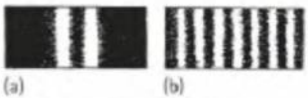
CHECK POINT

1. If electrons behaved only like particles, what pattern would you expect on the screen after the electrons passed through the double slits?
2. We don't notice the de Broglie wavelength for a pitched baseball. Is this because the wavelength is very large or because it is very small?
3. If an electron and a proton have the same de Broglie wavelength, which particle has the greater speed?



Check Your Answers

1. If electrons behaved only like particles, they would form two bands, as indicated in (a). Because of their wave nature, they actually produce the pattern shown in (b).



2. We don't notice the wavelength of a pitched baseball because it is extremely small—on the order of 10^{-20} times smaller than the atomic nucleus.
3. The same wavelength means that the two particles have the same momentum. This means that the less massive electron must travel faster than the heavier proton.

Uncertainty Principle

The wave–particle duality of quanta has inspired interesting discussions about the limits of our ability to accurately measure the properties of small objects. The discussions center on the idea that the act of measuring something affects the quantity being measured.

For example, we know that, if we place a cool thermometer in a cup of hot coffee, the temperature of the coffee is altered as it gives heat to the thermometer. The measuring device alters the quantity being measured. But we can correct for these errors in measurement if we know the initial temperature of the thermometer, the masses and specific heats involved, and so forth. Such corrections fall well within the domain of classical physics—these are *not* the uncertainties of quantum physics. Quantum uncertainties stem from the wave nature of matter. A wave, by its very nature, occupies some space and lasts for some time. It cannot be squeezed to a point in space or limited to a single instant of time, for then it would not be a wave. This inherent "fuzziness" of a wave gives a fuzziness or uncertainty of measurement at the quantum level. Innumerable experiments have shown that any measurement that in any way probes a system necessarily disturbs the system by at least one quantum of action, h—Planck's constant. So any measurement that involves interaction between the measurer and what is being measured is subject to this minimum inaccuracy.

We distinguish between observing and probing. Consider a cup of coffee on the other side of a room. If you passively glance at it and see steam rising from it, this act of "measuring" involves no physical interaction between your eyes and the coffee. Your glance neither adds nor subtracts energy from the coffee. You can assert that it's hot with no *probing*. Placing a thermometer in it is a different story. You physically interact with the coffee and thereby subject it to alteration. The quantum contribution to this alteration, however, is completely dwarfed by classical uncertainties and is negligible. Quantum uncertainties are significant only in the atomic and subatomic realm.

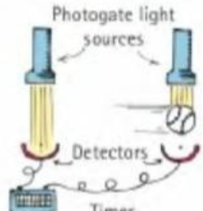


FIGURE 31.12

The ball's speed is measured by dividing the distance between the photogates by the time difference between crossing the two light paths. Photons hitting the ball alter its motion much less than the motion of an oil supertanker would be altered by a few fleas bumping into it.

Compare the acts of making measurements of a pitched baseball and of an electron. You can measure the speed of a pitched baseball by having it fly through a pair of photogates that are a known distance apart (Figure 31.12). The ball is timed as it interrupts beams of light in the gates. The accuracy of the ball's measured speed has to do with uncertainties in the measured distance between the gates and in the timing mechanisms. Interactions between the macroscopic ball and the photons it encounters are insignificant. But not so in the case of measuring submicroscopic things like electrons. Even a single photon bouncing off an electron appreciably alters the motion of the electron—and in an unpredictable way. If you wish to observe an electron and determine its whereabouts with light, the wavelength of the light would have to be very short. You fall into a dilemma. Light of a short wavelength, which can "see" the tiny electron better, corresponds to a large quantum of energy, which, in turn, greatly alters the electron's state of motion. If, on the other hand, you use a long wavelength that corresponds to a smaller quantum of energy, the change you induce to the electron's state of motion will be smaller, but the determination of its position by means of the coarser wave will be less accurate. The act of observing something as tiny as an electron probes the electron and, in so doing, produces a considerable uncertainty in either its position or its motion. Although this uncertainty is completely negligible for measurements of position and motion regarding everyday (macroscopic) objects, it is a predominant fact of life in the atomic domain.

Werner Heisenberg (1901–1976)

The uncertainty of measurement in the atomic domain, which was first stated mathematically by the German physicist Werner Heisenberg, is called the **uncertainty principle.** It is a fundamental principle in quantum mechanics. Heisenberg found that when the uncertainties in the measurement of momentum and position for a particle are multiplied together, the product must be equal to or greater than Planck's constant, h, divided by 2π, which is represented as $\hbar$ (called *h-bar*).[4] We can state the uncertainty principle in a simple formula:

$$\Delta p \Delta x \geq \hbar$$

[4]Quantum physicist Ken Ford celebrates $\hbar$ on the number plate of his Honda Civic Hybrid (back on page 353).

The Δ here means "uncertainty of": Δp is the uncertainty of momentum (the symbol for momentum is conventionally p), and Δx is the uncertainty of position. The product of these two uncertainties must be equal to or greater than ($\geq$) the size of $\hbar$. For minimum uncertainties, the product will equal $\hbar$; the product of larger uncertainties will be greater than $\hbar$. But in no case can the product of the uncertainties be less than $\hbar$. The significance of the uncertainty principle is that, even in the best of conditions, the lower limit of uncertainty is $\hbar$. This means that if we wish to know the momentum of an electron with great accuracy (small Δp), the corresponding uncertainty in position will be large. Or if we wish to know the position with great accuracy (small Δx), the corresponding uncertainty in momentum will be large. The sharper one of these quantities is, the less sharp is the other.[5]

You can never change only one thing! Every equation reminds us of this—you can't change a term on one side without affecting the other side.

The uncertainty principle operates similarly with energy and time. We cannot measure a particle's energy with complete precision in an infinitesimally short span of time. The uncertainty in our knowledge of energy, ΔE, and the duration taken to measure the energy, Δt, are related by the expression[6]

$$\Delta E \Delta t \geq \hbar$$

The greatest accuracy we can ever hope to attain is that case in which the product of the energy and time uncertainties equals $\hbar$. The more accurately we determine the energy of a photon, an electron, or a particle of whatever kind, the more uncertain we will be of the time during which it has that energy.

The uncertainty principle is relevant only to quantum phenomena. The inaccuracies in measuring the position and momentum of a baseball due to quantum effects are completely negligible. But the inaccuracies in measuring the position and momentum of an electron are far from negligible. This is because the uncertainties in the measurements of these subatomic quantities are comparable to the magnitudes of the quantities themselves.[7]

There is a danger in applying the uncertainty principle to areas outside of quantum mechanics. Some people conclude from statements about the interaction between the observer and the observed that the universe does not exist "out there," independent of all acts of observation, and that reality is created by the observer. Others interpret the uncertainty principle as nature's shield of forbidden secrets. Some critics of science use the uncertainty principle as evidence that science itself is uncertain. The reality of the universe (whether observed or not), nature's secrets, and the uncertainties of science have very little to do with Heisenberg's uncertainty principle. The profundity of the uncertainty principle has to do with the unavoidable interaction between nature at the atomic level and the means by which we probe it.

[5]In a hypothetical purely classical world, $\hbar$ would be zero and the uncertainties of both position and momentum could be arbitrarily small. In the real world, Planck's constant is greater than zero, and we cannot, in principle, simultaneously know both quantities with certainty.

[6]We can see that this is consistent with the uncertainty in momentum and position. Recall that Δmomentum = force × Δtime and that Δenergy = force × Δdistance. Then,

$$\begin{aligned} \hbar &= \Delta\text{momentum} \times \Delta\text{distance} \\ &= (\text{force} \times \Delta\text{distance}) \times \Delta\text{time} \\ &= \Delta\text{energy} \times \Delta\text{time} \end{aligned}$$

[7]The uncertainties in measurements of momentum, position, energy, or time that are related to the uncertainty principle for a pitched baseball are only 1 part in about 10 million billion billion billion (10^{-34}). Quantum effects are negligible even for the most sluggish bacterium, where the uncertainties are about 1 part in a billion (10^{-9}). Quantum effects become evident for atoms, where the uncertainties can be as large as 100%. For electrons moving in an atom, quantum uncertainties dominate, and we are in the full-scale quantum realm.

CHECK POINT

1. Is Heisenberg's uncertainty principle applicable to the practical case of using a thermometer to measure the temperature of a glass of water?
2. A Geiger counter measures radioactive decay by registering the electrical pulses produced in a gas tube when high-energy particles pass through it. The particles emanate from a radioactive source—say, radium. Does the act of measuring the decay rate of radium alter the radium or its decay rate?
3. Can the quantum principle that we cannot observe something without changing it be reasonably extrapolated to support the claim that you can make a stranger turn around and look at you by staring intently at his back?

Check Your Answers

1. No. Although we probably subject the temperature of water to a change by the act of probing it with a thermometer, especially one appreciably colder or hotter than the water, the uncertainties that relate to the precision of the thermometer are quite within the domain of classical physics. The role of uncertainties at the subatomic level is inapplicable here.
2. Not at all, because the interaction involved is between the Geiger counter and the particles, not between the Geiger counter and the radium. It is the behavior of the particles that is altered by measurement, not the radium from which they emanate. See how this relates to the next question.
3. No. Here we must be careful in defining what we mean by *observing*. If our observation involves probing (giving or extracting energy), we indeed change to some degree that which we observe. For example, if we shine a light source onto the person's back, our observation consists of probing, which, however slight, physically alters the configuration of atoms on his back. If he senses this, he may turn around. But simply staring intently at his back is observing in the passive sense. The light you receive (or block by blinking, for example) has already left his back. So whether you stare, squint, or close your eyes completely, you in no physical way alter the atomic configuration on his back. Shining a light or otherwise probing something is not the same thing as passively looking at something. A failure to make the simple distinction between *probing* and *passive observation* is at the root of much nonsense that is said to be supported by quantum physics. Better support for the above claim would be positive results from a simple and practical test, rather than the assertion that it rides on the hard-earned reputation of quantum theory.

Complementarity

The realm of quantum physics can seem confusing. Light waves that interfere and diffract deliver their energy in packages of quanta—particles. Electrons that move through space in straight lines and experience collisions as if they were particles distribute themselves spatially in interference patterns as if they were waves. In this confusion, there is an underlying order. The behavior of light and electrons is confusing in the same way! Light and electrons both exhibit wave and particle characteristics.

The Danish physicist Niels Bohr, one of the founders of quantum physics, formulated an explicit expression of the wholeness inherent in this dualism. He called his expression of this wholeness **complementarity.** As Bohr expressed it, quantum phenomena exhibit complementary (mutually exclusive) properties—appearing

FIGURE 31.13
Opposites are seen to complement one another in the yin–yang symbol of Eastern cultures.

either as particles or as waves—depending on the type of experiment conducted. Experiments designed to examine individual exchanges of energy and momentum reveal particle-like properties, while experiments designed to examine spatial distribution of energy reveal wavelike properties. The wavelike and particle-like properties of light complement one another—both are necessary for the understanding of "light." Which part is emphasized depends on what question one presents to nature.

Complementarity is not a compromise, and it doesn't mean that the whole truth about light lies somewhere in between particles and waves. It's rather like viewing the sides of a crystal. What you see depends on what facet you look at, which is why light, energy, and matter appear to be behaving as quanta in some experiments and as waves in others.

The idea that opposites are components of a wholeness is not new. Ancient Eastern cultures incorporated it as an integral part of their worldview. This is demonstrated in the yin–yang diagram of T'ai Chi Tu (Figure 31.13). One side of the circle is called *yin* (black), and the other side is called *yang* (white). Where there is yin, there is yang. Only the union of yin and yang forms a whole. Where there is low, there is also high. Where there is night, there is also day. Where there is birth, there is also death. A whole person integrates yin (feminine traits, right brain, emotion, intuition, darkness, cold, wetness) with yang (masculine traits, left brain, reason, logic, light, heat, dryness). Each has aspects of the other. For Niels Bohr, the yin–yang diagram symbolized the principle of complementarity. In later life, Bohr wrote broadly on the implications of complementarity. In 1947, when he was knighted for his contributions to physics, he chose for his coat of arms the yin–yang symbol.

Predictability and Chaos

We can make predictions about an orderly system when we know the initial conditions. For example, we can state precisely where a launched rocket will land, where a given planet will be at a particular time, or when an eclipse will occur. These are examples of events in the Newtonian macroworld. Similarly, in the quantum microworld, we can predict where an electron is *likely* to be in an atom and the *probability* that a radioactive particle will decay in a given time interval. Predictability in orderly systems, both Newtonian and quantum, depends on knowledge of initial conditions.

Some systems, however, whether Newtonian or quantum, are not orderly—they are inherently unpredictable. These are called "chaotic systems." Turbulent water flow is an example. No matter how precisely we know the initial conditions of a piece of floating wood as it flows downstream, we cannot predict its location later downstream. A feature of chaotic systems is that slight differences in initial conditions result in wildly different outcomes later. Two identical pieces of wood just slightly apart at one time may be vastly far apart soon thereafter.

Weather is chaotic. Small changes in one day's weather can produce big (and largely unpredictable) changes a week later. Meteorologists try their best, but they are bucking the hard fact of chaos in nature. This barrier to accurate prediction first led the meteorologist Edward Lorenz to ask, "Does the flap of a butterfly's wings in Brazil set off a tornado in Texas?" We now talk about the *butterfly effect* when we are dealing with situations in which very small effects can amplify into very big effects.

Interestingly, chaos is not all hopeless unpredictability. Even in a chaotic system there can be patterns of regularity. There is *order in chaos*. Scientists have learned how to treat chaos mathematically and how to find the parts of it that are orderly. Artists seek patterns in nature in a different way. Both scientists and artists look for the connections in nature that were always there but are not yet put together in our thinking.

SUMMARY OF TERMS

Quantum (*pl.* **quanta**) From the Latin word *quantus*, meaning "how much." A quantum is an elemental unit of a quantity, a discrete amount of something. One quantum of electromagnetic energy is called a photon.

Quantum physics The physics that describes the microworld, where many quantities are granular (in units called *quanta*), not continuous, and where particles of light (*photons*) and particles of matter (such as electrons) exhibit wave as well as particle properties.

Planck's constant A fundamental constant, h, that relates the energy of light quanta to their frequency:

$$h = 6.6 \times 10^{-34}\ \text{J}\cdot\text{s}$$

Photoelectric effect The emission of electrons from a metal surface when light shines upon it.

Uncertainty principle The principle, formulated by Werner Heisenberg, stating that Planck's constant, h, sets a limit on the accuracy of measurement. According to the uncertainty principle, it is not possible to measure exactly both the position and the momentum of a particle at the same time, nor the energy and the time during which the particle has that energy.

Complementarity The principle, enunciated by Niels Bohr, stating that the wave and particle aspects of both matter and radiation are necessary, complementary parts of the whole. Which part is emphasized depends on what experiment is conducted (i.e., on what question one puts to nature).

REVIEW QUESTIONS

Birth of the Quantum Theory

1. Which theory of light, the wave theory or the particle theory, did the findings of Young, Maxwell, and Hertz support?
2. Did Einstein's photon explanation of the photoelectric effect support the wave theory or the particle theory of light?
3. What exactly did Max Planck consider quantized, the energy of vibrating atoms or the energy of light itself?

Quantization and Planck's Constant

4. What is a quantum of light called?
5. In the formula $E = hf$, does f stand for wave frequency, as defined in Chapter 19?
6. Which has the lower energy quanta—red light or blue light? Radio waves or X-rays?

Photoelectric Effect

7. Which are more successful in dislodging electrons from a metal surface—photons of violet light or photons of red light? Why?
8. Why won't a very bright beam of red light impart more energy to an ejected electron than a feeble beam of violet light?

Wave–Particle Duality

9. Why do photographs in a book or magazine look grainy when magnified?
10. Does light behave primarily as a wave or as a particle when it interacts with the crystals of matter in photographic film?

Double-Slit Experiment

11. Does light travel from one place to another in a wavelike or a particle-like way?
12. Does light interact with a detector in a wavelike or a particle-like way?
13. When does light behave as a wave? When does it behave as a particle?

Particles as Waves: Electron Diffraction

14. What evidence can you cite for the wave nature of particles?
15. When electrons are diffracted through a double slit, do they hit the screen in a wavelike way or in a particle-like way? Is the pattern of hits wavelike or particle-like?

Uncertainty Principle

16. In which of the following are quantum uncertainties significant: measuring simultaneously the speed and location of a baseball; of a spitball; of an electron?
17. What is the uncertainty principle with respect to momentum and position?
18. If measurements show a precise position for an electron, can those measurements show precise momentum also? Explain.
19. If measurement shows a precise value for the energy radiated by an electron, can that measurement show a precise time for this event as well? Explain.
20. What is the distinction in this book between passively and actively observing an event?

Complementarity

21. What is the principle of complementarity?
22. Cite evidence that the idea of opposites as components of a wholeness preceded Bohr's principle of complementarity.

EXERCISES

1. What does it mean to say that something is quantized?
2. Distinguish between *classical physics* and *quantum physics*.
3. In the previous chapter, we learned the formula $E \sim f$. In this chapter, we learned the formula $E = hf$. Explain the difference between these two formulas. What is h?
4. The frequency of violet light is about twice that of red light. How does the energy of a violet photon compare with the energy of a red photon?
5. Which has more energy—a photon of visible light or a photon of ultraviolet light?
6. We speak of photons of red light and photons of green light. Can we speak of photons of white light? Why or why not?
7. Which laser beam carries more energy per photon—a red beam or a green beam?
8. If a beam of red light and a beam of blue light have exactly the same energy, which beam contains the greater number of photons?
9. One of the technical challenges facing the original developers of color television was the design of an image tube (camera) for the red portion of the image. From an energy point of view, why was finding a material that would respond to red light more difficult than finding materials to respond to green and blue light?
10. Phosphors on the inside of fluorescent lamps convert ultraviolet light to visible light. Why are there no substances that convert visible light to ultraviolet light?
11. Silver bromide (AgBr) is a light-sensitive substance used in some types of photographic film. To cause exposure of the film, it must be illuminated with light having sufficient energy to break apart the molecules. Why do you suppose this film may be handled without exposure in a darkroom illuminated with red light? How about blue light? How about very bright red light relative to very dim blue light?
12. Sunburn produces cell damage in the skin. Why is ultraviolet radiation capable of producing this damage, while visible radiation, even if more intense, is not?
13. In the photoelectric effect, does brightness or frequency determine the kinetic energy of the ejected electrons? Which determines the number of the ejected electrons?
14. A very bright source of red light has much more energy than a dim source of blue light, but the red light has no effect in ejecting electrons from a certain photosensitive surface. Why is this so?
15. Why are ultraviolet photons more effective at inducing the photoelectric effect than photons of visible light?
16. Why does light striking a metal surface eject only electrons, not protons?
17. Does the photoelectric effect depend on the wave nature or the particle nature of light?
18. Explain how the photoelectric effect is used to open automatic doors when someone approaches.
19. Explain briefly how the photoelectric effect is used in the operation of at least two of the following: an electric eye, a photographer's light meter, the sound track of a pre-digital motion picture.
20. If you shine an ultraviolet light on the metal ball of a negatively charged electroscope (shown in Exercises 11 and 12 in Chapter 22), it will discharge. But if the electroscope is positively charged, it won't discharge. Can you venture an explanation?
21. Discuss how the reading of the meter in Figure 31.1 will vary as the photosensitive plate is illuminated by light of various colors at a given intensity and by light of various intensities of a given color.
22. Does the photoelectric effect *prove* that light is made of particles? Do interference experiments *prove* that light is composed of waves? (Is there a distinction between what something *is* and how it *behaves*?)
23. Does Einstein's explanation of the photoelectric effect invalidate Young's explanation of the double-slit experiment? Explain.
24. The camera that took the photograph of the woman's face (Figure 31.4) used ordinary lenses that are well known to refract waves. Yet the step-by-step formation of the image is evidence of photons. How can this be? What is your explanation?
25. What evidence can you cite for the wave nature of light? For the particle nature of light?
26. When does a photon behave like a wave? When does it behave like a particle?
27. Light has been argued to be a wave and then a particle, and then back again. Does this indicate that light's true nature probably lies somewhere between these two models?
28. What laboratory device utilizes the wave nature of electrons?
29. How might an atom obtain enough energy to become ionized?
30. When an X-ray photon of a certain frequency hits an electron and gives it energy, make a hypothesis about the frequency of the photon that "leaves the scene" of the collision. (This phenomenon is called the *Compton effect*.)
31. A hydrogen atom and a uranium atom move at the same speed. Which possesses more momentum? Which has the longer wavelength?
32. If a cannonball and a BB have the same speed, which has the longer wavelength?
33. An electron and a proton travel at the same speed. Which has more momentum? Which has the longer wavelength?
34. One electron travels twice as fast as another. Which has the longer wavelength?
35. Does the de Broglie wavelength of a proton become longer or shorter as its velocity increases?
36. We don't notice the wavelength of moving matter in our common experience. Is this because the wavelength is extraordinarily large or extraordinarily small?
37. What principal advantage does an electron microscope have over an optical microscope?
38. Would a beam of protons in a "proton microscope" exhibit greater or less diffraction than electrons of the same speed in an electron microscope? Defend your answer.
39. Suppose nature were entirely different so that an infinite number of photons would be needed to make up even the tiniest amount of radiant energy, the wavelength of material particles was zero, light had no particle properties,

and matter had no wave properties. This would be the classical world described by the mechanics of Newton and the electricity and magnetism of Maxwell. What would be the value of Planck's constant for such a world with no quantum effects?

40. Suppose that you lived in a hypothetical world in which you'd be knocked down by a single photon, in which matter would be so wavelike that it would be fuzzy and hard to grasp, and in which the uncertainty principle would impinge on simple measurements of position and speed in a laboratory, making results irreproducible. In such a world, how would Planck's constant compare with the accepted value?

41. Comment on the idea that the theory one accepts determines the meaning of one's observations and not vice versa.

42. A friend says, "If an electron is not a particle, then it must be a wave." What is your response? (Do you hear "either-or" statements like this often?)

43. Consider one of the many electrons on the tip of your nose. If somebody looks at it, will its motion be altered? How about if it is viewed with one eye closed? With two eyes open, but crossed? Does Heisenberg's uncertainty principle apply here?

44. Does the uncertainty principle tell us that we can never know anything for certain?

45. Do we inadvertently alter the realities that we attempt to measure in a public opinion survey? Does Heisenberg's uncertainty principle apply here?

46. If the behavior of a system is measured exactly for some period of time and is understood, does it follow that the future behavior of that system can be exactly predicted? (Is there a distinction between properties that are *measurable* and properties that are *predictable*?)

47. When checking the pressure in tires, some air escapes. Why does Heisenberg's uncertainty principle not apply here?

48. If a butterfly causes a tornado, does it make sense to eradicate butterflies? Defend your answer.

49. We hear the expression "taking a quantum leap" to describe large changes. Is the expression appropriate? Defend your answer.

50. To measure the exact age of Old Methuselah, the oldest living tree in the world, a Nevada professor of dendrology, aided by an employee of the U.S. Bureau of Land Management, cut the tree down in 1965 and counted its rings. Is this an extreme example of altering that which you measure or an example of arrogant and criminal stupidity?

PROBLEMS

1. A typical wavelength of infrared radiation emitted by your body is 25 mm (2.5×10^{-2} m). Show that the energy per photon of such radiation is about 8.0×10^{-24} J.

2. Consider the de Broglie wavelength of an electron that strikes the back face of one of the early models of a TV screen at 1/10 the speed of light. Show that the electron wavelength is 2.4×10^{-11} m.

• **3.** You decide to roll a 0.1-kg ball across the floor so slowly that it will have a small momentum and a large de Broglie wavelength. If you roll it at 0.001 m/s, what is its wavelength? How does this compare with the de Broglie wavelength of the high-speed electron in the previous problem?

CHAPTER 31 ONLINE RESOURCES

Interactive Figures

- 31.1, 31.6

Quizzes

Flashcards

Links

PART SIX MULTIPLE-CHOICE PRACTICE EXAM

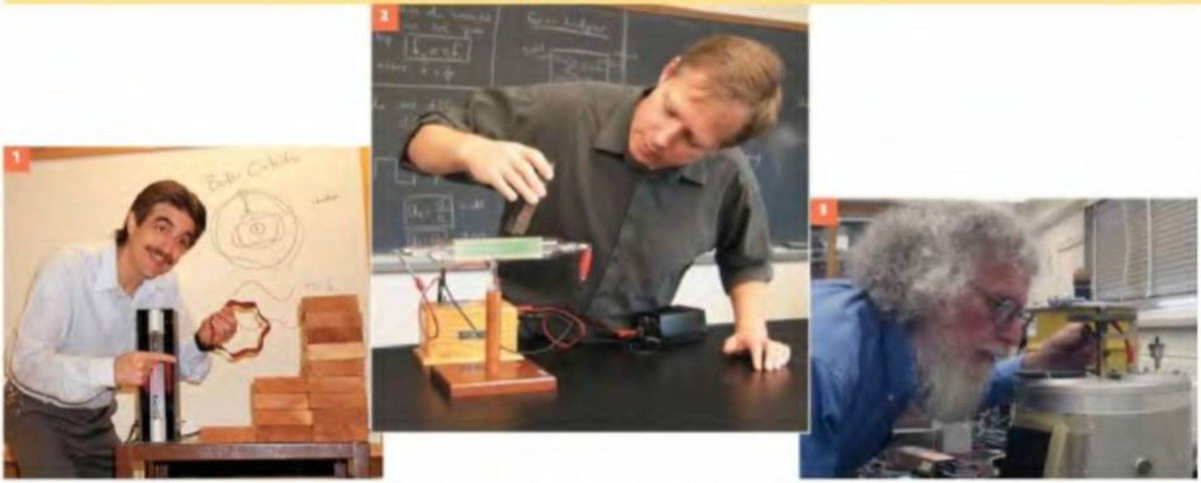
Choose the BEST answer to the following:

1. Which of these does NOT belong in the family of electromagnetic waves?
   (a) Light. (c) Radio waves.
   (b) Sound. (d) X-rays.
2. Light that is not transmitted by opaque materials is
   (a) converted to internal energy in the material.
   (b) mainly reflected.
   (c) mainly refracted.
   (d) transmitted at a lower frequency.
3. When the shadow of the Moon falls on Earth, we have a
   (a) lunar eclipse.
   (b) solar eclipse.
   (c) solar eclipse if it's daytime and lunar eclipse if it's nighttime.
   (d) very dangerous event.
4. Black is the combination of
   (a) all the colors together.
   (b) two or more appropriate colors.
   (c) light when a prism is held upside down.
   (d) None of these.
5. To say that a rose petal is red is to say that it
   (a) absorbs red. (c) emits red.
   (b) reflects red. (d) transmits red.
6. The color of light most intense in the solar radiation curve is
   (a) infrared. (c) yellow-green.
   (b) red. (d) violet.
7. When red and blue light are overlapped, the color produced is
   (a) magenta. (c) cyan.
   (b) yellow. (d) white.
8. The complementary color of blue is
   (a) magenta. (c) cyan.
   (b) yellow. (d) white.
9. The blueness of the daytime sky is due mostly to light
   (a) absorption. (c) reflection.
   (b) transmission. (d) scattering.
10. The redness of a sunrise or sunset is due mostly to light that hasn't been
    (a) absorbed. (c) scattered.
    (b) transmitted. (d) polarized.
11. The greenish blue of ocean water mostly involves light that is
    (a) absorbed. (c) scattered.
    (b) reflected. (d) refracted.
12. Your distance of your image behind a plane mirror is equal to
    (a) half your height.
    (b) half your distance from the mirror.
    (c) your distance in front of the mirror.
    (d) more than your distance in front of the mirror.
13. Refraction occurs when a wave crosses a boundary and changes
    (a) speed and direction. (c) frequency.
    (b) intensity. (d) amplitude.
14. When white light passes through a prism, the light that bends more than green is
    (a) red. (c) blue.
    (b) yellow. (d) None of these.
15. A rainbow is the result of light in raindrops that undergoes
    (a) internal reflection. (c) refraction.
    (b) dispersion. (d) All of these.
16. When a diver points a flashlight upward toward the surface of the water at an angle 20° from the normal, the beam of light
    (a) totally internally reflects.
    (b) passes into the air above.
    (c) is absorbed.
    (d) None of these.
17. A real image can be cast on a screen by a
    (a) converging lens. (c) Either of these.
    (b) diverging lens. (d) Neither of these.
18. Huygens' principle for light is primarily described by
    (a) waves. (c) particles.
    (b) rays. (d) photons.
19. A diffraction grating relies on light
    (a) interference.
    (b) amplitudes.
    (c) variations in brightness.
    (d) being composed of photons.
20. When light undergoes interference, it can sometimes
    (a) build up to more than the sum of amplitudes.
    (b) cancel completely.
    (c) Both of these.
    (d) Neither of these.
21. Colors in a soap bubble result from light
    (a) converted to a different frequency.
    (b) deflection.
    (c) subtracted from incident light.
    (d) amplification.
22. Polarization is a property of
    (a) transverse waves. (c) all waves.
    (b) longitudinal waves. (d) None of these.
23. A hologram best illustrates
    (a) polarization. (c) superposition.
    (b) diffraction. (d) electron interference.
24. In the proportion $E \sim f$, the f stands for the
    (a) frequency of light.
    (b) frequency of sound.
    (c) frequency of a tuning fork or vibrating string.
    (d) frictional force.
25. The energy of an emitted photon is related to its
    (a) amplitude. (c) momentum.
    (b) polarization. (d) frequency.
26. Among these colors, the one having the most energy per photon is
    (a) red. (c) blue.
    (b) yellow-green. (d) violet.
27. The red glow in the neon tube of an advertising sign is a result of
    (a) fluorescence. (c) excitation.
    (b) incandescence. (d) polarization.
28. All parts of a laser beam have the same
    (a) frequency. (c) speed.
    (b) phase. (d) All of these.
29. The model of light supported by the photoelectric effect is the
    (a) wave model. (c) Both of these.
    (b) particle model. (d) Neither of these.
30. Planck's constant can be found by dividing the energy of a photon by its
    (a) wavelength. (c) amplitude.
    (b) frequency. (d) None of these.

After you have made thoughtful choices, and discussed them with your friends, find the answers on page 681.

Part Seven
Atomic and Nuclear Physics

32 The Atom and the Quantum



These three physicists who excel in their teaching bring quantum physics down to Earth for their students. 1 David Kagan uses a strip of corrugated plastic in class to model an orbiting electron. The stacked wood blocks model electron energy levels. 2 Roger King uses a magnet to bend an electron beam in a Crooke's tube. 3 Dean Zollman investigates nuclear properties with a modern version of Rutherford's scattering experiment.

Niels Bohr was born in Copenhagen, Denmark, in 1885. His father, a Lutheran, was a professor of physiology at the University of Copenhagen. His mother came from a wealthy Jewish family prominent in Danish banking and parliamentary circles. His brother, Harald Bohr, was a mathematician and Olympic soccer player on the Danish national team. Niels was passionate about soccer as well, and the two brothers played a number of national matches in Copenhagen.

Neils Bohr (1885–1962)

Bohr earned his physics doctorate in Denmark in 1911. He then worked for a time in the laboratory of J. J. Thomson, the discoverer of the electron, at Trinity College in Cambridge, England, before going on to continue his research under Ernest Rutherford at the University of Manchester, also in England. Rutherford had just discovered that a tiny, positively charged nucleus sits at the center of every atom, surrounded, presumably, by Thomson's electrons. Bohr pondered this new picture of the atom and added quantum principles to it. He published his model of atomic structure in 1913, in which electrons travel only in certain orbits around the atomic nucleus, and the atom emits light when electrons make "quantum jumps" from one orbit to another. His theory brilliantly accounted for the observed spectral lines of hydrogen, the so-called Balmer series as well as other series.

Bohr won the Nobel Prize in physics in 1922 for his work on the quantum theory of atoms, a year after Albert Einstein won the Nobel Prize for his work on the photoelectric effect. After quantum theory evolved and matured in the mid-1920s, Einstein had great reservations about its probabilistic nature, much preferring the determinism of classical physics. He and Bohr debated these two views of physics throughout their lives, always maintaining the greatest respect for each other.

Because Bohr's mother was Jewish, he was in danger in Nazi-occupied Denmark during World War II. In 1943, shortly before an impending arrest, he escaped to Sweden with his family. The Allies, recognizing Bohr's importance, flew him from Sweden to London tucked into the bomb bay of an unarmed Mosquito bomber. Because he forgot to put on his oxygen mask, he passed out. Fortunately, the pilot, sensing that something was wrong when Bohr didn't respond to intercom messages, descended to lower altitude and delivered a still-living passenger to London. Bohr reportedly said that he had slept like a baby during the flight. He then went on to the United States to work on the U.S. Manhattan Project at the top-secret Los Alamos laboratory in New Mexico. For security reasons he was assigned the name of Nicholas Baker during the project.

After the war, Bohr returned to Copenhagen, advocating the peaceful use of nuclear energy and the sharing of nuclear information. When awarded the Order of the Elephant by the Danish government, he designed his own coat of arms, which featured a symbol of yin and yang, with the Latin motto *contraria sunt complementa:* "opposites are complementary."

Bohr's son Aage went on to become a very successful physicist and, like his father, won a Nobel Prize in physics, his in 1975. Niels Bohr died in Copenhagen in 1962. Much of this chapter involves his view of physics.

Discovery of the Atomic Nucleus

Half-a-dozen years after Einstein announced the photoelectric effect, the New Zealand-born British physicist Ernest Rutherford oversaw his now famous gold-foil experiment.[1] This significant experiment showed that the atom is mostly empty space, with most of its mass concentrated in the central region—the *atomic nucleus.*

In Rutherford's experiment, a beam of positively charged particles (alpha particles) from a radioactive source was directed through a sheet of extremely thin gold foil. Because alpha particles are thousands of times more massive than electrons, it was expected that the stream of alpha particles would not be impeded as it passed through the "atomic pudding." This was indeed observed—for the most part. Nearly all alpha particles passed through the gold foil with little or no deflection and produced a spot of light when they hit a fluorescent screen beyond the foil. But some particles were deflected from their straight-line paths as they emerged. A few alpha particles were widely deflected, and a small number were even scattered backward! These alpha particles must have hit something relatively massive—but what? Rutherford reasoned that the undeflected particles traveled through empty space in regions of the gold foil, while the small number of deflected particles were repelled from extremely dense, positively charged central cores. Each atom, he concluded, must contain one of these cores, which he named the **atomic nucleus.**

Rutherford later related that the discovery of alpha particles rebounding backward was the most incredible event of his life—as incredible as if a 15-inch cannon shell rebounded from a piece of tissue paper.

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Tutorial
Atoms and Isotopes

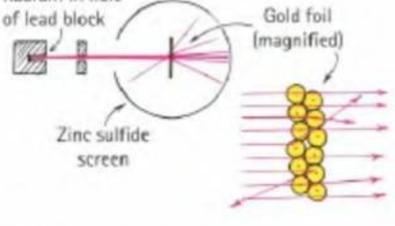

FIGURE 32.1
The occasional large-angle scattering of alpha particles from gold atoms led Rutherford to the discovery of the very massive small nuclei at their centers.

Ernest Rutherford (1871–1937)

[1]Why "oversaw"? To indicate that more investigators than Rutherford were involved in this experiment. The widespread practice of elevating a single scientist to the position of sole investigator, which seldom is the case, too often denies the involvement of other investigators. There's substance to the saying, "There are two things more important to people than sex and money—*recognition and appreciation.*"

FIGURE 32.2
Franklin's kite-flying experiment.

CHECK POINT

1. What convinced Rutherford that the gold foil was mostly empty space?
2. What convinced him that the particles in empty space were massive?

Check Your Answers

1. Finding most alpha particles were undeflected indicated much empty space.
2. Finding some bounced backward indicated something massive in the empty space.

Discovery of the Electron

Surrounding the atomic nucleus are electrons. The name *electron* comes from the Greek word for amber, a brownish-yellow fossil resin studied by the early Greeks. They found that when amber was rubbed by a piece of cloth, it attracted such things as bits of straw. This phenomenon, known as the *amber effect,* remained a mystery for almost 2000 years. In the late 1500s, William Gilbert, Queen Elizabeth's physician, found other materials that behaved like amber, and he called them "electrics." The concept of electric charge awaited experiments by the American scientist-statesman Benjamin Franklin nearly two centuries later. Recall from Chapter 22 that Franklin experimented with electricity and postulated the existence of an electric fluid that could flow from place to place. An object with an excess of this fluid he called *electrically positive,* and one with a deficiency of the fluid he called *electrically negative*. The fluid was thought to attract ordinary matter but to repel itself. Although we no longer talk about electric fluid, we still follow Franklin's lead in how we define positive and negative electricity. Franklin's 1752 experiment with the kite in the lightning storm showed that lightning is an electrical discharge between clouds and the ground. This discovery told him that electricity is not restricted to solid or liquid objects and that it can travel through a gas.

You'll note much of this chapter is background for chapters already covered—hopefully a "tying-it-together" chapter.

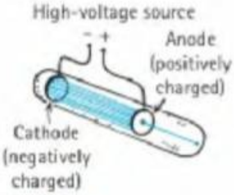

FIGURE 32.3
A simple cathode-ray tube. An electric current is produced in the gas when a high voltage is imposed across the electrodes inside the tube.

Franklin's experiments later inspired other scientists to produce electric currents through various dilute gases in sealed glass tubes. Among these, in the 1870s, was Sir William Crookes, an unorthodox English scientist who believed he could communicate with the dead. He is better remembered for his "Crookes's tube," a sealed glass tube containing gas under very low pressure and with electrodes inside the tube near each end (the forerunner to today's neon signs). The gas glowed when the electrodes were connected to a voltage source (such as a battery). Different gases glowed with different colors. Experiments conducted with tubes containing metal slits and plates showed that the gas was made to glow by some sort of a "ray" emerging from the negative terminal (the *cathode*). Slits could make the ray narrow and plates could prevent the ray from reaching the positive terminal (the *anode*). The apparatus was named the *cathode-ray tube* or CRT (Figure 32.3). When electric charges were brought near the tube, the ray was deflected. It bent toward positive

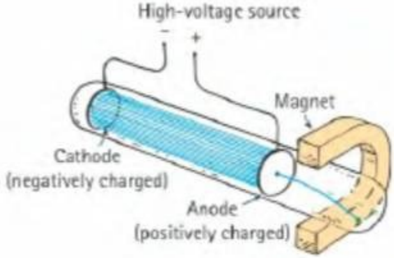

FIGURE 32.4
A cathode ray (electron beam) is deflected by a magnetic field. Deflection is at right angles to the field (not toward either pole).

charges and away from negative charges. The ray was also deflected by the presence of a magnet. These findings indicated that the ray consisted of negatively charged particles.

In 1897, the English physicist Joseph John Thomson ("J. J.," as his friends called him) showed that the cathode rays were particles smaller and lighter than atoms. He created narrow beams of cathode rays and measured their deflection in electric and magnetic fields. Thomson reasoned that the amount of the beams' deflection depended on the mass of the particles and their electrical charge. How? The greater each particle's mass, the greater the inertia and the less the deflection. The greater each particle's charge, the greater the force and the greater the deflection. The greater the speed, the less the deflection.

From careful measurements of the deflection of the beam, Thomson succeeded in calculating the mass-to-charge ratio of the cathode-ray particle, which was named the **electron.** All electrons are identical; they are copies of one another. For establishing the existence of the electron, J. J. Thomson was awarded the Nobel Prize in Physics in 1906.

A dozen years later, in 1909, American physicist Robert Millikan carried out an experiment that enabled him to calculate the numerical value of a single unit of electric charge. In his experiment, Millikan sprayed tiny oil droplets into a chamber between electrically charged plates—into an *electric field.* When the field was strong, some of the droplets moved upward, indicating that they carried a very slight negative charge. Millikan adjusted the field so that droplets hovered motionless. He knew that the downward force of gravity on the droplets was exactly balanced by the upward electrical force. Investigation showed that the charge on each drop was always some multiple of a single very small value, which he proposed to be the fundamental unit of charge carried by each electron. Using this value and the mass-to-charge ratio discovered by Thomson, he calculated the mass of an electron to be about 1/2000 the mass of the lightest known atom, hydrogen. This confirmed Thomson's supposition that the electron is a lightweight and it established the quantum unit of charge. For his work in physics, Millikan received the 1923 Nobel Prize.

If atoms contained negatively charged electrons, it stood to reason that atoms must also contain some balancing positively charged matter. J. J. Thomson proposed what he called a "plum-pudding" model of the atom in which electrons were like plums in a sea of positively charged pudding. The experimentation of Rutherford and the gold-foil experiment, previously mentioned, proved this model wrong.

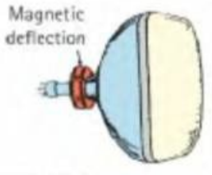

FIGURE 32.5
CRTs like this were common before flat-screen displays largely replaced them.

FIGURE 32.6
Millikan's oil-drop experiment for determining the charge on the electron. The pull of gravity on a particular drop can be balanced by an upward electrical force.

The electron was the first of many fundamental particles that were later discovered.

Atomic Spectra: Clues to Atomic Structure

During the period of Rutherford's experiments, chemists were using the spectroscope (discussed in Chapter 30) for chemical analysis, while physicists were busily occupied trying to find order in the confusing arrays of spectral lines. It had long been known that the lightest element, hydrogen, has a far more orderly spectrum than the other elements (Figure 32.7). An important sequence of lines in the hydrogen spectrum starts with a line in the red region, followed by one in the blue, then by several lines in the violet, and many in the ultraviolet. Spacing between successive lines becomes smaller and smaller from the first in the red to the last in the ultraviolet, until the lines become so close that they seem to merge. A Swiss schoolteacher, Johann Jakob Balmer, first expressed the wavelengths of these lines in a single mathematical formula in 1884. Balmer, however, was unable to provide a reason why his formula worked so successfully. His guess that his formula could be extended to predict other lines of hydrogen proved to be correct, leading to the prediction of lines that had not yet been measured.

FIGURE 32.7
A portion of the hydrogen spectrum. Each line, an image of the slit in the spectroscope, represents light of a specific frequency emitted by hydrogen gas when excited (higher frequency is to the right).

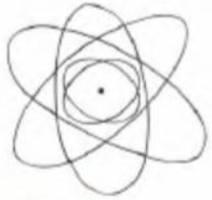

FIGURE 32.8
The Bohr model of the atom. Although this model is very oversimplified, it is still useful in understanding light emission.

Another regularity in atomic spectra was found by the Swedish physicist and mathematician Johannes Rydberg. He noticed that the frequencies of lines in certain series in other elements followed a formula similar to Balmer's and that the sum of the frequencies of two lines in such series often equals the frequency of a third line. This relationship was later advanced as a general principle by the Swiss physicist Walter Ritz and is called the **Ritz combination principle.** It states that the spectral lines of any element include frequencies that are either the sum or the difference of the frequencies of two other lines. Like Balmer, Ritz was unable to offer an explanation for this regularity. These regularities were the clues that the Danish physicist Niels Bohr used to understand the structure of the atom itself.

Bohr Model of the Atom

In 1913, Bohr applied the quantum theory of Planck and Einstein to the nuclear atom of Rutherford and formulated the well-known planetary model of the atom.[2] Bohr reasoned that electrons occupy "stationary" states (of fixed energy, not fixed position) at different distances from the nucleus and that the electrons can make "quantum jumps" from one energy state to another. He reasoned that light is emitted when such a quantum jump occurs (from a higher to a lower energy state). Furthermore, Bohr realized that the frequency of emitted radiation is determined by $E = hf$ (actually, $f = E/h$), where E is the difference in the atom's energy when the electron is in the different orbits. This was an important breakthrough, because he said that the emitted photon's frequency is not the classic frequency at which an electron is vibrating but, instead, is determined by the energy *differences* in the atom (as discussed in Chapter 30). From there, Bohr could advance to the next step and determine the energies of the individual orbits.

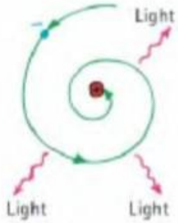

FIGURE 32.9
According to classical theory, an electron accelerating around its orbit should continuously emit radiation. This loss of energy should cause it to spiral rapidly into the nucleus. But this does not happen.

Bohr's planetary model of the atom begged a major question. Accelerated electrons, according to Maxwell's theory, radiate energy in the form of electromagnetic waves. So an electron accelerating around a nucleus should radiate energy continuously. This radiating away of energy should cause the electron to spiral into the nucleus (Figure 32.9). Bohr boldly deviated from classical physics by stating that the electron doesn't radiate light while it accelerates around the nucleus in a single orbit, but that radiation of light occurs only when the electron makes a transition from a higher energy level to a lower energy level. As we now know, the atom emits a photon whose energy is equal to the *difference* in energy between the two energy levels, $E = hf$. As we learned in Chapter 30, the frequency of the emitted photon, its color, depends on the size of the jump. So the quantization of light energy neatly corresponds to the quantization of electron energy.

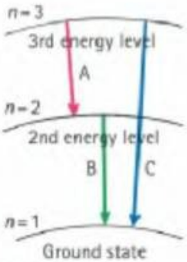

FIGURE 32.10
Three of many energy levels in an atom. An electron jumping from the third level to the second level (red A), and one jumping from the second level to the ground state (green B). The sum of the energies (and the frequencies) for these two jumps equals the energy (and the frequency) of the single jump from the third level to the ground state (blue C).

Bohr's views, as outlandish as they seemed at the time, explained the regularities found in atomic spectra. Bohr's explanation of the Ritz combination principle is shown in Figure 32.10. If an electron is raised to the third energy level, it can return to its initial level either by a single jump from the third to the first level or by a double jump, first to the second level and then to the first level. These two return paths will produce three spectral lines. Note that the sum of the energy jumps along paths A and B is equal to the single energy jump along path C. Since frequency is proportional to energy, the frequencies of light emitted along paths A and B when added equal the frequency of light emitted when the transition is along path C. Now we can see why the sum of two frequencies in the spectrum is equal to a third frequency in the spectrum.

[2]This model, like most models, has major defects because the electrons do not revolve in planes as planets do. The model was revised; "orbits" became "shells" and "clouds." We use *orbit* because it was, and still is, commonly used. Electrons are not just bodies, like planets, but rather behave like waves concentrated in certain parts of the atom.

Bohr was able to account for X-rays in heavier elements, showing that they are emitted when electrons jump from outer to innermost orbits. He predicted X-ray frequencies that were later experimentally confirmed. Bohr was also able to calculate the "ionization energy" of a hydrogen atom—the energy needed to knock the electron out of the atom completely. This also was verified by experiment.

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Bohr's Shell Model

Using measured frequencies of X-rays as well as visible, infrared, and ultraviolet light, scientists could map energy levels of all the atomic elements. Bohr's model had electrons orbiting in neat circles (or ellipses) arranged in groups or shells. This model of the atom accounted for the general chemical properties of the elements. It also predicted a missing element, which led to the discovery of hafnium.

Bohr solved the mystery of atomic spectra while providing an extremely useful model of the atom. He was quick to stress that his model was to be interpreted as a crude beginning, and the picture of electrons whirling about the nucleus like planets about the Sun was not to be taken literally (to which popularizers of science paid no heed). His sharply defined orbits were conceptual representations of an atom whose later description involved waves—quantum mechanics. His ideas of quantum jumps and frequencies being proportional to energy differences remain part of today's modern theory.

CHECK POINT

1. What is the maximum number of paths for de-excitation available to a hydrogen atom excited to level 3 in changing to the ground state?
2. Two predominant spectral lines in the hydrogen spectrum, an infrared one and a red one, have frequencies 2.7×10^{14} Hz and 4.6×10^{14} Hz, respectively. Can you predict a higher-frequency line in the hydrogen spectrum?

Check Your Answers

1. Two (a single jump and a double jump), as shown in Figure 32.10.
2. The sum of the frequencies is $2.7 \times 10^{14} + 4.6 \times 10^{14} = 7.3 \times 10^{14}$ Hz, which happens to be the frequency of a violet line in the hydrogen spectrum. Using Figure 32.10 as a model, can you see that if the infrared line is produced by a transition similar to path A and the red line corresponds to path B, then the violet line corresponds to path C?

Explanation of Quantized Energy Levels: Electron Waves

Back in Chapter 11 we discussed the different sizes of atoms. This was shown in Figure 11.10. In Chapter 30 we discussed atomic excitation and how atoms emit photons when their electrons make energy-level transitions. The idea that electrons may occupy only certain levels was very perplexing to early investigators and to Bohr himself. It was perplexing because the electron was at first thought to be analogous to a particle, a tiny BB, whirling around the nucleus like a planet whirling around the Sun. Just as a satellite can orbit at any distance from the Sun, it would seem that an electron should be able to orbit around the nucleus at any radial distance—depending, of course, like the satellite, on its speed. Moving among all orbits would enable the electrons to emit all energies of light. But this doesn't happen (recall Figure 32.9). Why the electron occupies only discrete levels is understood by considering the electron to be not a particle but a *wave*.

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Video
Electron Waves

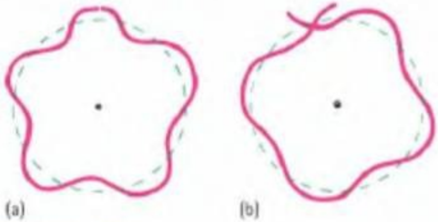

FIGURE 32.11

(a) An orbiting electron forms a standing wave only when the circumference of its orbit is equal to a whole-number multiple of the wavelength.
(b) When the wave does not close in on itself in phase, it undergoes destructive interference. Hence, orbits exist only where waves close in on themselves in phase.

Louis de Broglie introduced the concept of matter waves in 1924. He hypothesized that a wave is associated with every particle and that the wavelength of a matter wave is inversely related to a particle's momentum. These *matter waves* behave just like other waves; they can be reflected, refracted, diffracted, and caused to interfere. Using the idea of interference, de Broglie showed that the discrete values of radii of Bohr's orbits are a natural consequence of standing electron waves. A Bohr orbit exists where an electron wave closes on itself constructively. The electron wave becomes a standing wave, like a wave on a musical string. In this view, the electron is thought of not as a particle located at some point in the atom but as if its mass and charge were spread out into a standing wave surrounding the atomic nucleus—with an integral number of wavelengths fitting evenly into the circumferences of the orbits (Figure 32.11). The circumference of the innermost orbit, according to this picture, is equal to one wavelength. The second orbit has a circumference of two electron wavelengths, the third has three, and so forth (Figure 32.12). This is similar to a chain necklace made of paper clips. No matter what size necklace is made, its circumference is equal to some multiple of the length of a single paper clip.[3] Since the circumferences of electron orbits are discrete, it follows that the radii of these orbits, and hence the energy levels, are also discrete.

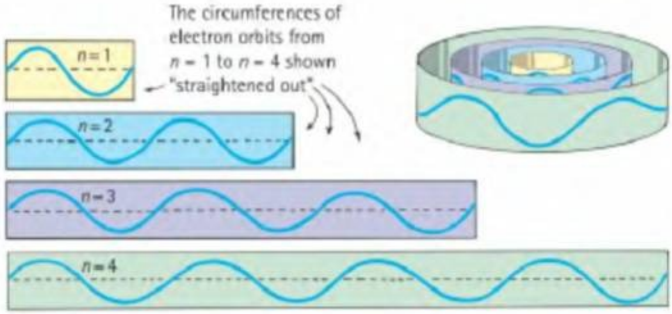

FIGURE 32.12

INTERACTIVE FIGURE

The electron orbits in an atom have discrete radii because the circumferences of the orbits are whole-number multiples of the electron wavelength. This results in a discrete energy state for each orbit. (The figure is greatly oversimplified, as the standing waves make up spherical and ellipsoidal shells rather than flat, circular ones.)

This model explains why electrons don't spiral closer and closer to the nucleus, causing atoms to shrink to the size of the tiny nucleus. If each electron orbit is described by a standing wave, the circumference of the smallest orbit can be no smaller than one wavelength—no fraction of a wavelength is possible in a circular (or elliptical) standing wave. As long as an electron carries the momentum necessary for wave behavior, atoms don't shrink in on themselves.

In the still more modern wave model of the atom, electron waves move not only around the nucleus but also in and out, toward and away from the nucleus. The electron wave is spread out in three dimensions, leading to the picture of an electron "cloud." As we shall see, this is a cloud of *probability*, not a cloud made up of a pulverized electron scattered over space. The electron, when detected, remains a point particle.

[3]For each orbit, the electron has a unique speed, which determines its wavelength. Electron speeds are less, and wavelengths are longer, for orbits of increasing radii; so, for our analogy to be accurate, we'd have to use not only more paper clips to make increasingly longer necklaces but increasingly larger paper clips as well.

Quantum Mechanics

Many changes in physics occurred in the mid-1920s. Not only was the particle nature of light established experimentally but particles of matter were found to have wave properties. Starting with de Broglie's matter waves, the Austrian physicist Erwin Schrödinger formulated an equation that describes how matter waves change under the influence of external forces. Schrödinger's equation plays the same role in **quantum mechanics** that Newton's equation (acceleration = force/mass) plays in classical physics.[4] The matter waves in Schrödinger's equation are mathematical entities that are not directly observable, so the equation provides us with a purely mathematical rather than a visual model of the atom—which places it beyond the scope of this book. So our discussion will be brief.[5]

In **Schrödinger's wave equation,** the thing that "waves" is the nonmaterial *matter wave amplitude*—a mathematical entity called a *wave function,* represented by the symbol ψ (the Greek letter psi). The wave function given by Schrödinger's equation represents the possibilities that can occur for a system. For example, the location of the electron in a hydrogen atom may be anywhere from the center of the nucleus to a radial distance far away. An electron's possible position and its probable position at a particular time are not the same. A physicist can calculate its probable position by multiplying the wave function by itself ($|\psi|^2$). This produces a second mathematical entity called a *probability density function,* which at a given time indicates the probability per unit volume for each of the possibilities represented by ψ.

Experimentally, there is a finite probability (chance) of finding an electron in a particular region at any instant. The value of this probability lies between the limits 0 and 1, where 0 indicates never and 1 indicates always. For example, if the probability is 0.4 for finding the electron within a certain radius, this signifies a 40% chance that the electron will exist there. So the Schrödinger equation cannot tell a physicist where an electron can be found in an atom at any moment, but only the *likelihood* of finding it there—or, for a large number of measurements, what fraction of measurements will find the electron in each region. When an electron's position in its Bohr energy level (state) is repeatedly measured and each of its locations is plotted as a dot, the resulting pattern resembles a sort of electron cloud (Figure 32.13). An individual electron may, at various times, be detected anywhere in this probability cloud; it even has an extremely small but finite probability of momentarily existing inside the nucleus. It is detected most of the time, however, close to an average distance from the nucleus, which fits the orbital radius described by Niels Bohr.

Erwin Schrödinger (1887–1961)

"I think it is safe to say that no one understands quantum mechanics." —*Richard P. Feynman*

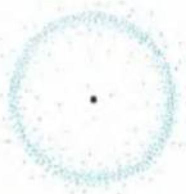

FIGURE 32.13

Probability distribution of an electron cloud for a particular excited state.

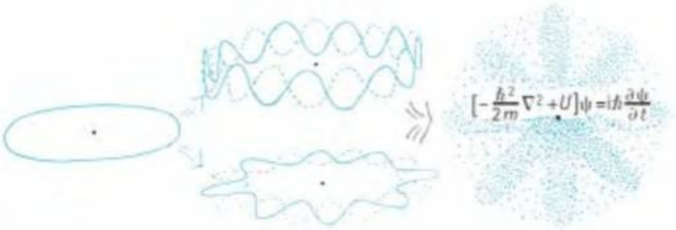

FIGURE 32.14

From the Bohr model of the atom, to the modified model with de Broglie waves, to a wave model with the electrons distributed in a "cloud" throughout the atomic volume.

[4] Schrödinger's wave equation, strictly for math types, is $\left(-\frac{\hbar^2}{2m}\nabla^2 + U\right)\psi = i\hbar\frac{\partial\psi}{\partial t}$.

[5] Our short treatment of this complex subject is hardly conducive to any real understanding of quantum mechanics. At best, it serves as a brief overview and possible introduction to further study. For example, read Ken Ford's *The Quantum World: Quantum Physics for Everyone.* Harvard University Press, paperback edition 2005.

Most physicists, but not all, view quantum mechanics as a fundamental theory of nature. Interestingly enough, Albert Einstein, one of the founders of quantum physics, never accepted it as fundamental; he considered the probabilistic nature of quantum phenomena as the outcome of a deeper, as yet undiscovered, physics. He stated, "Quantum mechanics is certainly imposing. But an inner voice tells me it is not yet the real thing. The theory says a lot, but does not really bring us closer to the secret of 'the Old One.'"[6]

Considering something to be impossible may reflect a *lack of* understanding, as when scientists thought a single atom could never be seen. Or it may represent a *deep* understanding, as when scientists (and the Patent Office!) reject perpetual motion machines.

CHECK POINT

1. Consider 100 photons diffracting through a thin slit to form a diffraction pattern. If we detect 5 photons in a certain region in the pattern, what is the probability (between 0 and 1) of detecting a photon in this region?
2. Suppose that you open a second identical slit and that the diffraction pattern is one of bright and dark bands. Suppose the region where 5 photons hit before now has none. A wave theory says that waves that hit before are now canceled by waves from the other slit—that crests and troughs combine to zero. But our measurement is of photons that either make a hit or don't. How does quantum mechanics reconcile this?

Check Your Answers

1. We have approximately a 0.05 probability of detecting a photon at this location. The true probability could be somewhat more or less than 0.05. Put the other way around, if the true probability is 0.05, the number detected could be somewhat more or less than 5.
2. Quantum mechanics says that photons propagate as waves and are absorbed as particles, with the probability of absorption governed by the maxima and minima of wave interference. Where the combined wave from the two slits has zero amplitude, the probability of a particle being absorbed is zero.

Correspondence Principle

The correspondence principle is a general rule not only for good science but for all good theory—even in areas as far removed from science as government, religion, and ethics. If a new theory is valid, it must account for the verified results of the old theory. This is the **correspondence principle,** first articulated by Bohr. New theory and old theory must correspond; that is, they must overlap and agree in the region where the results of the old theory have been fully verified.

Bohr introduced the correspondence principle in connection with his 1913 theory of the hydrogen atom. He reasoned that when an electron is in a highly excited state, orbiting far from the atomic nucleus, its behavior should resemble (correspond to) classical behavior. And indeed when an electron in such a highly excited state makes a series of quantum jumps, from one state to the next lower one and on downward, it emits photons of gradually increasing frequency that match its own frequency of motion. It seems to spiral inward, as classical physics predicts.

When the techniques of quantum mechanics are applied to still larger systems, the results are essentially identical with those of classical mechanics. The two domains blend when the de Broglie wavelength is small compared with the dimensions of the system or of the pieces of matter in the system. It is satisfying to know that quantum theory and classical theory, which make such completely different

[6]Although Einstein practiced no religion, he often invoked God as the "Old One" in his statements about the mysteries of nature.

predictions at the level of a single atom, blend smoothly into a description of nature that extends from the smallest to the largest things in the universe.

SUMMARY OF TERMS

Atomic nucleus Positively charged center of an atom, containing protons and neutrons and almost the entire mass of the atom, but only a tiny fraction of its volume.

Electron Negative particle in the outer part of an atom.

Ritz combination principle The statement that the frequencies of some spectral lines of the elements are either the sums or the differences of the frequencies of two other lines.

Quantum mechanics The theory of the microworld based on wave functions and probabilities developed especially by Werner Heisenberg (1925) and Erwin Schrödinger (1926).

Schrödinger's wave equation A fundamental equation of quantum mechanics, which relates probability wave amplitudes to the forces acting on a system. It is as basic to quantum mechanics as Newton's laws of motion are to classical mechanics.

Correspondence principle The rule that a new theory must produce the same results as the old theory where the old theory is known to be valid.

REVIEW QUESTIONS

Discovery of the Atomic Nucleus

1. Why do most alpha particles fired through a piece of gold foil emerge almost undeflected, and why do others bounce backward?
2. What did Rutherford discover about the atomic nucleus?

Discovery of the Electron

3. What did Benjamin Franklin postulate about electricity?
4. What is a cathode ray?
5. What property of a cathode ray is indicated when a magnet is brought near the tube?
6. What did J. J. Thomson discover about the cathode ray?
7. What did Robert Millikan discover about the electron?

Atomic Spectra: Clues to Atomic Structure

8. What did Johann Jakob Balmer discover about the spectrum of hydrogen?
9. What did Johannes Rydberg and Walter Ritz discover about atomic spectra?

Bohr Model of the Atom

10. What relationship between electron orbits and light emission did Bohr postulate?
11. According to Niels Bohr, can a single electron in one excited state give off more than one photon when it jumps to a lower energy state?
12. What is the relationship between the energy differences of orbits in an atom and the light emitted by the atom?

Explanation of Quantized Energy Levels: Electron Waves

13. How does treating the electron as a wave rather than as a particle solve the riddle of why electron orbits are discrete?
14. According to the simple de Broglie model, how many wavelengths are there in an electron wave in the first orbit? In the second orbit? In the *n*th orbit?
15. How can we explain why electrons don't spiral into the attracting nucleus?

Quantum Mechanics

16. What does the wave function Ψ represent?
17. Distinguish between a *wave function* and a *probability density function*.
18. How does the probability cloud of the electron in a hydrogen atom relate to the orbit described by Niels Bohr?

Correspondence Principle

19. Exactly what is it that "corresponds" in the correspondence principle?
20. Would Schrödinger's equation be valid if applied to the solar system? Would it be useful?

EXERCISES

1. Consider photons emitted from an ultraviolet lamp and a TV transmitter. Which has the greater (a) wavelength, (b) energy, (c) frequency, and (d) momentum?
2. Which color light is the result of a greater energy transition, red or blue?
3. In what way did Rutherford's gold-foil scattering experiment show that the atomic nucleus is both small and very massive?
4. How does Rutherford's model of the atom account for the back-scattering of alpha particles directed at the gold foil?

5. At the time of Rutherford's gold-foil experiment, scientists knew that negatively charged electrons exist within the atom, but they did not know where the positive charge resides. What information about the positive charge was provided by Rutherford's experiment?

6. Why does classical physics predict that atoms should collapse?

7. If the electron in a hydrogen atom obeyed classical mechanics instead of quantum mechanics, would it emit a continuous spectrum or a line spectrum? Explain.

8. Why are spectral lines often referred to as "atomic fingerprints"?

9. When an electron makes a transition from its first quantum level to ground level, the energy difference is carried by the emitted photon. In comparison, how much energy is needed to return an electron at ground level to the first quantum level?

10. Figure 32.10 shows three transitions among three energy levels that would produce three spectral lines in a spectroscope. If the energy spacing between the levels were equal, would this affect the number of spectral lines?

11. How can elements with low atomic numbers have so many spectral lines?

12. In terms of wavelength, what is the smallest orbit that an electron can have about the atomic nucleus?

13. Which best explains the photoelectric effect—the particle nature or the wave nature of the electron? Which best explains the discrete levels in the Bohr model of the atom? Defend your answers.

14. How does the wave model of electrons orbiting the nucleus account for discrete energy values rather than a continuous range of energy values?

15. Why do helium and lithium exhibit very different chemical behavior, even though they differ by only one electron?

16. The Ritz combination principle can be considered to be a statement of energy conservation. Explain.

17. Does the de Broglie model assert that an electron must be moving in order to have wave properties? Defend your answer.

18. Why does no stable electron orbit with a circumference of 2.5 de Broglie wavelengths exist in any atom?

19. An orbit is a distinct path followed by an object in its revolution around another object. An atomic orbital is an electron spread out over a *volume of space* in which the electron is most likely to be found. What do orbits and orbitals have in common?

20. Can a particle be diffracted? Can it exhibit interference?

21. How does the amplitude of a matter wave relate to probability?

22. If Planck's constant, h, were larger, would atoms be larger also? Defend your answer.

23. What is it that waves in the Schrödinger wave equation?

24. If the world of the atom is so uncertain and subject to the laws of probabilities, how can we accurately measure such things as light intensity, electric current, and temperature?

25. When we say that electrons have particle properties and then continue to say that electrons have wave properties, aren't we contradicting ourselves? Explain.

26. Did Einstein support quantum mechanics as being fundamental physics, or did he think quantum mechanics was incomplete?

27. When only a few photons are observed, classical physics fails. When many are observed, classical physics is valid. Which of these two facts is consistent with the correspondence principle?

28. When and where do Newton's laws of motion and quantum mechanics overlap?

29. What does Bohr's correspondence principle say about quantum mechanics versus classical mechanics?

30. Does the correspondence principle have application to macroscopic events in the everyday macroworld?

31. Richard Feynman, in his book *The Character of Physical Law*, states: "A philosopher once said, 'It is necessary for the very existence of science that the same conditions always produce the same results.' Well, they don't!" Who was speaking of classical physics, and who was speaking of quantum physics?

32. What does the wave nature of matter have to do with the fact that we can't walk through solid walls, as Hollywood movies often show using special effects?

33. Largeness or smallness has meaning only relative to something else. Why do we usually call the speed of light "large" and Planck's constant "small"?

34. Make up a multiple-choice question that would check a classmate's understanding of the difference between the domains of classical mechanics and quantum mechanics.

CHAPTER 32 ONLINE RESOURCES

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Interactive Figure

- 32.12

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- Atoms and Isotopes
- Bohr's Shell Model

Video

- Electron Waves

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33 The Atomic Nucleus and Radioactivity

1 When Rosa Alvis moves the tube of a Geiger counter close to a piece of uranium ore (carnotite), an increased rate of clicks is heard by students in her Conceptual Physics class at City College of San Francisco. 2 Radioactive decay in Earth's interior heats the water that feeds hot springs worldwide. These impressive ones, loaded with calcium carbonate, are in Pamukkale, Turkey. 3 University of Melbourne professor Roger Rassool uses a scintillation counter to show that the paths of gamma rays are unaffected by a magnetic field, as illustrated in Figure 33.3.

What physicist won two Nobel Prizes, one in physics and one in chemistry, and had a daughter who also earned a Nobel Prize in chemistry? The answer is Madame Curie. Born in 1867 as Marie Sklodowska in Warsaw, then part of the Russian Empire, she received her general education in local schools with some scientific training from her father, a secondary-school teacher. Encouraged by her elder sister Bronislawa, who was a physician and had relocated to Paris, Marie moved to Paris to continue her studies at the Sorbonne. There she lived in a primitive garret, which she chose because it was affordable and close to the university. In 1894, after earning her first degree, she met the love of her life, physics professor Pierre Curie. In 1895, they were married and soon began working together.

In 1896, the French physicist Henri Becquerel discovered that uranium salts emitted rays that resembled X-rays in their ability to penetrate solid matter. Marie and Pierre began investigating uranium. They were the first to coin the word *radioactivity*. It became Marie's life's work. By this time (1898) a French citizen, Marie named the first new chemical element that she and Pierre discovered polonium—for her native country. They also discovered and named the element radium. In 1903, Pierre and Marie shared the Nobel Prize in Physics with Henri Becquerel for their work with radioactivity. Some sources say that the Curies shared money from the prize with needy acquaintances, including students. The Sorbonne in Paris honored Pierre with a professorship and a laboratory in which Marie became chief of laboratory work.

Marie Curie (1867–1934)

In 1906, Pierre was struck by a horse-drawn vehicle while crossing a street in the rain. Pierre fell under its wheels and was killed by a skull fracture. Marie was devastated by her husband's death. The Sorbonne physics department entrusted Pierre's chair to Marie. She was the first female professor at the Sorbonne, where she continued her work and earned her Nobel Prize in Chemistry in 1911. She was also appointed Director of the Curie Laboratory in the Radium Institute of the University of Paris, founded in 1914.

During World War I she donated her Nobel Prize gold medals to the war effort. In 1921, she was welcomed triumphantly on her first tour of the United States, where she raised funds for radium research. She toured America again in 1929, when President Hoover presented her with a check for $50,000, enough to buy 1 gram of radium for the Radium Institute in Paris.

Madame Curie visited Poland for the last time in 1934. A couple of months later she died—probably from the excessive exposures to radiation she endured during her lifetime of work. At that time, the damaging effects of ionizing radiation were not fully appreciated. She was buried at the cemetery in Sceaux, alongside her husband Pierre. Sixty years later, in 1995, in honor of their achievements, the remains of both were transferred to the Paris Panthéon. She became the first woman so honored.

X-rays and Radioactivity

Deeper probing into the atom began in 1895 when the German physicist Wilhelm Roentgen discovered **X-rays**—rays of an unknown nature. Roentgen discovered these "new kind of rays" produced by a beam of "cathode rays" (later found to be electrons) striking the glass surface of a gas-discharge tube. He found that X-rays could pass through solid materials, could ionize the air, showed no refraction in glass, and were undeflected by magnetic fields. Today we know that X-rays are high-frequency electromagnetic waves, usually emitted by the de-excitation of the innermost orbital electrons of atoms. Whereas the electron current in a fluorescent lamp excites the outer electrons of atoms and produces ultraviolet and visible photons, a more energetic beam of electrons striking a solid surface excites the innermost electrons and produces higher-frequency photons of X-radiation.

X-ray photons have high energy and can penetrate many layers of atoms before being absorbed or scattered. X-rays do this when they pass through your soft tissue to produce an image of the bones inside your body (Figure 33.1). In a modern X-ray tube, the target of the electron beam is a metal plate rather than the glass wall of the tube.

fyi

- So far we've treated *atomic physics*—the study of the clouds of electrons that make up the atom. Now we'll burrow beneath the electrons and go deeper into the atom—to the atomic nucleus—where available energies dwarf those available to electrons. This is *nuclear physics*, a topic of great public interest—and public fear—not unlike the fear of electricity more than a century ago. With safeguards and well-informed consumers, society has determined that the benefits of electricity outweigh its risks. Likewise today with nuclear technology's risks versus its benefits.

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Tutorial
Nuclear Physics

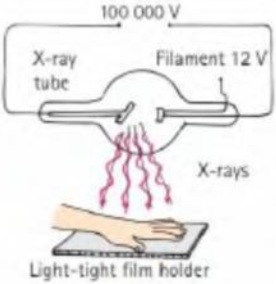

FIGURE 33.1
X-rays emitted by excited metallic atoms in the electrode penetrate flesh more readily than bone and produce an image on the film.

In early 1896, a few months after Roentgen announced his discovery of X-rays, the French physicist Antoine Henri Becquerel stumbled upon a new kind of penetrating radiation. Becquerel was studying fluorescence and phosphorescence created by both light and the newly discovered X-rays, and one evening happened to leave a wrapped photographic plate in a drawer next to some crystals that contained uranium. The next day he discovered to his surprise that the photographic plate had been darkened, apparently by spontaneous radiation from the uranium. He went on to show that this new radiation differed from X-rays in that it could ionize air and could be deflected by electric and magnetic fields.

It was soon discovered that similar rays are emitted by other elements, such as thorium, actinium, and two new elements discovered by Marie and Pierre Curie—polonium and radium. The emission of these rays was evidence of much more drastic changes in the atom than atomic excitation. These rays, as it turned out, were the result not of changes in the electron energy states of the atom but of changes occurring within the central atomic core—the nucleus. This process is **radioactivity**, which, because it involves the decay of the atomic nucleus, is often called *radioactive decay*.

Radioactivity has been around since Earth's beginning.

A common misconception is that radioactivity is something new in the environment, but it has been around far longer than the human race. It is as much a part of our environment as the Sun and the rain. It has always been in the soil we walk on and in the air we breathe, and it is what warms the interior of Earth and makes it molten. In fact, radioactive decay in Earth's interior is what heats the water that spurts from a geyser or wells up from a natural hot spring. Even the helium in a child's balloon is nothing more than the product of radioactive decay. Radioactivity is as natural as sunshine and rain.

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Video
Radioactive Decay

Alpha, Beta, and Gamma Rays

More than 99.9% of the atoms in our everyday environment are stable. The nuclei in those atoms will be unlikely to change over the lifetime of the universe. But some kinds of atoms are unstable. All elements having an atomic number greater than 82 (lead) are radioactive. These elements, and others, emit three distinct types of radiation, named by the first three letters of the Greek alphabet, α, β, γ—*alpha, beta,* and *gamma*.

Light is emitted by energy-level transitions in atoms; gamma rays are emitted by similar energy transitions within the atomic nucleus.

Alpha rays have a positive electrical charge, **beta rays** have a negative electrical charge, and **gamma rays** have no charge at all (Figure 33.2). The three rays can be separated by placing a magnetic field across their paths (Figure 33.3). Further investigation has shown that an alpha ray is a stream of helium nuclei, and a beta ray is a stream of electrons. Hence, we often call these *alpha particles* and *beta particles*. A gamma ray is electromagnetic radiation (a stream of photons) whose frequency is even higher than that of X-rays. Whereas X-rays originate in the electron cloud outside the atomic nucleus,

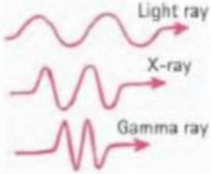

FIGURE 33.2
INTERACTIVE FIGURE
A gamma ray is part of the electromagnetic spectrum. It is simply electromagnetic radiation that is much higher in frequency and energy than light and X-rays.

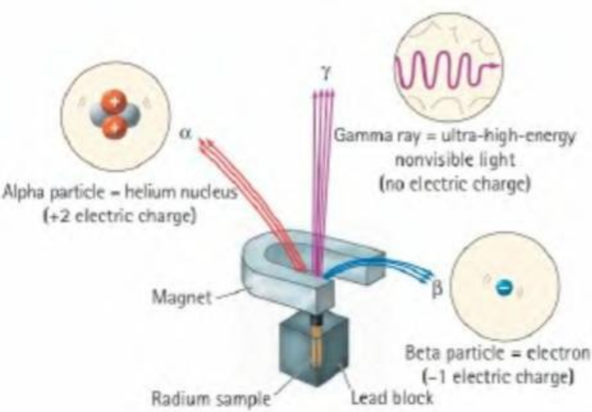

FIGURE 33.3
INTERACTIVE FIGURE
In a magnetic field, alpha rays bend one way, beta rays bend the other way, and gamma rays don't bend at all. The combined beam comes from a radioactive source placed at the bottom of a hole drilled in a lead block.

alpha, beta, and gamma rays originate in the nucleus. Gamma photons provide information about nuclear structure, much as visible and X-ray photons provide information about atomic electron structure.

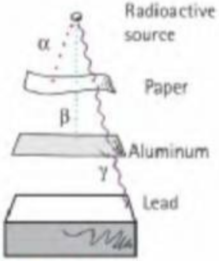

FIGURE 33.4

INTERACTIVE FIGURE

Alpha particles are the least penetrating and can be stopped by a few sheets of paper. Beta particles will readily pass through paper, but not through a sheet of aluminum. Gamma rays penetrate several centimeters into solid lead.

FIGURE 33.5

The shelf life of fresh strawberries and other perishables is markedly increased when the food is subjected to gamma rays from a radioactive source. The strawberries on the right were treated with gamma radiation, which kills the microorganisms that normally lead to spoilage. The food is only a receiver of radiation and is in no way transformed into an emitter of radiation, as can be confirmed with a radiation detector.

CHECK POINT

Pretend you are given three radioactive rocks—one an alpha emitter, one a beta emitter, and one a gamma emitter. You can throw away one, but of the remaining two, you must hold one in your hand and the other you must place in your pocket. What can you do to minimize your exposure to radiation?

Check Your Answer

Hold the alpha emitter in your hand because the skin on your hand will shield you. Put the beta emitter in your pocket because beta particles will likely be stopped by the combined thickness of your clothing and skin. Throw away the gamma emitter because it would penetrate your body from any of these locations. Ideally, of course, you should distance yourself as much as possible from all the rocks.

Once alpha and beta particles are slowed by collisions, they combine to become harmless helium atoms.

Environmental Radiation

Common rock and minerals in our environment contain significant quantities of radioactive isotopes because most of them contain trace amounts of uranium. As a matter of fact, people who live in brick, concrete, or stone buildings are exposed to greater amounts of radiation than people who live in wooden buildings.

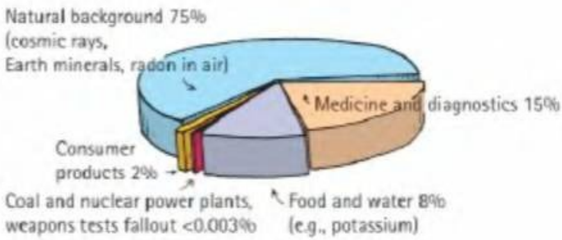

FIGURE 33.6

Origins of radiation exposure for an average individual in the United States.

The leading source of naturally occurring radiation is radon-222, an inert gas arising from uranium deposits. Radon is a heavy gas that tends to accumulate in basements after it seeps up through cracks in the floor. Levels of radon vary from region to region, depending upon local geology. You can check the radon level in your home with a radon detector kit (Figure 33.7). If levels are abnormally high, corrective measures, such as sealing the basement floor and walls and maintaining adequate ventilation, are recommended.

About one-sixth of our annual exposure to radiation comes from nonnatural sources, primarily medical procedures. Smoke detectors, fallout from long-ago nuclear testing, and the coal and nuclear power industries are also contributors. The coal industry far outranks the nuclear power industry as a source of radiation. Globally, the combustion of coal annually releases about 13,000 tons of radioactive thorium and uranium into the atmosphere. Both these minerals are found naturally in coal deposits so that their release is a natural consequence of burning coal. Worldwide, the nuclear power industries generate about 10,000 tons of radioactive waste each year. Most all of this waste, however, is contained and *not* released into the environment.

FIGURE 33.7

A commercially available radon test kit for the home.

UNITS OF RADIATION

Radiation dosage is commonly measured in *rads* (*r*adiation *a*bsorbed *d*ose), a unit of absorbed energy. One **rad** is equal to 0.01 joule of radiant energy absorbed per kilogram of tissue.

The capacity for nuclear radiation to cause damage is not just a function of its level of energy, however. Some forms of radiation are more harmful than others. For example, suppose you have two arrows, one with a pointed tip and one with a suction cup at its tip. Shoot both arrows at an apple at the same speed and both have the same kinetic energy. The one with the pointed tip, however, will invariably do more damage to the apple than the one with the suction cup. Similarly, some forms of radiation cause greater harm than other forms even when we receive the same number of rads from both forms.

The unit of measure for radiation dosage based on potential damage is the **rem** (*r*oentgen *e*quivalent *m*an).[1] In calculating the dosage in rems, we multiply the number of rads by a factor that corresponds to different health effects of different types of radiation determined by clinical studies. For example, 1 rad of alpha particles has the same biological effect as 10 rads of beta particles.[2] We call both of these dosages 10 rems.

Particle	Radiation Dosage		Factor		Health Effect
alpha	1 rad	×	10	=	10 rems
beta	10 rad	×	1	=	10 rems

CHECK POINT

Which is more harmful, being exposed to 1 rad of alpha particles or 1 rad of beta particles?

Check Your Answer

Alpha particles: Multiply these quantities of radiation by the appropriate factor to get the dosages in rems. Alpha: 1 rad × 10 = 10 rems; beta: 1 rad × 1 = 1 rem. The factors show us that, physiologically speaking, alpha particles are 10 times more damaging than beta particles.

[1]This unit is named for Wilhelm Roentgen, the discoverer of X-rays.

[2]This is true even though beta particles have more penetrating power, as previously discussed.

DOSES OF RADIATION

Lethal doses of radiation begin at 500 rems. A person has about a 50% chance of surviving a dose of this magnitude delivered to the whole body over a short period of time. During radiation therapy, a patient may receive localized doses in excess of 200 rems each day for a period of weeks (Figure 33.8).

FIGURE 33.8

Nuclear radiation is focused on harmful tissue, such as a cancerous tumor, to selectively kill or shrink the tissue in a technique known as *radiation therapy*. This application of nuclear radiation has saved millions of lives—a clear-cut example of the benefits of nuclear technology. The inset shows the internationally used symbol indicating an area where radioactive material is being handled or produced.

All the radiation we receive from natural sources and from diagnostic medical procedures is only a fraction of 1 rem per year. For convenience, the smaller unit *millirem* is used, where 1 millirem (mrem) is 1/1000th of a rem. The average person in the United States is exposed to about 360 mrem a year, as Table 33.1 indicates. About 80% of this radiation comes from natural sources, such as cosmic rays and Earth itself. A typical chest X-ray exposes a person to 5 to 30 mrem (0.005 to 0.030 rem), less than one ten-thousandth of the lethal dose. Interestingly, the human body is a significant source of natural radiation, primarily from the potassium we ingest. Our bodies contain about 200 grams of potassium. Of this quantity, about 20 milligrams is the radioactive isotope potassium-40, which is a gamma-ray emitter. Between every heartbeat about 60,000 potassium-40 isotopes in the average human body undergo spontaneous radioactive decay. Radiation is indeed everywhere.

When radiation encounters the intricately structured molecules in the watery, ion-rich brine that makes up our cells, the radiation can create chaos on the atomic scale. Some molecules are broken, and this change alters other molecules, which can be harmful to life processes.

FIGURE 33.9

The film badges worn by Tammy and Larry contain audible alerts for both radiation surge and accumulated exposure. Information from the individualized badges is periodically downloaded to a database for analysis and storage.

TABLE 33.1

Annual Radiation Exposure

Source	Typical Dose (mrem) Received Annually
Natural Origin	
Cosmic radiation	26
Ground	33
Air (radon-222)	198
Human tissues (K-40; Ra-226)	35
Human Origin	
Medical procedures	
Diagnostic X-rays	40
Nuclear diagnostics	15
Consumer products	8
Weapons-test fallout	1
Commercial fossil-fuel power plants	<1
Commercial nuclear power plants	<<1

Cells are able to repair most kinds of molecular damage caused by radiation if the radiation is not too severe. A cell can survive an otherwise lethal dose of radiation if the dose is spread over a long period of time to allow intervals for healing. When radiation is sufficient to kill cells, the dead cells can be replaced by new ones (except for most nerve cells, which are irreplaceable). Sometimes a radiated cell will survive with a damaged DNA molecule. New cells arising from the damaged cell retain the altered genetic information, producing a *mutation*. Usually the effects of a mutation are insignificant, but occasionally the mutation results in cells that do not function as well as unaffected ones, sometimes leading to a cancer. If the damaged DNA is in an individual's reproductive cells, the genetic code of the individual's offspring may retain the mutation.

RADIOACTIVE TRACERS

In scientific laboratories radioactive samples of all the elements have been made. This is accomplished by bombardment with neutrons or other particles. Radioactive materials are extremely useful in scientific research and industry. To check the action of a fertilizer, for example, researchers combine a small amount of radioactive material with the fertilizer and then apply the combination to a few plants. The amount of radioactive fertilizer taken up by the plants can be easily measured with radiation detectors. From such measurements, scientists can inform farmers of the proper amount of fertilizer to use. Radioactive isotopes used to trace such pathways are called *tracers*.

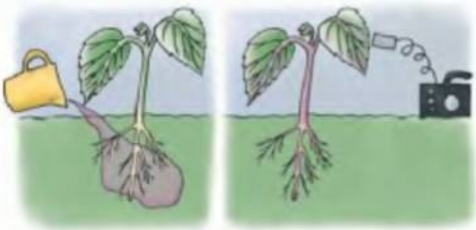

FIGURE 33.10
Tracking fertilizer uptake with a radioactive isotope.

In a technique known as medical imaging, tracers are used for the diagnosis of internal disorders. This technique works because the path the tracer takes is influenced only by its physical and chemical properties, not by its radioactivity. The tracer may be introduced alone or along with some other chemical that helps target the tracer to a particular type of tissue in the body.

FIGURE 33.11
The thyroid gland, located in the neck, absorbs much of the iodine that enters the body through food and drink. Images of the thyroid gland, such as the one shown here, can be obtained by giving a patient a small amount of the radioactive isotope iodine-131. These images are useful in diagnosing metabolic disorders.

The Atomic Nucleus and the Strong Force

The atomic nucleus occupies only a few quadrillionths of the volume of the atom, leaving most of the atom as empty space. The nucleus is composed of **nucleons,** which is the collective name for protons and neutrons. (Each nucleon is composed of three smaller particles called **quarks**—believed to be fundamental, not made of smaller parts.)

fyi

- Among nature's fundamental particles are six kinds of *quark*, of which two are the fundamental building blocks of all nucleons (protons and neutrons). Quarks carry fractional electrical charges. One kind, the *up* quark, carries +2/3 the proton charge, and another, the *down* quark, has −1/3 the proton charge. (The name *quark*, inspired by a quotation from *Finnegans Wake* by James Joyce, was chosen in 1963 by Murray Gell-Mann, who first proposed their existence.) Quarks in the proton are the combination *up up down*, and in the neutron *up down down*. The other four quarks bear the whimsical names *strange*, *charm*, *top*, and *bottom*. No quarks have been isolated and experimentally observed. Most theorists think quarks, by their nature, cannot be isolated.

Just as there are energy levels for the orbital electrons of an atom, there are energy levels within the nucleus. Whereas orbiting electrons emit photons when making transitions to lower orbits, similar changes of energy states in radioactive nuclei result in the emission of gamma-ray photons. This is gamma radiation.

We know that electrical charges of like sign repel one another. So how is it possible that positively charged protons in the nucleus stay clumped together? This question led to the discovery of an attraction called the **strong force,** which acts between all nucleons. This force is very strong, but only over extremely short distances (about 10^{-15} m, the approximate diameter of a proton or neutron). Repulsive electrical interactions, on the other hand, are relatively long-ranged. Figure 33.12 suggests a comparison of the strengths of these two forces over distance. For protons that are close together, as in small nuclei, the attractive strong nuclear force easily overcomes the repulsive electrical force. But for protons that are far apart, like those on opposite edges of a large nucleus, the attractive strong nuclear force may be weaker than the repulsive electrical force.

Without the nuclear strong force—strong interaction—there would be no atoms beyond hydrogen.

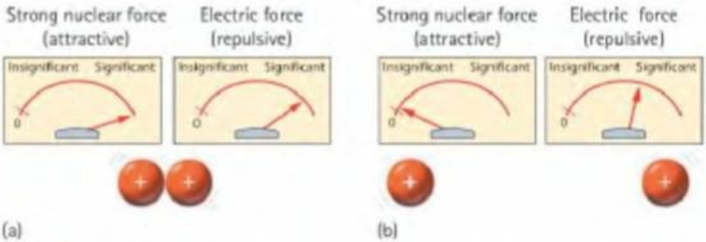

FIGURE 33.12

Imaginary meter readings of comparative forces: (a) Two nearby protons experience both an attractive strong nuclear force and a repulsive electric force. At this tiny separation distance, the strong nuclear force overcomes the electric force, and they stay together. (b) When they are far apart, the electric force predominates and they repel. This proton–proton repulsion in large atomic nuclei reduces nuclear stability.

A large nucleus is not as stable as a small one. In a helium nucleus, for example, each of the two protons feels the repulsive effect of the other. In a uranium nucleus, each of the 92 protons feels the repulsive effects of the other 91 protons! The nucleus is unstable. We see that there is a limit to the size of the atomic nucleus. It is for this reason that all nuclei having more than 82 protons are radioactive (number 83, bismuth, just barely so).

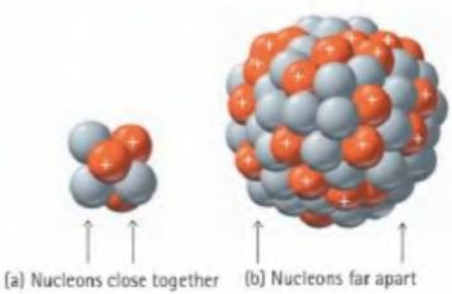

FIGURE 33.13

(a) All nucleons in a small atomic nucleus are close to one another; hence, they experience an attractive strong nuclear force.
(b) Nucleons on opposite sides of a larger nucleus are not as close to one another, and so the attractive strong nuclear forces holding them together are much weaker. The result is that the large nucleus is less stable.

CHECK POINT

Two protons in the atomic nucleus repel each other, but they also attract each other. Why?

Check Your Answer

Two forces are acting—electrical and nuclear. While protons electrically repel each other, they also simultaneously attract each other by the strong nuclear force. When the attractive strong nuclear force is stronger than the repulsive electric force, the protons remain together. When far apart, the electrical force can overcome the nuclear force, and they tend to fly apart.

Neutrons serve as a "nuclear cement" that holds the atomic nucleus together. Protons attract both protons and neutrons by the strong nuclear force. Protons also repel other protons by the electric force. Neutrons, on the other hand, have no electric charge and so only attract other protons and neutrons by the strong nuclear force. The presence of neutrons therefore adds to the attraction among nucleons and helps hold the nucleus together (Figure 33.14).

All nucleons, both protons and neutrons, attract one another by the strong nuclear force.

Only protons repel one another by the electric force.

FIGURE 33.14

The presence of neutrons helps hold the nucleus together by increasing the effect of the strong nuclear force, represented by the single-headed arrows.

The more protons there are in a nucleus, the more neutrons are needed to help balance the repulsive electric forces. For light elements, it is sufficient to have about as many neutrons as protons. The most common isotope of carbon, C-12, for instance, has equal numbers of each—six protons and six neutrons. For large nuclei, more neutrons than protons are needed. Because the strong nuclear force diminishes rapidly over distance, nucleons must be practically touching in order for the strong nuclear force to be effective. Nucleons on opposite sides of a large atomic nucleus are not as attracted to one another. The electric force, however, does not diminish by much across the diameter of a large nucleus and so begins to win out over the strong nuclear force. To compensate for the weakening of the strong nuclear force across the diameter of the nucleus, large nuclei have more neutrons than protons. Lead, for example, has about one-and-a-half times as many neutrons as protons.

So we see that neutrons are stabilizing and large nuclei require an abundance of them—up to a point beyond which not even neutrons can hold a nucleus together. Interestingly, neutrons are not stable when they are by themselves. A lone neutron is radioactive and spontaneously transforms to a proton and an electron (Figure 33.15a). A neutron needs protons around to keep this from happening. The alpha particles emitted in alpha decay are literally nuclear "chunks," and only heavy nuclei emit them.[3] Beta and gamma particles, on the other hand, can be emitted by

[3]An exception to the rule that alpha decay is limited to heavy nuclei is the highly radioactive nucleus of beryllium 8, with four protons and four neutrons, which splits into two alpha particles—a form of nuclear fission.

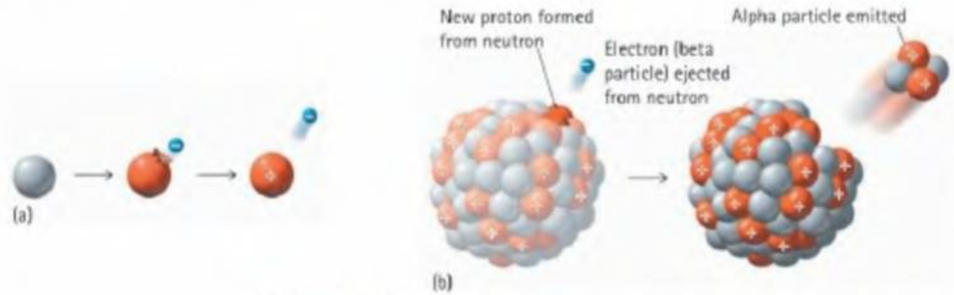

FIGURE 33.15

(a) A neutron near a proton is stable, but a neutron by itself is unstable and decays to a proton by emitting an electron. (b) Destabilized by an increase in the number of protons, the nucleus begins to shed fragments, such as alpha particles.

radioactive nuclei both heavy and light. The beta decay of a single neutron and the alpha decay of a heavy nucleus are shown in Figure 33.15b.

CHECK POINT

What role do neutrons serve in the atomic nucleus? What is the fate of a neutron when alone or distant from one or more protons?

Check Your Answers

Neutrons serve as a nuclear cement in nuclei and add to nuclear stability. But when alone, a neutron is radioactive and spontaneously transforms to a proton and an electron.

Radioactive Half-Life

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The radioactive decay rate of an element is measured in terms of a characteristic time, the **half-life.** This is the time it takes for half of an original quantity of a radioactive isotope to decay. Radium-226, for example, has a half-life of 1620 years. This means that half of any given specimen of radium-226 will be converted into

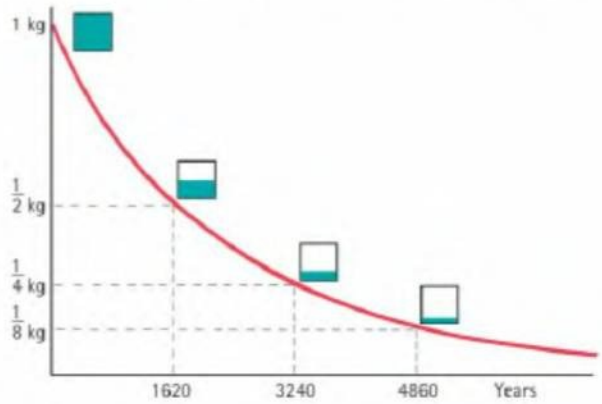

FIGURE 33.16

INTERACTIVE FIGURE

Every 1620 years, the amount of radium decreases by half.

other elements by the end of 1620 years. In the following 1620 years, half of the remaining radium will decay, leaving only one-fourth the original amount of radium (after 20 half-lives, the initial quantity radium-226 will be diminished by a factor of about 1 million).

Half-lives are remarkably constant and not affected by external conditions.[4] Some radioactive isotopes have half-lives that are less than a millionth of a second, while others have half-lives of more than a billion years. Uranium-238 has a half-life of 4.5 billion years. All uranium eventually decays in a series of steps to lead. In 4.5 billion years, half the uranium presently in Earth today will be lead.

It is not necessary to wait through the duration of a half-life in order to measure it. The half-life of an element can be calculated at any given moment by measuring the rate of decay of a known quantity. This is easily done using a radiation detector. In general, the shorter the half-life of a substance, the faster it disintegrates, and the more radioactivity per amount is detected.

The radioactive half-life of a material is also the time for its decay rate to reduce to half.

CHECK POINT

If a sample of radioactive isotopes has a half-life of 1 day, how much of the original sample will be left at the end of the second day? The third day?

Check Your Answers

One-quarter at the end of the second day, one-eighth at the end of the third day.

Radiation Detectors

Ordinary thermal motions of atoms bumping one another in a gas or liquid are not energetic enough to dislodge electrons, and the atoms remain neutral. But when an energetic particle such as an alpha or a beta particle shoots through matter, electrons one after another are knocked from the atoms in the particle's path. The result is a trail of freed electrons and positively charged ions. This ionization process is responsible for the harmful effects of high-energy radiation in living cells. Ionization also makes it relatively easy to trace the paths of high-energy particles. We will briefly discuss five radiation detection devices.

1. A *Geiger counter* consists of a central wire in a hollow metal cylinder filled with low-pressure gas. An electrical voltage is applied across the cylinder and wire so that the wire is more positive than the cylinder. If radiation enters the tube and ionizes an atom in the gas, the freed electron is attracted to the

(a)

(b)

FIGURE 33.17

Radiation detectors. (a) A Geiger counter detects incoming radiation by a short pulse of current triggered when radiation ionizes a gas in the tube. (b) A scintillation counter indicates incoming radiation by flashes of light produced when charged particles or gamma rays pass through the counter.

[4]In 2008, researchers at Purdue University claimed to see a small solar influence on radioactive decay rates. As of this writing, the claim remains to be checked.

FIGURE 33.18

A cloud chamber. Charged particles moving through supersaturated vapor leave trails. When the chamber is in a strong electric or magnetic field, bending of the tracks provides information about the charge, mass, and momentum of the particles.

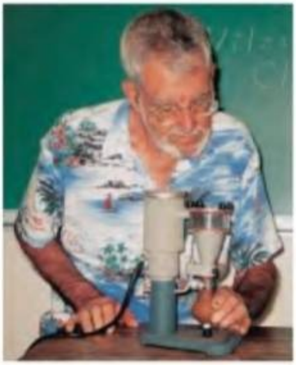

FIGURE 33.19

Walter Steiger examines vapor trails in a small cloud chamber.

positively charged central wire. As this electron is accelerated toward the wire, it collides with other atoms and knocks out more electrons, which, in turn, produce more electrons, and so on, resulting in a cascade of electrons moving toward the wire. This makes a short pulse of electric current, which activates a counting device connected to the tube. Amplified, this pulse of current produces the familiar clicking sound we associate with radiation detectors.

2. A *cloud chamber* shows a visible path of ionizing radiation in the form of fog trails. It consists of a cylindrical chamber closed at the upper end by a glass window and at the lower end by a movable piston. Water vapor or alcohol vapor in the chamber can be saturated by adjusting the piston. The source of radiation can be outside the chamber or inside it, as shown in Figure 33.18. When a charged particle passes through the chamber, ions are produced along its path. If the saturated air in the chamber is then suddenly cooled by motion of the piston, tiny droplets of moisture condense about these ions and form vapor trails, showing the paths of the radiation. These are the atomic versions of the ice-crystal trails left in the sky by jet planes.

   Even simpler is the continuous cloud chamber. It contains a steady supersaturated vapor, because it rests on a slab of dry ice, with a temperature gradient from near room temperature at the top to very low temperature at the bottom. Fog tracks that form are illuminated with a lamp and may be seen or photographed through the glass top. The chamber may be placed in a strong electric or magnetic field, which will bend the paths in a manner that provides information about the charge, mass, and momentum of the radiation particles. Positively and negatively charged particles will bend in opposite directions.

   Cloud chambers, which were critically important tools in early cosmic ray research, are now used principally for classroom demonstrations. Perhaps your instructor will show you one, as does Walter Steiger in Figure 33.19.

3. The particle trails seen in a *bubble chamber* are minute bubbles of gas in liquid hydrogen (Figure 33.20). The liquid hydrogen is heated under pressure in a glass and stainless steel chamber to a point just short of boiling. If the pressure in the chamber is suddenly released at the moment an ion-producing particle enters, a thin trail of bubbles is left along the particle's path. All the liquid then erupts to a boil, but, in the few thousandths of a second before this happens, photographs are taken of the particle's short-lived trail. As with the cloud chamber, a magnetic field in the bubble chamber reveals information about the charge and relative mass of the particles being studied. Bubble chambers have been widely used by researchers in past decades, but presently there is greater interest in spark chambers.

4. A *spark chamber* is a counting device that consists of an array of closely spaced parallel plates. Every other plate is grounded, and the plates in between are

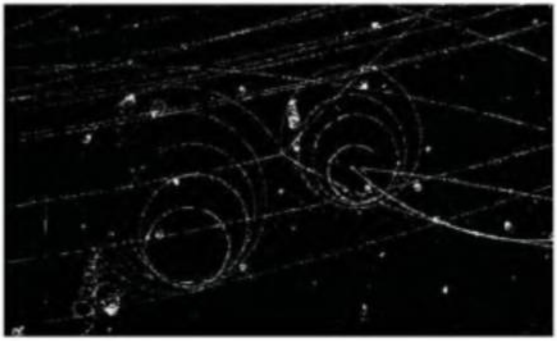

FIGURE 33.20

Tracks of elementary particles in a bubble chamber. (The trained eye notes that two particles were destroyed at the point where the spirals emanate, with four others created in the collision.)

maintained at a high voltage (about 10 kV). Ions are produced in the gas between the plates as charged particles pass through the chamber. Discharge along the ionic path produces a visible spark between pairs of plates. A trail of many sparks reveals the path of the particle. A different design, called a *streamer chamber*, consists of only two widely spaced plates, between which an electric discharge, or "streamer," closely follows the path of the incident charged particle. The principal advantage of spark and streamer chambers over the bubble chamber is that more events can be monitored in a given time.

5. A *scintillation counter* uses the fact that certain substances are easily excited and emit light when charged particles or gamma rays pass through them. Tiny flashes of light, or scintillations, are converted into electric signals by special photomultiplier tubes. A scintillation counter is much more sensitive to gamma rays than a Geiger counter, and, in addition, it can measure the energy of charged particles or gamma rays absorbed in the detector. The radiation detector that Roger Rassool shows in the chapter-opener photo is a scintillator. Interestingly, ordinary water, when highly purified, can serve as a scintillator.

FIGURE 33.21

Installation of the Big European Bubble Chamber (BEBC) at CERN, near Geneva, typical of the large bubble chambers used in the 1970s to study particles produced by high-energy accelerators.

CHECK POINT

Which will give a higher counting rate on a radiation detector, radioactive material that has a short half-life or radioactive material that has a long half-life?

Check Your Answer

The material with the shorter half-life is more active and will show a higher counting rate on a radiation detector.

Transmutation of Elements

When a radioactive nucleus emits an alpha or a beta particle, there is a change in atomic number—a different element is formed. The changing of one chemical element to another is called **transmutation.** Transmutation occurs in natural events, and is also initiated artificially in the laboratory.

NATURAL TRANSMUTATION

Consider uranium-238, the nucleus of which contains 92 protons and 146 neutrons. When an alpha particle is ejected, the nucleus loses two protons and two neutrons. Because an element is defined by the number of protons in its nucleus, the 90 protons and 144 neutrons left behind are no longer identified as being uranium. What we have is the nucleus of a different element—*thorium*. This transmutation can be written as a nuclear equation:

$$^{238}_{92}\text{U} \rightarrow {}^{234}_{90}\text{Th} + {}^{4}_{2}\text{He}$$

We see that $^{238}_{92}$U transmutes to the two elements written to the right of the arrow. When this transmutation occurs, energy is released, partly in the form of kinetic energy of the alpha particle ($^{4}_{2}$He), partly in the kinetic energy of the thorium nucleus, and partly in the form of gamma radiation. In this and all such equations, the mass numbers at the top balance ($238 = 234 + 4$) and the atomic numbers at the bottom also balance ($92 = 90 + 2$).

Thorium-234, the product of this reaction, is also radioactive. When it decays, it emits a beta particle.[5] Since a beta particle is an electron, the atomic number of the resulting nucleus is *increased* by 1. So after beta emission by thorium with 90 protons, the resulting element has 91 protons. It is no longer thorium, but the element protactinium. Although the atomic number has increased by 1 in this process, the mass number (protons + neutrons) remains the same. The nuclear equation is

$$^{234}_{90}\text{Th} \rightarrow {}^{234}_{91}\text{Pa} + {}^{0}_{-1}e$$

We write an electron as $^{0}_{-1}e$. The superscript 0 indicates that the electron's mass is insignificant relative to that of protons and neutrons. The subscript -1 is the electric charge of the electron.

One ton of ordinary granite contains about 9 grams of uranium and 20 grams of thorium. One ton of basalt contains 3.5 grams of uranium and 7.7 grams of thorium.

So we see that when an element ejects an alpha particle from its nucleus, the mass number of the resulting atom is decreased by 4 and its atomic number is decreased by 2. The resulting atom is an element two spaces back in the periodic table of the elements. When an element ejects a beta particle from its nucleus, the mass of the atom is practically unaffected, meaning there is no change in mass number, but its atomic number increases by 1. The resulting atom belongs to an element one place forward in the periodic table. Gamma emission results in no change in either the mass number or the atomic number. So we see that radioactive elements can decay backward or forward in the periodic table.[6]

The successions of radioactive decays of $^{238}_{92}\text{U}$ to $^{206}_{82}\text{Pb}$, an isotope of lead, is shown in Figure 33.22. Each blue arrow shows an alpha decay, and each red arrow shows a beta decay. Notice that some of the nuclei in the series can decay in both ways. This is one of several similar radioactive series that occur in nature.

CHECK POINT

1. Complete the following nuclear reactions.
   a. $^{226}_{88}\text{Ra} \rightarrow {}^{?}_{?}? + {}^{0}_{-1}e$
   b. $^{209}_{84}\text{Po} \rightarrow {}^{205}_{82}\text{Pb} + {}^{?}_{?}?$
2. What finally becomes of all the uranium that undergoes radioactive decay?

Check Your Answers

1. a. $^{226}_{88}\text{Ra} \rightarrow {}^{226}_{89}\text{Ac} + {}^{0}_{-1}e$
   b. $^{209}_{84}\text{Po} \rightarrow {}^{205}_{82}\text{Pb} + {}^{4}_{2}\text{He}$
2. All uranium will ultimately become lead. On the way to becoming lead, it will exist as a series of elements, as indicated in Figure 33.22.

[5]Beta emission is always accompanied by the emission of a neutrino (actually, an antineutrino), a neutral particle with nearly zero mass that travels at about the speed of light. The neutrino ("little neutral one") was postulated by Wolfgang Pauli in 1930 and detected in 1956. Neutrinos are hard to detect because they interact very weakly with matter. Whereas a piece of solid lead a few centimeters thick will stop most gamma rays from a radium source, a piece of lead about 8 light-years thick would be needed to stop half the neutrinos produced in typical nuclear decays. Thousands of neutrinos are flying through you every second of every day, because the universe is filled with them. Only occasionally, one or two times a year or so, does a neutrino interact with the matter of your body.

At this writing, the mass of neutrinos is unknown, but is established to be no more than about a millionth the mass of an electron. Yet neutrinos are so numerous they might comprise most of the mass of the universe. Neutrinos may be the "glue" that holds the universe together.

[6]Sometimes a nucleus emits a positron, which is the "antiparticle" of an electron. In this case, a proton becomes a neutron, and the atomic number is decreased.

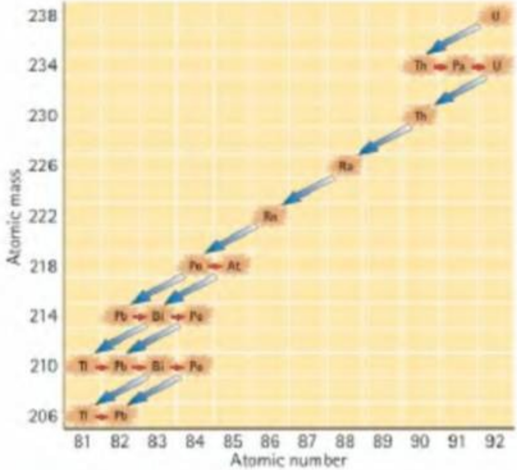

FIGURE 33.22
U-238 decays to Pb-206 through a series of alpha and beta decays.

ARTIFICIAL TRANSMUTATION

Ernest Rutherford, in 1919, was the first of many investigators to succeed in deliberately transmuting a chemical element. He bombarded nitrogen gas with alpha particles from a piece of radioactive ore. The impact of an alpha particle on a nitrogen nucleus can transmute nitrogen into oxygen:

$$^{4}_{2}\text{He} + ^{14}_{7}\text{N} \rightarrow ^{17}_{8}\text{O} + ^{1}_{1}\text{H}$$

Rutherford used a cloud chamber to record this event. From a quarter-of-a-million cloud-chamber tracks photographed on movie film, he showed seven examples of atomic transmutation. Analysis of tracks bent by a strong external magnetic field showed that sometimes when an alpha particle collided with a nitrogen atom, a proton bounced out and the heavy atom recoiled a short distance. The alpha particle disappeared. The alpha particle was absorbed in the process, transforming nitrogen to oxygen.

Since Rutherford's announcement in 1919, experimenters have carried out many other nuclear reactions, first with natural bombarding projectiles from radioactive ores and then with still more energetic projectiles—protons and other particles hurled by huge particle accelerators. Artificial transmutation is what produces the hitherto unknown synthetic elements from atomic number 93 to 118. All these artificially made elements have short half-lives. Any that may have existed naturally when Earth was formed have long since decayed.

Radiometric Dating

Earth's atmosphere is continuously bombarded by cosmic rays, and this bombardment causes many atoms in the upper atmosphere to transmute. These transmutations result in many protons and neutrons being "sprayed out" into the environment. Most of the protons are stopped as they collide with the atoms of

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the upper atmosphere, stripping electrons from these atoms to become hydrogen atoms. The neutrons, however, keep going for longer distances because they have no electrical charge and therefore do not interact electrically with matter. Eventually, many of them collide with the nuclei in the denser lower atmosphere. A nitrogen nucleus that captures a neutron, for instance, can emit a proton and become the nucleus of a carbon isotope:

$$^{1}_{0}n + {}^{14}_{7}N \rightarrow {}^{14}_{6}C + {}^{1}_{1}H$$

This carbon-14 isotope, which makes up less than one-millionth of 1% of the carbon in the atmosphere, has eight neutrons and is radioactive. (The most common isotope, carbon-12, has six neutrons and is not radioactive.) Because both carbon-12 and carbon-14 are forms of carbon, they have the same chemical properties. Both these isotopes can chemically react with oxygen to form carbon dioxide, which is taken in by plants. This means that all plants contain a tiny bit of radioactive carbon-14. All animals eat plants (or other animals that ate plants), and therefore have a little carbon-14 in them. In short, all living things on Earth contain some carbon-14.

Carbon-14 is a beta emitter and decays back to nitrogen by the following reaction:

$$^{14}_{6}C \rightarrow {}^{14}_{7}N + {}^{0}_{-1}e$$

Because plants continue to take in carbon dioxide as long as they live, any carbon-14 lost by decay is immediately replenished with fresh carbon-14 from the atmosphere. In this way, a radioactive equilibrium is reached where there is a constant ratio of about one carbon-14 atom to every 100 billion carbon-12 atoms. When a plant dies, replenishment of carbon-14 stops. Then the percentage of carbon-14 decreases at a constant rate given by its half-life.[7] The longer a plant or other organism is dead, therefore, the less carbon-14 it contains relative to the constant amount of carbon-12.

The half-life of carbon-14 is about 5730 years. This means that half of the carbon-14 atoms that are now present in a plant or animal that dies today will decay in the next 5730 years. Half of the remaining carbon-14 atoms will then decay in the following 5730 years, and so forth.

FIGURE 33.23

The amount of radioactive carbon-14 in the skeleton diminish by one-half every 5730 years, with the result that today the skeleton contains only a fraction of the carbon-14 it originally had. The red arrows symbolize relative amounts of carbon-14.

[7]A 1-g sample of contemporary carbon contains about 5×10^{22} atoms, 6.5×10^{10} of which are C-14 atoms, and has a beta disintegration rate of about 13.5 decays per minute.

Food Irradiation

Each week in the United States about 100 people, most of them children or elderly, die from illnesses they contract from food. People stricken ill each week from food-borne diseases number in the millions, according to the Centers for Disease Control and Prevention in Atlanta, Georgia. But never astronauts. Why? Because diarrhea in orbit is a no-no, and food taken on space missions is irradiated with high-energy gamma rays from a radioactive cobalt source (Co-60). Astronauts, as well as patients in many hospitals and nursing homes, don't have to contend with salmonella, *E. coli*, microbes, or parasites in food irradiated by Co-60. So why isn't more irradiated food available in the marketplace? The answer is public phobia about the *r* word—*radiation*.

Food irradiation kills insects in grains, flour, fruits, and vegetables. Small doses prevent stored potatoes, onions, and garlic from sprouting and significantly increase the shelf life of soft fruits, such as strawberries. Larger doses kill microbes, insects, and parasites in spices, pork, and poultry. Irradiation can penetrate through sealed cans and packages. What irradiation does *not* do is leave the irradiated food radioactive. No radioactive material touches the food. Gamma rays pass through the food like light passing through glass, destroying most bacteria that can cause disease. No food becomes radioactive, for the gamma rays lack the energy needed to knock neutrons from atomic nuclei.

Irradiation does, however, leave behind traces of broken compounds—identical to those resulting from pyrolysis when charbroiling foods we already eat. Compared with canning and cold storage, irradiation has less effect on nutrition and taste. It's been around for most of the 1900s, and it has been tested for more than 40 years, with no evidence of danger to consumers. Irradiation of foods is endorsed by all major scientific societies, the United Nations' World Health Organization, the U.S. Food and Drug Administration, and the American Medical Association. Irradiation is the method of choice for 37 countries worldwide. Although widely used in Belgium, France, and the Netherlands, its use in the United States is presently small, as controversy continues.

This controversy is another example of risk evaluation and management. Shouldn't risks of injury or death from irradiated food be judged rationally and weighed against the benefits it would bring? Shouldn't the choice be based upon the number of people who *might* die of irradiated food versus those who in fact *do* die because food is not irradiated?

Perhaps what is needed is a name change—expunging the *r* word, as was done with the *n* word when the resisted medical procedure once known as NMRI (nuclear magnetic resonance imaging) was given a more acceptable name, MRI (magnetic resonance imaging).

With this knowledge, scientists are able to calculate the age of carbon-containing artifacts, such as wooden tools or skeletons, by measuring their current level of radioactivity. This process, known as **carbon dating,** enables us to probe as much as 50,000 years into the past. Beyond this time span, there is too little carbon-14 remaining to permit accurate analysis.

Carbon-14 dating would be an extremely simple and accurate dating method if the amount of radioactive carbon in the atmosphere had been constant over the ages. But it hasn't been. Fluctuations in the Sun's magnetic field as well as changes in the strength of Earth's magnetic field affect cosmic-ray intensities in Earth's atmosphere, which in turn produce fluctuations in the production of C-14. In addition, changes in Earth's climate affect the amount of carbon dioxide in the atmosphere. The oceans are great reservoirs of carbon dioxide. When the oceans are cold, they release less carbon dioxide into the atmosphere than when they are warm.

CHECK POINT

Suppose an archeologist extracts a gram of carbon from an ancient ax handle and finds it one-fourth as radioactive as a gram of carbon extracted from a freshly cut tree branch. About how old is the ax handle?

Check Your Answer

Assuming the ratio of C-14/C-12 was the same when the ax was made, the ax handle is two half-lives of C-14, or about 11,500 years, old.

The dating of older, but nonliving, things is accomplished with radioactive minerals, such as uranium. The naturally occurring isotopes U-238 and U-235 decay very slowly and ultimately become isotopes of lead—but not the common lead isotope Pb-208. For example, U-238 decays through several stages to finally become

Pb-206, whereas U-235 finally becomes the isotope Pb-207. Lead isotopes 206 and 207 that now exist were at one time uranium. The older the uranium-bearing rock, the higher the percentage of these remnant isotopes. From the half-lives of uranium isotopes, and the percentage of lead isotopes in uranium-bearing rock, it is possible to calculate the date at which the rock was formed.

SUMMARY OF TERMS

X-ray Electromagnetic radiation of higher frequencies than ultraviolet; emitted by electron transitions to the lowest energy states in atoms.

Radioactivity Process of the atomic nucleus that results in the emission of energetic subatomic particles.

Alpha ray A stream of alpha particles (helium nuclei) ejected by certain radioactive elements.

Beta ray A stream of electrons (or positrons) emitted during the radioactive decay of certain nuclei.

Gamma ray High-frequency electromagnetic radiation emitted by the nuclei of radioactive atoms.

Rad Acronym (*r*adiation *a*bsorbed *d*ose) for a unit of absorbed energy. One rad is equal to 0.01 J of energy absorbed per kilogram of tissue.

Rem Acronym (*r*oentgen *e*quivalent *m*an) for a unit used to measure the effect of ionizing radiation on humans.

Nucleon A nuclear proton or neutron; the collective name for either or both.

Quarks The elementary constituent particles or building blocks of nuclear matter.

Strong force Force that attracts nucleons to each other within the atomic nucleus; a force that is very strong at close distances, and that greatly weakens as distance increases.

Half-life The time required for half the atoms in a sample of a radioactive isotope to decay.

Transmutation The conversion of an atomic nucleus of one element into an atomic nucleus of another element through a loss or gain in the number of protons.

Carbon dating Process of determining the time that has elapsed since death by measuring the radioactivity of the remaining carbon14 atoms.

REVIEW QUESTIONS

X-Rays and Radioactivity

1. What did the physicist Roentgen discover about a cathode-ray beam striking a glass surface?
2. What is the similarity between a beam of X-rays and a beam of light? What is the principal difference between the two?
3. What did the physicist Becquerel discover about uranium?
4. What two elements did Pierre and Marie Curie discover?

Alpha, Beta, and Gamma Rays

5. Why are gamma rays not deflected in a magnetic field?
6. What is the origin of a beam of gamma rays? A beam of X-rays?

Environmental Radiation

7. Distinguish between a *rad* and a *rem*.
8. Do humans receive more radiation from artificial or from natural sources of radiation?
9. Is the human body radioactive? Explain.
10. What kinds of cells are in most danger when they are irradiated?
11. What is a radioactive tracer?

The Atomic Nucleus and the Strong Force

12. Name the two different nucleons.
13. Why doesn't the repulsive electric force of protons in the atomic nucleus cause the protons to fly apart?
14. Why is a larger nucleus generally less stable than a smaller nucleus?
15. What is the role of neutrons in the atomic nucleus?
16. Which contains the bigger percentage of neutrons, large nuclei or small nuclei?

Radioactive Half-Life

17. How does the rate of decay of a long-half-life material normally compare with the rate of decay of a short-half-life material?
18. What is the half-life of Ra-226?

Radiation Detectors

19. What kind of trail is left when an energetic particle shoots through matter?
20. Which two radiation detectors operate primarily by sensing the trails left by energetic particles that shoot through matter?
21. Which detector senses flashes of light produced by charged particles or gamma rays?

Transmutation of Elements

22. What is transmutation?

23. When thorium (atomic number 90) decays by emitting an alpha particle, what is the atomic number of the resulting nucleus?
24. When thorium decays by emitting a beta particle, what is the atomic number of the resulting nucleus?
25. What is the change in atomic mass for each of the above two reactions?
26. What change in atomic number occurs when a nucleus emits an alpha particle? A beta particle? A gamma ray?
27. What is the long-range fate of all the uranium that exists in the world?
28. When, and by whom, did the first successful intentional transmutation of an element occur?

Radiometric Dating

29. What occurs when a nitrogen nucleus captures an extra neutron?
30. Which are more prominent in the food we eat, carbon-12 or carbon-14?

RANKING

1. Rank these three types of radiation by their ability to penetrate this page of your book, from greatest penetration to least.
   a. Alpha particle.
   b. Beta particle.
   c. Gamma ray.
2. Consider these three nuclei: A. Th-233; B. U-235; C. U-238. From most to least, rank them by the number of
   a. protons in the nucleus.
   b. neutrons in the nucleus.
   c. electrons that normally surround the nucleus.
3. Consider the following reactions: A. uranium-238 emits an alpha particle; B. plutonium-239 emits an alpha particle; C. thorium-239 emits a beta particle.
   a. Rank the resulting nucleus by atomic number, from most to least.
   b. Rank the resulting nucleus by the number of neutrons, from most to least.

PROJECT

Write a letter to one of your favorite relatives that will help dispel any notion they may have about radioactivity being something new in the world. Briefly discuss the role of radioactivity in dating ancient objects. Also discuss how radioactivity is a major source of natural heat in Earth's interior, and cite its role in hot springs and volcanoes.

EXERCISES

1. In the 19th century, the famous physicist Lord Kelvin estimated the age of Earth to be much less than the present estimate. What information that Kelvin did not have might have allowed him to avoid making his erroneous estimate?
2. X-rays are most similar to which of the following—alpha, beta, or gamma rays?
3. Gamma radiation is fundamentally different from alpha and beta radiation. What is this basic difference?
4. Why is a sample of radioactive material always a little warmer than its surroundings?
5. Some people say that all things are possible. Is it at all possible for a common hydrogen nucleus to emit an alpha particle? Defend your answer.
6. Why are alpha and beta rays deflected in opposite directions in a magnetic field? Why are gamma rays not deflected?
7. The alpha particle has twice the electric charge of the beta particle but, for the same kinetic energy, deflects less than the beta in a magnetic field. Why is this so?
8. How do the paths of alpha, beta, and gamma rays compare in an electric field?
9. Which type of radiation—alpha, beta, or gamma—produces the greatest change in *mass number* when emitted by an atomic nucleus? Which produces the greatest change in *atomic number?*
10. Which type of radiation—alpha, beta, or gamma—produces the least change in mass number? In atomic number?
11. Which type of radiation—alpha, beta, or gamma—predominates within an enclosed elevator descending into a uranium mine?
12. In bombarding atomic nuclei with proton "bullets," why must the protons be accelerated to high energies if they are to make contact with the target nuclei?
13. Just after an alpha particle leaves the nucleus, would you expect it to speed up? Defend your answer.
14. What do all isotopes of the same element have in common? How do they differ?
15. Why would you expect alpha particles, with their greater charge, to be less able to penetrate into materials than beta particles of the same energy?

16. Two protons in an atomic nucleus repel each other, but they are also attracted to each other. Explain.

17. Which interaction tends to hold the particles in an atomic nucleus together and which interaction tends to push them apart?

18. What evidence supports the contention that the strong nuclear interaction can dominate over the electrical interaction at short distances within the nucleus?

19. Can it be truthfully stated that whenever a nucleus emits an alpha or beta particle, it necessarily becomes the nucleus of another element?

20. Exactly what is a positively charged hydrogen atom?

21. Why do different isotopes of the same element have the same chemical properties?

22. If you make an account of 1000 people born in the year 2000 and find that half of them are still living in 2060, does this mean that one-quarter of them will be alive in 2120 and one-eighth of them alive in 2180? What is different about the death rates of people and the "death rates" of radioactive atoms?

23. Radiation from a point source obeys the inverse-square law. If a Geiger counter 1 m from a small sample registers 360 counts per minute, what will be its counting rate 2 m from the source? What will it be 3 m from the source?

24. Why do the charged particles flying through bubble chambers travel in spiral paths rather than in the circular or helical paths they might ideally follow?

25. What two quantities are always conserved in all nuclear equations?

26. Judging from Figure 33.22, how many alpha and beta particles are emitted in the series of radioactive decay events from a U-238 nucleus to a Pb-206 nucleus? Does it matter which path is followed?

27. If an atom has 100 electrons, 157 neutrons, and 100 protons, what is its approximate atomic mass? What is the name of this element?

28. When a $^{226}_{88}Ra$ nucleus decays by emitting an alpha particle, what is the atomic number of the resulting nucleus? What is the resulting atomic mass?

29. When a nucleus of $^{218}_{84}Po$ emits a beta particle, it transforms into the nucleus of a different element. What are the atomic number and the atomic mass of this "daughter" element?

30. When a nucleus of $^{218}_{84}Po$ emits an alpha particle, what are the atomic number and the atomic mass of the resulting element?

31. Which has the greater number of protons, U-235 or U-238? Which has the greater number of neutrons?

32. State the number of neutrons and protons in each of the following nuclei: $^{2}_{1}H$, $^{12}_{6}C$, $^{56}_{26}Fe$, $^{197}_{79}Au$, $^{90}_{38}Sr$, and $^{238}_{92}U$.

33. How is it possible for an element to decay "forward in the periodic table"—that is, to decay to an element of higher atomic number?

34. How could an element emit alpha and beta particles and result in the same element?

35. When radioactive phosphorus (P) decays, it emits a positron. Will the resulting nucleus be another isotope of phosphorus? If not, what will it be?

36. "Strontium-90 is a pure beta source." How could a physicist test this statement?

37. A friend suggests that nuclei are composed of equal numbers of protons and electrons, and not neutrons. What evidence can you cite to show that your friend is mistaken?

38. Radium-226 is a common isotope on Earth, but it has a half-life of about 1600 years. Given that Earth is some 5 billion years old, why is there any radium left at all?

39. Elements above uranium in the periodic table do not exist in any appreciable amounts in nature because they have short half-lives. Yet there are several elements below uranium in atomic number with equally short half-lives that do exist in appreciable amounts in nature. How can you account for this?

40. Your friend says that the helium used to inflate balloons is a product of radioactive decay. Another friend disagrees. With whom do you agree?

41. Another friend, fretful about living near a fission power plant, wishes to get away from radiation by traveling to the high mountains and sleeping at night on granite outcroppings. Comment on this.

42. Still another friend has journeyed to the mountain foothills to escape the effects of radioactivity altogether. While bathing in the warmth of a natural hot spring, she wonders aloud how the spring gets its heat. What do you tell her?

43. Although coal contains only minute quantities of radioactive materials, there is more radiation emitted by a coal-fired power plant than a fission power plant simply because of the vast amount of coal that is burned in coal-fired plants. What does this indicate about methods of preventing the release of radioactivity that are typically implemented at the two kinds of power plants?

44. A friend produces a Geiger counter to check the local normal background radiation. It clicks randomly but repeatedly. Another friend, whose tendency is to fear most that which is least understood, makes an effort to avoid Geiger counters and looks to you for advice. What do you say?

45. When food is irradiated with gamma rays from a cobalt-60 source, does the food become radioactive? Defend your answer.

46. When the author attended high school some 60 years ago, his teacher showed a piece of uranium ore and measured its radioactivity with a Geiger counter. Would that reading for the same piece of ore be different today?

47. Why is carbon dating ineffective in finding the ages of dinosaur bones?

48. Is carbon dating appropriate for measuring the age of materials that are a few years old? A few thousand years old? A few million years old?

49. The age of the Dead Sea Scrolls was found by carbon dating. Could this technique apply if they were carved in stone tablets? Explain.

50. Make up two multiple-choice questions that would check a classmate's understanding of radioactive dating.

PROBLEMS

1. If a sample of a radioactive isotope has a half-life of 1 year, how much of the original sample will be left at the end of the second year? At the end of the third year? At the end of the fourth year?
2. A sample of a particular radioisotope is placed near a Geiger counter, which is observed to register 160 counts per minute. Eight hours later, the detector counts at a rate of 10 counts per minute. What is the half-life of the material?
3. The isotope cesium-137, which has a half-life of 30 years, is a product of nuclear power plants. Show that it will take 120 years for this isotope to decay to about one-sixteenth its original amount.
4. At 6:00 AM a hospital uses its cyclotron to make 1 milligram of the isotope fluorine-18 for use as a diagnostic tool with its PET scanner. The half-life of F-18 is 1.8 hours. How much F-18 is left at 3:00 PM? At midnight? Should the hospital plan to make more F-18 the next morning?
5. Suppose that you measure the intensity of radiation from carbon-14 in an ancient piece of wood to be 6% of what it would be in a freshly cut piece of wood. Show that the age of this artifact is 23,000 years old.
6. Suppose that you want to find out how much gasoline is in an underground storage tank. You pour in 1 gallon of gasoline that contains some radioactive material with a long half-life that gives off 5000 counts per minute. The next day, you remove a gallon from the underground tank and measure its radioactivity to be 10 counts per minute. How much gasoline is in the tank?

CHAPTER 33 ONLINE RESOURCES

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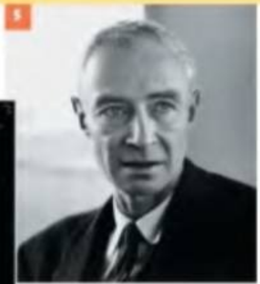
34 Nuclear Fission and Fusion







1 Lise Meitner, the discoverer of nuclear fission, 2 Otto Frisch, her physicist nephew who aided in her discovery, and 3 Otto Hahn, who took the credit for it. 4 Italian physicist Enrico Fermi received the 1938 Nobel Prize for work leading to nuclear fission. When he left Stockholm after receiving the prize to return to his native Italy, he said jokingly that he got lost and ended up in New York. In fact, he and his Jewish wife Laura carefully planned their escape from Fascist Italy. Four years later in Chicago, he was the first to initiate controlled fission, and he became an American citizen in 1945. 5 Robert J. Oppenheimer headed the Los Alamos labs for the Manhattan Project during World War II. He was considered a national hero—until he was professionally and personally devastated by political witch hunts in the 1950s.

Lise Meitner was born in 1878 in Vienna. Girls at that time had no public schooling after their early teen years. Lise received her school "completion certificate" while still 13. Since her parents could not afford to send her to Switzerland to a private boarding school, she enrolled in a "young ladies school" to prepare for teaching French. But her heart was in mathematics and physics, not French. At 19, she joined a group of other ambitious young women who studied on their own—with some help from private tutors—to prepare for the university. After just 2 years of intensive work, she passed the test for admission to the University of Vienna (1 of just 4 of 14 women who tried that year), and in 1906, at age 27, she earned a doctorate with highest honors.

With the encouragement and financial support of her father, Meitner went to Berlin to further her career. Max Planck departed from his policy of not letting women attend his lectures and allowed her into his class. After one year, she became his assistant. She then joined the chemist Otto Hahn in what was to be a fruitful 30-year collaboration. They soon discovered several new isotopes, and in 1909 she published two papers on beta radiation.

During World War I, both she and Hahn took some time off for war work—she to work as a nurse and X-ray technician—but they also found time to continue their research, and in 1918 they discovered element number 91, protactinium. In the 1920s she became the first woman in Berlin, perhaps the first in all of Germany, to be named a professor. Soon her work on radioactivity led to her scientific recognition worldwide.

When Adolf Hitler came to power in 1933, Meitner, although Jewish, was able to continue her work, at least for a time, protected by her Austrian citizenship. Most other Jewish scientists, including her nephew Otto Frisch, were dismissed or forced to resign from their posts, and most of them, including Albert Einstein, emigrated from Germany.

In 1934 came word of the work of Enrico Fermi and his colleagues in Rome, in which they had bombarded many elements, including uranium, with neutrons, and seemingly created new elements. Meitner and Hahn joined the international hunt for "transuranics," elements heavier than uranium—a hunt that unexpectedly led to nuclear fission.

In July 1938, when Meitner was threatened with dismissal, with the help of Dutch physicists she escaped to Holland. After a close call with German immigration officials, she reached safety, but without her possessions. She had hastily left Germany with only 10 marks in her purse, plus a ring that Otto Hahn had given her, one inherited from his mother, to be used to bribe the frontier guards if needed. Meitner then moved on to Stockholm, where she took up a post and established a working relationship with Niels Bohr, who traveled regularly between Copenhagen and Stockholm. She continued to correspond with Hahn and other German scientists.

In the fall of 1938, Hahn and Meitner met clandestinely in Copenhagen to plan a new round of experiments with uranium. In December of that year, Hahn wrote to Meitner that he and his associate Fritz Strassmann had discovered the element barium in samples of pure uranium that had been bombarded with neutrons. They were good chemists and sure of their result but were at a loss to explain the appearance of barium. During the Christmas holidays, Meitner and her visiting nephew Otto Frisch, on a walk in snowy woods in Sweden, came up with an explanation: The uranium nucleus was breaking apart into lighter nuclei, including nuclei of barium. Frisch rushed back to Copenhagen and performed an experiment that confirmed their hypothesis of nuclear breakup. Borrowing a term from biology, they called it *fission*.[1] When Niels Bohr boarded a boat for America on January 7, he carried the news of fission with him. (The possibility of nuclear fission had actually been suggested 5 years earlier by the German scientist Ida Noddack, based on hints from Fermi's work, but no one at the time took her suggestion seriously.)

Meitner and Frisch realized that based on the known masses of nuclei and Einstein's famous equation $E = mc^2$, the fission process should release a lot of energy. This energy release is what made it easy for Frisch, and later other scientists, to quickly verify the reality of fission in the laboratory.

In a letter to Hahn, Meitner explained the new idea. But it was politically impossible for the exiled Meitner to publish jointly with Hahn in 1939. So it was Hahn and Strassmann who published the now historic paper reporting the production of barium when uranium was bombarded with neutrons. And it was Hahn alone who, in 1944, received the Nobel Prize in Chemistry for the discovery of nuclear fission. Nowhere in his acceptance did he mention the role of Meitner and Frisch. He alone got the "limelight" of the prestigious award.

Scientists around the world realized, almost at once, that nuclear fission had potential to power a weapon. Émigré scientists in America jumped into action and urged Albert Einstein to write a letter of warning to President Roosevelt. But, instead, the Manhattan Project and the creation of the atomic bomb began under the direction of Robert J. Oppenheimer.

After the war was over, Meitner expressed outrage at the German scientists who helped Hitler (but who, fortunately, did not succeed in making an atomic bomb). She became a Swedish citizen in 1949 but moved to Britain in 1960 and died in Cambridge in 1968, shortly before her 90th birthday. Her nephew Otto composed the inscription on her headstone: "Lise Meitner: a physicist who never lost her humanity." A more recent memorial is found in the name of element number 109, meitnerium.

Nuclear Fission

Nuclear fission involves a delicate balance within the nucleus between nuclear attraction and the electrical repulsion between protons. In all nuclei of elements found in nature, the nuclear forces dominate. In uranium, however, this domination is tenuous. If the uranium nucleus is stretched into an elongated shape (Figure 34.1), the electrical forces may push it into an even more elongated shape. If the elongation passes a critical point, nuclear forces yield to electrical ones, and the

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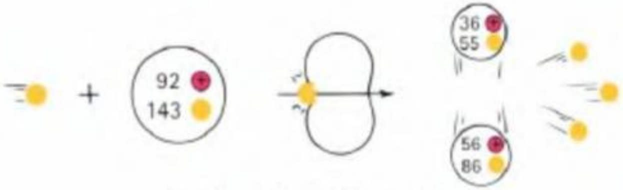
[1]Similarly, Ernest Rutherford used a biological term when he chose the word *nucleus* for the center of an atom.

nucleus separates. This is fission.[2] The absorption of a neutron by a uranium nucleus supplies enough energy to cause such an elongation. The resultant fission process may produce many different combinations of smaller nuclei. A typical example is



$$^{1}_{0}n + {}^{235}_{92}U \rightarrow {}^{91}_{36}Kr + {}^{142}_{56}Ba + 3({}^{1}_{0}n)$$

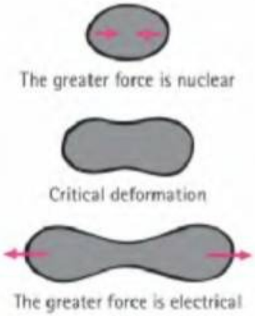


FIGURE 34.1
Nuclear deformation may continue all the way to fission when repulsive electrical forces overcome attractive nuclear forces.

In this reaction, note that one neutron starts the fission of the uranium nucleus and that the fission produces three neutrons (yellow).[3] Because neutrons have no charge and are not repelled by atomic nuclei, they make good "nuclear bullets" and can cause the fissioning of additional uranium atoms, releasing still more neutrons, which can cause still more fissions and release an avalanche of still more neutrons. Such a sequence is called **a chain reaction**—a self-sustaining reaction in which the products of one reaction event stimulate further reaction events (Figure 34.2).

A typical fission reaction releases energy of about 200,000,000 electron volts (eV).[4] (By comparison, the explosion of a TNT molecule releases only 30 eV.) The combined mass of the fission fragments and neutrons produced in fission is less than the mass of the original uranium nucleus. The tiny amount of missing mass converted to this awesome amount of energy is in accord with Einstein's equation $E = mc^2$. Quite remarkably, the energy of fission is mainly in the form of kinetic energy of the fission fragments that fly apart from one another and of the ejected neutrons. Interestingly, a smaller amount of energy is that of gamma radiation.

The scientific world was jolted by the news of nuclear fission—not only because of the enormous energy release but also because of the extra neutrons liberated in the process. A typical fission reaction releases two or three neutrons. These new neutrons can, in turn, cause the fissioning of two or three other atomic nuclei, releasing more energy and a total of from four to nine more neutrons. If each of these neutrons splits just one nucleus, the next step in the reaction will produce between 8 and 27 neutrons, and so on. Thus, a whole chain reaction can proceed at an exponential rate.

Why do chain reactions not occur in naturally occurring uranium ore deposits? They would if all uranium atoms fissioned so easily. Fission occurs mainly for the rare isotope U-235, which makes up only 0.7% of the uranium in pure uranium metal. When the more abundant isotope U-238 absorbs neutrons created by fission of U-235, the U-238 typically does not undergo fission. So any chain reaction is snuffed out by the neutron-absorbing U-238, as well as by the rock in which the ore

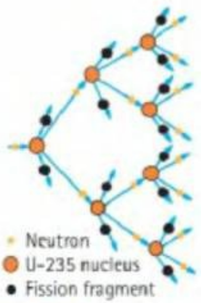


FIGURE 34.2
A chain reaction.

[2]Fission resulting from neutron absorption is called *induced fission*. In rare instances, especially among the transuranics (elements heavier than uranium), nuclei can also undergo *spontaneous fission* without initial neutron absorption.

[3]In this reaction, three neutrons are ejected when fission occurs. In some other reactions, two neutrons may be ejected—or, occasionally, one or four. On average, fission produces 2.5 neutrons per reaction.

[4]The *electron volt* (eV) is defined as the amount of kinetic energy an electron acquires in accelerating through a potential difference of V.

is imbedded. In today's world, naturally occurring uranium is too "impure" to undergo a chain reaction spontaneously.[5]

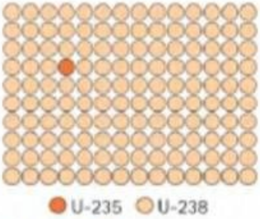


FIGURE 34.3
Only 1 part in 140 (0.7%) of naturally occurring uranium is U-235.

If a chain reaction occurred in a baseball-size chunk of pure U-235, an enormous explosion would result. If the chain reaction were started in a smaller chunk of pure U-235, however, no explosion would occur. This is because of geometry: The ratio of surface area to mass is larger in a small piece than in a large one (just as there is more skin on six small potatoes having a combined mass of 1 kg than there is on a single 1-kg potato). So there is more surface area on a bunch of small pieces of uranium than on a large piece. In a small piece of U-235, neutrons leak through the surface before an explosion can occur. In a bigger piece, the chain reaction builds up to enormous energies before the neutrons get to the surface and escape (Figure 34.4). For masses greater than a certain amount, called the **critical mass,** an explosion of enormous magnitude may occur.

Consider a large quantity of U-235 divided into two pieces, each having a mass less than critical. The units are *subcritical.* Neutrons in either piece readily reach a surface and escape before a sizable chain reaction builds up. But if the pieces are suddenly driven together, the total surface area decreases. If the timing is right and the combined mass is greater than critical, called *supercritical,* the chain reaction builds up explosively. This is what can happen in a nuclear fission bomb (Figure 34.5). A bomb in which pieces of uranium are driven together is a so-called "gun-type" weapon, as opposed to the now more common "implosion weapon."

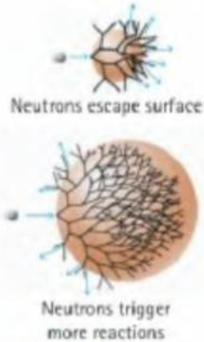


FIGURE 34.4
A chain reaction in a small piece of pure U-235 dies out because neutrons leak from the surface too readily. The small piece has a lot of surface area relative to its mass. In a larger piece, more uranium atoms and less surface area are presented to the neutrons.

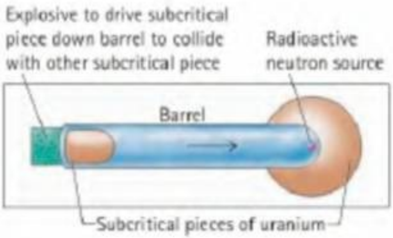


FIGURE 34.5
Simplified diagram of an idealized uranium fission bomb of the "gun type."

Constructing a fission bomb is a formidable task. The difficulty is separating enough U-235 from the more abundant U-238. Scientists took more than 2 years to extract enough U-235 from uranium ore to make the bomb that was detonated at Hiroshima in 1945. A chunk of U-235 probably a little larger than a softball was used in this historic blast. To this day, uranium isotope separation remains a difficult process, although advanced centrifuges have made it less formidable than it was in World War II. Project scientists at the secret Manhattan Project at that time used two methods of isotope separation. One method employed diffusion, where molecules of a gaseous compound (uranium hexafluoride) containing the lighter U-235 have a slightly greater average speed than molecules containing U-238 at the same temperature. The faster isotope has a higher rate of diffusion through a thin membrane or small opening, resulting in a slightly enriched gas containing U-235 on the other side (Figure 34.6). Diffusion through thousands of chambers ultimately produced a sufficiently enriched sample of U-235.

FIGURE 34.6
Lighter molecules move faster than heavier ones at the same temperature and diffuse more readily through a thin membrane.

The other method, used only for partial enrichment, employed magnetic separation of uranium ions shot into a magnetic field. The smaller-mass U-235 ions

[5]Much earlier in Earth's history, the percentage of U-235 in natural uranium was greater than it is today. U-235 has a shorter half-life than U-238, so, over time, the percentage of U-235 declines. In 1972 the French physicist Francis Perrin turned up evidence that some 1.7 billion years ago, natural reactors existed in uranium deposits in what is now Gabon in West Africa.

were deflected more by the magnetic field than the U-238 ions and were collected atom by atom through a slit positioned to capture them (look ahead to Figure 34.14). After a couple of years, the two methods yielded a few tens of kilograms of U-235.

Uranium-isotope separation today is more easily accomplished with a gas centrifuge. Uranium hexafluoride gas is whirled in a drum at tremendously high rim speeds (on the order of 1500 km/h). Gas molecules containing the heavier U-238 gravitate to the outside like milk in a dairy separator, and gas containing the lighter U-235 is extracted from the center. Engineering difficulties, overcome only in recent years, prevented the use of this method during the Manhattan Project.

CHECK POINT

1. A 10-kg ball of U-235 is supercritical, but the same ball broken up into small chunks isn't. Explain.
2. Why will molecules of uranium hexafluoride gas made with U-235 move slightly faster at the same temperature than molecules of uranium hexafluoride gas made with U-238?

Check Your Answers

1. The small chunks have more combined surface area than the ball from which they came (just as the combined surface area of gravel is greater than the surface area of a boulder of the same mass). Neutrons escape via the surface before a sustained chain reaction can build up.
2. At the same temperature, the molecules of both compounds have the same kinetic energy ($1/2\ mv^2$). So the molecule made with the less massive U-235 must have a correspondingly higher speed.

Nuclear Fission Reactors

A chain reaction cannot ordinarily take place in *pure* natural uranium, since it is mostly U-238. The neutrons released by fissioning U-235 atoms are fast neutrons, readily captured by U-238 atoms, which do not fission. A crucial experimental fact is that *slow* neutrons are far more likely to be captured by U-235 than by U-238.[6] If neutrons can be slowed down, there is an increased chance that a neutron released by fission will cause fission in another U-235 atom, even amid the more plentiful and otherwise neutron-absorbing U-238 atoms. This increase may be enough to allow a chain reaction to take place.

FIGURE 34.7
An artist's depiction of the setting in the squash court beneath the stands at the University of Chicago's Stagg Field, where Enrico Fermi and his colleagues constructed the first nuclear reactor.

Within less than a year after the discovery of fission, scientists realized that a chain reaction with ordinary uranium metal might be possible if the uranium were broken up into small lumps and separated by a material that would slow down the neutrons released by nuclear fission. Enrico Fermi, who came to America from Italy in December 1938, led the

[6] This is similar to the selective absorption of various frequencies of light. Just as atoms of various elements absorb light differently, various isotopes of the same element, though chemically almost identical, can have quite different nuclear properties and absorb neutrons differently.

construction of the first nuclear reactor—or *atomic pile*, as it was called—in a squash court underneath the grandstands of the University of Chicago's Stagg Field. He and his group used graphite, a common form of carbon, to slow the neutrons. They achieved the first self-sustaining controlled release of nuclear energy on December 2, 1942.

FIGURE 34.8

The bronze plaque at Chicago's Stagg Field commemorates Enrico Fermi's historic fission chain reaction.

Three fates are possible for a neutron in ordinary uranium metal. It may (1) cause fission of a U-235 atom, (2) escape from the metal into nonfissionable surroundings, or (3) be absorbed by U-238 without causing fission. Graphite was used to make the first fate more probable. Uranium was divided into discrete parcels and buried at regular intervals in nearly 400 tons of graphite. A simple analogy clarifies the function of the graphite: If a golf ball rebounds from a massive wall, it loses hardly any speed; but if it rebounds from a baseball, it loses considerable speed. The case of the neutron is similar. If a neutron rebounds from a heavy nucleus, it loses hardly any speed; but if it rebounds from a lighter carbon nucleus, it loses considerable speed. The graphite was said to "moderate" the neutrons.[7] The whole apparatus is called a *reactor*.

Today's fission reactors contain three components: nuclear fuel, control rods, and a fluid (usually water) to extract heat from the reactor. The nuclear fuel is primarily U-238 plus about 3% U-235. Because the U-235 is so highly diluted with U-238, an explosion like that of a nuclear bomb is not possible.[8] The reaction rate, which depends on the number of neutrons available to initiate fission of other U-235 nuclei, is usually controlled by rods inserted into the reactor. The control rods are made of a neutron-absorbing material, usually cadmium or boron. Water surrounding the nuclear fuel is kept under high pressure to keep it at a high temperature without boiling. Heated by fission, this water then transfers heat to a second, lower-pressure water system, which operates a turbine and electric generator. Two separate water systems are used so that no radioactivity reaches the turbine.

fyi

- Plenty of nuclear fuel for fission reactors will be available when the thousands of nuclear weapons developed during previous decades are dismantled. When bomb-grade Pu-239 is blended with the tons of depleted U-238 presently in storage, reactors can supply the world with clean electrical power for many years.

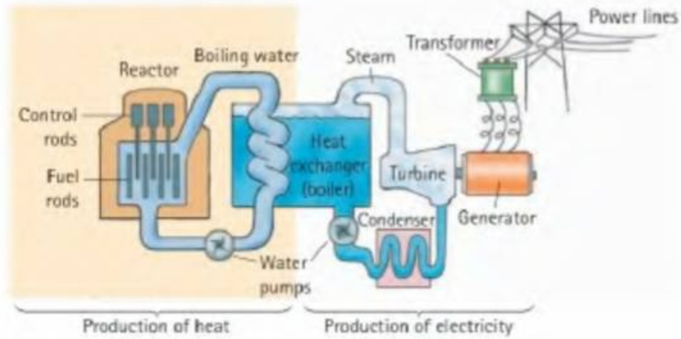


FIGURE 34.9

Diagram of a nuclear fission power plant.

[7] *Heavy water*, which contains the heavy hydrogen isotope deuterium, is an even more effective moderator. This is because, in an elastic collision, a neutron transfers a greater portion of its energy to the deuterium nucleus than it would to the heavier carbon nucleus, and a deuteron never absorbs a neutron, as a carbon nucleus occasionally does.

[8] In a worst-case accident, however, heat sufficient to melt the reactor core is possible—and, if the reactor building is not strong enough, radioactivity will scatter into the environment. One such accident occurred at the Chernobyl reactor in 1986 in Ukraine, which was then a constituent republic of the Soviet Union.

CHECK POINT

What is the function of a *moderator* in a nuclear reactor? Of *control rods*?

Check Your Answers

A moderator slows down neutrons that are normally too fast to be absorbed readily by fissionable isotopes, such as U-235. Control rods absorb more neutrons when they are pushed into the reactor and fewer neutrons when they are pulled out of the reactor. They thereby control the number of neutrons that participate in the chain reaction.

Plutonium

Early in the 19th century, the farthermost planet known in the solar system was Uranus. The first planet to be discovered beyond Uranus was named Neptune. In 1930, what seemed to be a planet beyond Neptune was discovered and was named Pluto. During this time the heaviest element known was uranium. Appropriately enough, the first transuranic element to be discovered was named *neptunium* and the second transuranic element was named *plutonium*.

Neptunium is produced when a neutron is absorbed by a U-238 nucleus. Rather than undergoing fission, the nucleus emits a beta particle and becomes neptunium, the first synthetic element beyond uranium. The half-life of neptunium is only 2.3 days, so it isn't around very long. Neptunium is a beta emitter and very soon becomes plutonium. The half-life of plutonium is about 24,000 years, so it lasts a considerable time. The isotope plutonium-239, like U-235, will undergo fission when it captures a neutron. Whereas the separation of fissionable U-235 from uranium metal is a very difficult process (because U-235 and U-238 have the same chemistry), the separation of plutonium from uranium metal is relatively easy. This is because plutonium is an element distinct from uranium, with its own chemical properties.

PhysicsPlace.com
Video
Plutonium

The element plutonium is chemically poisonous in the same sense as are lead and arsenic. It attacks the nervous system and can cause paralysis. Death can follow if the dose is sufficiently large. Fortunately, plutonium does not remain in its elemental form for long because it rapidly combines with oxygen to form three compounds: PuO, PuO_2, and Pu_2O_3, all of which chemically are relatively benign. They will not dissolve in water or in biological systems. These plutonium compounds do not attack the nervous system and have been found to be chemically harmless.

Plutonium in any form, however, is radioactively toxic. It is more toxic than uranium, although less toxic than radium. Plutonium emits high-energy alpha particles, which kill cells rather than simply disrupting them and leading to mutations. Interestingly, damaged cells rather than dead cells contribute to cancer. This is why plutonium ranks relatively low as a cancer-producing substance. The greatest danger that plutonium presents to humans is its potential for use in nuclear fission bombs. Its usefulness is in fission reactors—particularly breeder reactors.

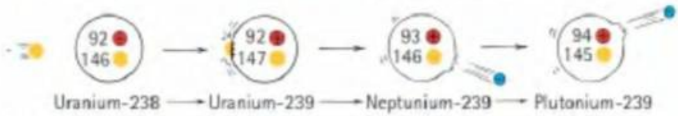


FIGURE 34.10

When a nucleus of U-238 absorbs a neutron, it becomes a nucleus of U-239. Within about half an hour, this nucleus emits a beta particle, resulting in a nucleus of about the same mass but with one more unit of charge. This is no longer uranium; it's a new element—*neptunium*. After the neptunium, in turn, emits a beta particle, it becomes plutonium. (In both events, an antineutrino, not shown, is also emitted.)

CHECK POINT

Why does plutonium not occur in appreciable amounts in natural ore deposits?

Check Your Answer

On a geological time scale, plutonium has a relatively short half-life, so any that exists is produced by very recent transmutations of uranium isotopes.

fyi

- Weapons-grade plutonium is 90% pure Pu-239.

The Breeder Reactor

A remarkable feature of fission power is the *breeding* of plutonium from nonfissionable U-238. Breeding occurs when small amounts of fissionable U-235 are mixed with U-238 in a reactor. Fissioning liberates neutrons that convert the relatively abundant nonfissionable U-238 to U-239, which beta-decays to become Np-239, which, in turn, beta-decays to fissionable plutonium—Pu-239. So, in addition to the abundant energy produced, fission fuel is bred from relatively abundant U-238 in the process.

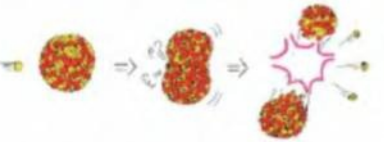


FIGURE 34.11

INTERACTIVE FIGURE

Pu-239 or U-233, like U-235, undergoes fission when it captures a neutron.

Some breeding occurs in all fission reactors, but a **breeder reactor** is specifically designed to breed more fissionable fuel than is put into it. Using a breeder reactor is analogous to filling your car's gas tank with water, adding some gasoline, then driving the car and having more gasoline at the end of the trip than at the beginning! The basic principle of the breeder reactor is very attractive: After a few years of operation, a breeder-reactor power plant can produce vast amounts of power while breeding twice as much fuel as it had in the beginning.

The downside of breeder reactors is the enormous complexity of successful and safe operation. The United States gave up on breeders in the 1980s, and only France, Germany, India, and China are still investing in them. Officials in these countries point out that supplies of naturally occurring U-235 are limited. At present rates of consumption, all natural sources of U-235 may be depleted within a century. Countries then deciding to use breeder reactors may well find themselves digging up radioactive wastes they once buried.[9]

Some public outcry is against nuclear power—"No Nukes!" The position of this book, in contrast, is "Know Nukes!"—first know something about the promises of, as well as the drawbacks to, nuclear power before saying *yes* or *no* to nukes.

CHECK POINT

Complete these reactions, which occur in a breeder reactor:

$^{239}_{92}U \rightarrow$ _____ $+ ^{0}_{-1}e$

$^{239}_{93}NP \rightarrow$ _____ $+ ^{0}_{-1}e$

Check Your Answers

$^{239}_{93}NP$; $^{239}_{94}Pu$. (Antineutrinos are also emitted in these beta-decay processes, and they escape unobserved.)

Fission Power

Energy available from nuclear fission was introduced to the world in the form of nuclear bombs. This violent image still impacts our thinking about nuclear power. Add to this the fearsome 1986 Chernobyl disaster in the Soviet Union, and we find many people viewing nuclear power as evil technology. Nevertheless, about 20%

[9]Many nuclear scientists do not think that deep burial is a desirable solution to the problem of nuclear waste. Devices are presently being studied that could, in principle, convert long-lived radioactive atoms of spent reactor fuel into short-lived or nonradioactive atoms. Nuclear wastes may not plague future generations indefinitely, as has been commonly thought.

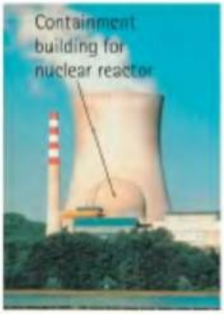


FIGURE 34.12

The nuclear reactor is housed within a dome-shaped containment building that is designed to prevent the release of radioactive isotopes in the event of an accident.

of electric energy in the United States is generated by nuclear-fission reactors. These reactors, sometimes called *nukes*, are simply nuclear furnaces. Like fossil-fuel furnaces, they do nothing more elegant than boil water to produce steam for a turbine. The greatest practical difference is the amount of fuel involved. One kilogram of uranium fuel, a chunk smaller than a baseball, yields more energy than 30 freight car loads of coal.

One disadvantage of fission power is the generation of radioactive waste products. Light atomic nuclei are most stable when composed of equal numbers of protons and neutrons, and it is mainly heavy nuclei that need more neutrons than protons for stability. For example, there are 143 neutrons but only 92 protons in U-235. When uranium fissions into two medium-weight elements, the extra neutrons in their nuclei make them unstable. These fragments are therefore radioactive, and most of them have very short half-lives. Some of them, however, have half-lives of thousands of years. Safely disposing of these waste products as well as materials made radioactive in the production of nuclear fuels requires special storage casks and procedures. Although fission power goes back a half century, the technology of radioactive waste disposal remains in the developmental stage.

The benefits of fission power are (1) plentiful electricity; (2) the conservation of the many billions of tons of coal, oil, and natural gas that every year are literally converted to heat and smoke and that in the long run may be far more precious as sources of organic molecules than as sources of heat; and (3) the elimination of the megatons of sulfur oxides and other poisons, as well as the greenhouse gas carbon dioxide, that are released into the air each year by the burning of these fuels.

The drawbacks include (1) the problem of storing radioactive wastes; (2) the production of plutonium and the danger of nuclear weapons proliferation; (3) the low-level release of radioactive materials into the air and groundwater; and, most importantly, (4) the risk of an accidental release of large amounts of radioactivity.

Reasoned judgment requires not only that we examine the benefits and drawbacks of fission power but also that we compare its benefits and drawbacks with those of other power sources.

fyi

- Nuclear waste can be "burned" in special reactors that transmutes it into more benign elements, thus eliminating the objection that nuclear wastes are in the laps of future generations.

The energy value of radioactive materials released in coal-burning power plants is some 1.5 times more than the energy provided by coal itself.

CHECK POINT

More environmental radiation surrounds a typical coal-fired power plant than surrounds a fission power plant. What does this indicate about the shielding typically surrounding the two types of power plants?

Check Your Answer

Coal-fired power plants are, seemingly, as American as apple pie, with (at this writing) no required shielding to restrict the emissions of radioactive particles. Fission power plants, on the other hand, are required to have shielding to ensure strictly low levels of radioactive emissions.

Mass–Energy Equivalence

In 1905, Albert Einstein discovered that mass is actually "congealed" energy. Mass and energy are two sides of the same coin, as stated in his celebrated equation $E = mc^2$. In this equation, E stands for the energy that any mass has at rest, m stands for mass, and c is the speed of light. The quantity c^2 is the proportionality constant of energy and mass. This relationship between energy and mass is the key to understanding why and how energy is released in nuclear reactions.

The more energy that is stored in a particle, the greater is the mass of the particle. Is the mass of a nucleon inside a nucleus the same as that of the same nucleon outside a nucleus? This question can be answered by considering the work that would be required to separate nucleons from a nucleus. From physics we know that work, which is expended energy, is equal to *force* × *distance*. Think of the amount of force required to pull a nucleon out of the nucleus through a sufficient distance to overcome the attractive strong nuclear force, comically indicated in Figure 34.13. Enormous work would be required. This work is energy added to the nucleon that is pulled out.

FIGURE 34.13

Work is required to pull a nucleon from an atomic nucleus. This work goes into mass energy.

The mass difference in a nucleon outside a nucleus and locked inside a nucleus is related to the "binding energy" of the nucleus. For uranium, the mass difference is about 0.8%, or 8 parts in 1000. The 0.8% reduction in the average nucleon mass within a uranium atom indicates the binding energy of the nucleus—how much work would be required to disassemble the nucleus.[10] That works out to be about 8 million eV per nucleon.

The experimental verification of this conclusion is one of the triumphs of modern physics. The average mass per nucleon within the nuclei of the isotopes of the various elements can be measured with an accuracy of 1 part per million or better. One means of doing this is with a *mass spectrometer* (Figure 34.14).

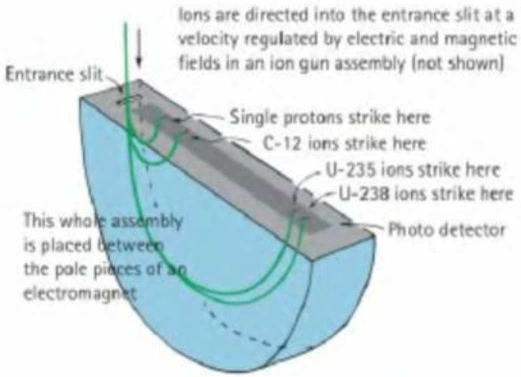


FIGURE 34.14

The mass spectrometer. Ions of a fixed speed are directed into the semicircular "drum," where they are swept into semicircular paths by a strong magnetic field. Which will be swept into smaller arcs, heavy nuclei or light nuclei?

In a mass spectrometer, charged ions with identical speeds are directed into a magnetic field, where they deflect into circular arcs. The greater the inertia of the ion, the more it resists deflection and the greater the radius of its curved path. The magnetic force sweeps the heavier ions into larger arcs and the lighter ions into smaller arcs. The ions pass through exit slits, where they may be collected, or they strike a detector, such as photographic film. An isotope is chosen as a standard, and its position on the film of the mass spectrometer is used as a reference point. The standard is the common isotope of carbon, C-12, the atomic mass of which is assigned the value of 12.00000 atomic mass units. Recall that the atomic mass unit (amu) is defined to be precisely one-twelfth the mass of the common carbon-12 atom. With this reference, the amu values of the other atoms are measured. You can see that in a C-12 atom, the average mass per nucleon is exactly 1.00000. This is less than the mass of either a hydrogen atom or a free neutron, which are, respectively, 1.007825 and 1.00867 amu.

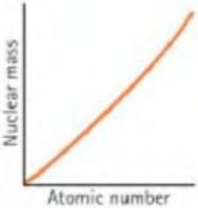


FIGURE 34.15

The plot shows how nuclear mass increases with increasing atomic number.

A graph of nuclear mass as a function of atomic number is shown in Figure 34.15. The graph slopes upward with increasing atomic number, as expected, telling

[10] Strictly speaking, it isn't possible to measure the mass of an individual nucleon within a nucleus. We can only measure the total mass of the nucleus and divide by the number of nucleons therein to get the average mass per nucleon, which is what comes out to be about 0.8% less than the mass of a free nucleon.

TABLE 34.1

Masses and Masses per Nucleon of Some Isotopes

Isotope	*Symbol*	*Mass (amu)*	*Mass/Nucleon (amu)*
Neutron	n	1.008665	1.008665
Hydrogen	$^{1}_{1}H$	1.007825	1.007825
Deuterium	$^{2}_{1}H$	2.01410	1.00705
Tritium	$^{3}_{1}H$	3.01605	1.00535
Helium-4	$^{4}_{2}He$	4.00260	1.00065
Carbon-12	$^{12}_{6}C$	12.00000	1.000000
Iron-58	$^{58}_{26}Fe$	57.93328	0.99885
Copper-63	$^{63}_{29}Cu$	62.92960	0.99888
Krypton-90	$^{90}_{36}Kr$	89.91952	0.99911
Barium-143	$^{143}_{56}Ba$	142.92063	0.99944
Uranium-235	$^{235}_{92}U$	235.04393	1.00019

us that elements are more massive as atomic number increases. (The slope curves because there are proportionally more neutrons in the more massive atoms.)

A more important graph results from a plot of average mass *per nucleon* for the elements hydrogen through uranium (Figure 34.16). This is perhaps the most important graph in this book, for it is the key to understanding the energy associated with nuclear processes—fission as well as fusion. To obtain the average mass per nucleon, you divide the total mass of an atom by the number of nucleons in the nucleus. (Similarly, if you divide the total mass of a roomful of people by the number of people in the room, you get the average mass per person.) The major fact we learn from Figure 34.16 is that the average mass per nucleon varies from one nucleus to another.

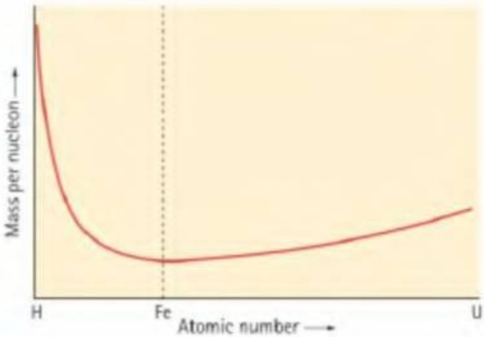


FIGURE 34.16

INTERACTIVE FIGURE

The graph shows that the average mass per nucleon in the nucleus varies from one end of the periodic table to the other. You can say that individual nucleons have the most mass in the lightest (hydrogen) nuclei, the least mass in iron nuclei, and intermediate mass in the heaviest (uranium) nuclei. (The vertical scale is exaggerated.)

The graph of Figure 34.16 reveals the energy of the atomic nucleus, likely the primary source of energy in the universe—which is why it can be considered the most important graph in this book.

The greatest mass per nucleon occurs for hydrogen, whose lone central proton has no binding energy to pull its mass down. As we progress to elements beyond hydrogen, Figure 34.16 tells us that the mass per nucleon decreases and is least for iron. The iron nucleus holds its nucleons more tightly than any other nucleus does. Beyond iron, the trend reverses itself as proton repulsion becomes more important and the binding energy per nucleon gradually decreases (meaning that the mass per nucleon gradually increases). This continues all the way through the list of elements.

From this graph, we can see why energy is released when a uranium nucleus is split into two nuclei of lower atomic number. When the uranium nucleus splits, the masses of the two fission fragments lie about halfway between the masses of uranium and hydrogen on the horizontal scale of the graph. It is most important to

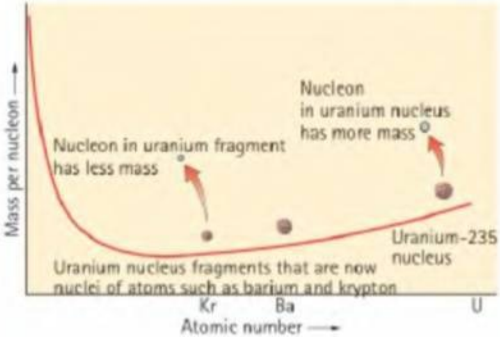


FIGURE 34.17

The average mass of each nucleon in a uranium nucleus is greater than the average mass of each nucleon in any one of its nuclear-fission fragments. This decrease in mass is transformed into energy. Hence, nuclear fission is an energy-releasing process.

note that the mass per nucleon in the fission fragments is *less than* the mass per nucleon when the same set of nucleons is combined in the uranium nucleus. When this decrease in mass is multiplied by the speed of light squared, it equals 200,000,000 eV, the energy yielded by each uranium nucleus that undergoes fission. As mentioned earlier, most of this enormous energy is the kinetic energy of the fission fragments.

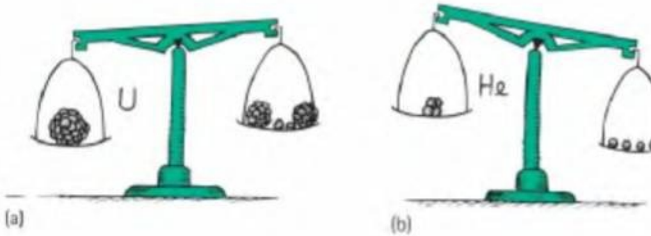


FIGURE 34.18

INTERACTIVE FIGURE

The mass of a nucleus is *not* equal to the sum of the masses of its parts. (a) The fission fragments of a heavy nucleus like uranium are less massive than the uranium nucleus. (b) Two protons and two neutrons are more massive in their free states than when they are combined to form a helium nucleus.

We can think of the mass-per-nucleon curve as an energy valley that starts at the highest point (hydrogen), slopes steeply down to the lowest point (iron), and then slopes more gradually up to uranium. Iron is at the bottom of the energy valley and is the most stable nucleus. It is also the most tightly bound nucleus; more energy per nucleon is required to separate a nucleon from its nucleus than from any other nucleus.

All nuclear power today is by way of nuclear fission. A more promising long-range source of energy is to be found on the left side of the energy valley.

Binding energy reduces the mass of a nucleus by exactly the mass equivalence (E/c^2) of that binding energy. The more binding energy, the less mass. The iron nucleus has the greatest binding energy per nucleon and the least mass per nucleon.

TABLE 34.2

Energy Gain from Fission of Uranium

Reaction:	$^{235}U + n \rightarrow {}^{143}Ba + {}^{90}Kr + 3n + \Delta m$
Mass balance:	$235.04393 + 1.008665 = 142.92063 + 89.91952 + 3(1.008665) + \Delta m$
Loss of mass:	$\Delta m = 0.186$ amu
Gain of energy:	$\Delta E = \Delta mc^2 = 0.186 \times 931$ MeV $= 173$ MeV
Energy gain/nucleon:	$\Delta E/236 = 173$ MeV$/236 = 0.73$ MeV/nucleon

(1 amu $\times$ c^2 = 931 MeV, the energy equivalent of 1 amu. In addition to the above, there is an additional delayed energy release of about 25 MeV from the radioactive fission fragments, for a total energy release per fission event of close to 200 MeV.)

Physics at Airport Security

A version of the mass spectrometer shown in Figure 34.14 is employed in airport security. Ion mobility rather than electromagnetic separation is used to sniff out certain molecules, mainly the few nitrogen-rich ones characteristic of explosives. Security personnel swab your luggage or other belongings with a small disk of paper, which they place in a device that heats it to expel vapors from it. Molecules in the vapor are ionized by exposure to beta radiation from a radioactive source. Most molecules become positive ions, whereas nitrogen-rich molecules become negative, which drift against a flow of air to a positively charged detector. The time for a negative ion to reach the detector indicates the ion's mass—the heavier the ion, the slower it will be to reach the detector.

The same process occurs in body scans, in which a person stands momentarily in an enclosed region the size of a telephone booth where upward puffs of air impinge on the body. The air is then "sniffed" by the same technique, searching for some 40 types of explosives and 60 types of drug residues. Presto, green light means none were detected, and red light means—uh-oh!

CHECK POINT

1. Wait a minute! If isolated protons and neutrons have masses greater than 1.0000 amu, why don't 12 of them in a carbon nucleus have a combined mass greater than 12.0000 amu?
2. Correct the following incorrect statement: When a heavy element, such as uranium, undergoes fission, there are fewer nucleons after the reaction than before.

Check Your Answers

1. When you pull a nucleon from the nucleus, you do work on it and it gains energy. When that nucleon falls back into the nucleus, it does work on its surroundings and *loses* energy. Losing energy means losing mass. It's as if each nucleon, on average, slims down to a mass of exactly 1.0000 amu when it joins with 11 other nucleons to form C-12. If you pull them back out, you'll get back the original mass. Indeed, $E = mc^2$.
2. When a heavy element, such as uranium, undergoes fission, there aren't fewer nucleons after the reaction. Instead, there's *less mass* in the same number of nucleons.

Nuclear Fusion

Inspection of the mass-per-nucleon versus atomic-number graph will show that the steepest part of the energy hill is from hydrogen to iron. Energy is gained as light nuclei *fuse* (which means that they combine). This combining of nuclei is **nuclear fusion**—the opposite of nuclear fission. We can see from Figure 34.19 that as we move along the list of elements from hydrogen to iron (left side of the energy valley), the average mass per nucleon decreases. Thus, if two small nuclei were to

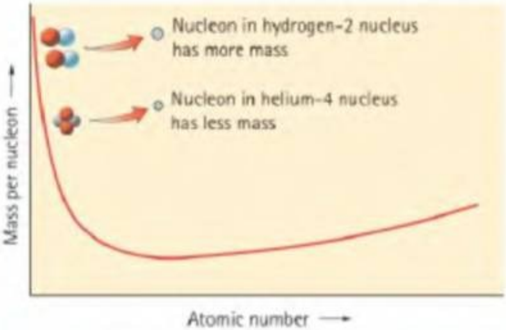


FIGURE 34.19

The average mass of a nucleon in hydrogen is greater than its average mass when fused with another to become helium. The decreased mass is mass that is converted to energy, which is why nuclear fusion of light elements is an energy-releasing process.

fuse, the mass of the fused nucleus would be less than the mass of the two single nuclei before fusion. Energy is released as light nuclei fuse.

Consider hydrogen fusion. For a fusion reaction to occur, the nuclei must collide at a very high speed in order to overcome their mutual electric repulsion. The required speeds correspond to the extremely high temperatures that are found in the Sun and other stars. Fusion brought about by high temperatures is called **thermonuclear fusion.** In the high temperatures of the Sun, approximately 657 million tons of hydrogen are fused to 653 million tons of helium each second. The "missing" 4 million tons of mass convert to energy. Such reactions are, quite literally, nuclear burning.

In a sense, nucleons in the heavy elements wish to lose mass and be like nucleons in iron. And nucleons in the light elements also wish to lose mass and become more like those in iron.

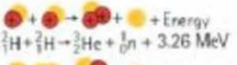
FIGURE 34.20

Fictitious example: The "hydrogen magnets" weigh more when they are apart than they do when they are together.

Interestingly, most of the energy of nuclear fusion is in the kinetic energy of fragments. When the fragments are stopped and captured, the energy of fusion turns into heat. In the Sun, this heat ends up as photons radiated from the surface. In fusion reactions of the future, part of this heat will be transformed to electricity.

Thermonuclear fusion is analogous to ordinary chemical combustion. In both chemical and nuclear burning, a high temperature starts the reaction; the release of energy by the reaction maintains a sufficient temperature to spread the fire. The net result of the chemical reaction is a combination of atoms into more tightly bound molecules. In nuclear reactions, the net result is nuclei that are more tightly bound. In both cases, mass decreases as energy is released. The difference between chemical and nuclear burning is essentially one of scale.

In fission reactions, the amount of matter that is converted to energy is about 0.1%; in fusion, it can be as much as 0.7%. These numbers apply whether the process takes place in bombs, in reactors, or in stars. Some typical fusion reactions are shown in Figure 34.21. Most reactions produce at least a pair of particles—for example, a pair of deuterium nuclei that fuse produce a tritium nucleus and a neutron rather than a lone helium nucleus. Either reaction is okay as far as adding the nucleons and charges is concerned, but the lone-nucleus case is not in accord with conservation of momentum and energy. If a lone helium nucleus flies away



$${}^{2}_{1}H + {}^{2}_{1}H \rightarrow {}^{3}_{2}He + {}^{1}_{0}n + 3.26\ MeV$$

$${}^{2}_{1}H + {}^{3}_{1}H \rightarrow {}^{4}_{2}He + {}^{1}_{0}n + 17.6\ MeV$$

FIGURE 34.21

Two of many fusion reactions.

TABLE 34.3
Energy Gain from Fusion of Hydrogen

Reaction:	$^{2}H + {}^{3}H \rightarrow {}^{4}_{2}H + n + \Delta m$
Mass balance:	$2.01410 + 3.01605 = 4.00260 + 1.008665 + \Delta m$
Mass defect:	$\Delta m = 0.01888$ amu
Energy gain:	$\Delta E = \Delta mc^2 = 0.018888 \times 931$ MeV $= 17.6$ MeV
Energy gain/nucleon:	$\Delta E\ 5 = 17.6$ MeV/5 $= 3.5$ MeV/nucleon

after the reaction, it adds momentum that wasn't there initially. Or if it remains motionless, there's no mechanism for energy release. So, because a single product particle can't move and it can't sit still, it isn't formed. Fusion normally requires the creation of at least two particles to share the released energy.[11]

Table 34.3 shows the energy gain from the fusion of hydrogen isotopes deuterium and tritium. This is the reaction proposed for plasma fusion power plants of the future. The high-energy neutrons, according to plan, will escape from the plasma in the reactor vessel and heat a surrounding blanket of material to provide useful energy. The helium nuclei remaining behind will help to keep the plasma hot. Another reaction, not described here, will provide the tritium, which is not found in nature on Earth.

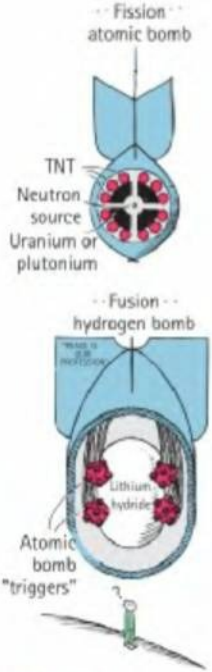


FIGURE 34.22
Fission and fusion bombs.

Elements somewhat heavier than hydrogen release energy when fused. But they release much less energy per fusion reaction than hydrogen. The fusion of still heavier elements occurs in the advanced stages of a star's evolution. The energy released per gram during the various fusion stages from helium to iron amounts to only about one-fifth of the energy released in the fusion of hydrogen to helium.

Prior to the development of the atomic bomb, the temperatures required to initiate nuclear fusion on Earth were unattainable. When it was found that the temperatures inside an exploding atomic bomb are 4 to 5 times the temperature at the center of the Sun, the thermonuclear bomb was but a step away. This first hydrogen bomb was detonated in 1952. Whereas the critical mass of fissionable material limits the size of a fission bomb (atomic bomb), no such limit is imposed on a fusion bomb (thermonuclear, or hydrogen, bomb). Just as there is no limit to the size of an oil-storage depot, there is no theoretical limit to the size of a fusion bomb. Like the oil in a storage depot, any amount of fusion fuel can be stored with safety until it is ignited. Although a mere match can ignite an oil depot, nothing less energetic than a fission bomb can ignite a thermonuclear bomb. We can see that there is no such thing as a "baby" hydrogen bomb. It cannot be less energetic than its fuse, which is a fission bomb.

The hydrogen bomb is another example of a discovery applied to destructive rather than constructive purposes. The potential constructive side of the picture is the controlled release of vast amounts of clean energy.

[11]One of the reactions in the Sun's proton–proton fusion cycle does have a one-particle final state. It is proton + deuteron → He-3. This happens because the density in the center of the Sun is great enough that "spectator" particles share in the energy release. So, even in this case, the energy released goes to two or more particles. Fusion in the Sun involves more complicated (and slower!) reactions in which a small part of the energy also appears in the form of gamma rays and neutrinos. The neutrinos escape unhindered from the center of the Sun and bathe the solar system. Interestingly, the fusion of nuclei in the Sun is an occasional process, for the mean spacing between nuclei is vast, even at the high pressures in its center. That's why it takes some 10 billion years for the Sun to consume its hydrogen fuel.

CHECK POINT

1. First it was stated that nuclear energy is released when atoms split apart. Now it is stated that nuclear energy is released when atoms combine. Is this a contradiction? How can energy be released by opposite processes?
2. To obtain energy from the element iron, should iron nuclei be fissioned or fused?

Check Your Answers

1. Energy is released in any nuclear reaction in which the mass of the nuclei after the reaction is less than the mass of the nuclei before. When light nuclei, such as those of hydrogen, fuse to form heavier nuclei, total nuclear mass decreases. The fusion of light nuclei therefore releases energy. When heavy nuclei, such as those of uranium, split to become lighter nuclei, total nuclear mass also decreases. The splitting of heavy nuclei, therefore, releases energy. For energy release, "decrease mass" is the name of the game—any game, chemical or nuclear.
2. Neither, because iron is at the very bottom of the curve (energy valley). If you fuse two iron nuclei, the product lies somewhere on the upper right of iron on the curve, which means the product has a higher mass per nucleon. If you split an iron nucleus, the products lie on the upper left of iron on the curve, which again means a higher mass per nucleon. Because no mass decrease occurs in either reaction, no energy is ever released.

fyi

- The energy released in fusing a pair of hydrogen nuclei is less than that of fissioning a uranium nucleus. But because there are more atoms in a gram of hydrogen than in a gram of uranium, gram for gram, fusion of hydrogen releases several times as much energy as fission of uranium.

Controlling Fusion

The fuel for nuclear fusion is hydrogen, the most plentiful element in the universe. The reaction that works best at "moderate" temperature is the fusion of the hydrogen isotopes deuterium (^2_1H) and tritium (^3_1H). Deuterium is found in ordinary water. Deuterium in the world's oceans has the potential to release vastly more energy than all the world's fossil fuels and much more than the world's supply of uranium. Tritium, with a half-life of 12 years, is almost completely absent in nature, but it can be created by reacting deuterons (as in Figure 34.21) or in a reaction involving lithium.

Fusion, therefore, is a dream source of long-term energy needs. The outlook for fusion power in the foreseeable future, however, is bleak. Various fusion schemes have been tried. The earliest approach, still being pursued, involves confining a hot plasma with a magnetic field. Other approaches have harnessed high-energy lasers. One scheme is to drop hydrogen pellets into a crossfire of lasers that would ignite pulses of fusion power. The problems, after many years of effort, have been overwhelming. Implosion of a variety of particles, electrons, and many kinds of ions has also been unsuccessful. All scenarios have been in quest of an "energy breakeven," where energy output at least equals energy input. Except for brief spurts, it hasn't happened.

Will there be a breakthrough, where sustained energy output in a device will be greater than the energy input to initiate and sustain fusion? Will we find a way to tame the power of the Sun and stars? We don't know. If and when that comes to be, humans may synthesize their own elements and produce energy in the process, just as the stars have always done. At that point, fusion will likely be the primary energy source for generations to come. Keep tuned to the web.

SUMMARY OF TERMS

Nuclear fission The splitting of the nucleus of a heavy atom, such as uranium-235, into two smaller nuclei, accompanied by the release of much energy.

Chain reaction A self-sustaining reaction in which the products of one reaction event stimulate further reaction events.

Critical mass The minimum mass of fissionable material in a reactor or nuclear bomb that will sustain a chain reaction.

Breeder reactor A fission reactor that is designed to breed more fissionable fuel than is put into it by converting nonfissionable isotopes to fissionable isotopes.

Nuclear fusion The combination of light atomic nuclei to form heavier nuclei, with the release of much energy.

Thermonuclear fusion Nuclear fusion produced by high temperature.

REVIEW QUESTIONS

Nuclear Fission

1. Why does a chain reaction not occur in uranium mines?
2. Why is a chain reaction more likely in a big piece of uranium than it is in a small piece?
3. What is meant by the idea of a critical mass?
4. Which will leak more neutrons, two separate pieces of uranium or the same pieces stuck together?
5. What were the two methods used to separate U-235 from U-238 in the Manhattan Project during World War II?

Nuclear Fission Reactors

6. What are the three possible fates of neutrons in uranium metal?
7. What are the three main components of a fission reactor?
8. What are the safeguards to prevent a reactor exploding like a fission bomb?
9. What isotope is produced when U-238 absorbs a neutron?
10. What isotope is produced when U-239 emits a beta particle?
11. What isotope is produced when Np-239 emits a beta particle?
12. What do U-235 and Pu-239 have in common?

The Breeder Reactor

13. What is the effect of placing small amounts of fissionable isotopes with large amounts of U-238?
14. Name three isotopes that undergo nuclear fission.
15. How does a breeder reactor breed nuclear fuel?

Fission Power

16. How is a nuclear reactor similar to a conventional fossil-fuel plant? How is it different?
17. Cite a main advantage of fission power. Cite a main drawback.

Mass–Energy Equivalence

18. What celebrated equation shows the equivalence of mass and energy?
19. Is work required to pull a nucleon out of an atomic nucleus? Does the nucleon, once outside, have more energy than it did when it was inside the nucleus? In what form is this energy?
20. Which ions are least deflected in a mass spectrometer?
21. What is the basic difference between the graphs of Figure 34.15 and Figure 34.16?
22. In which atomic nucleus do nucleons have the greatest average mass? In which nucleus do they have the least average mass?
23. If the graph in Figure 34.16 is seen as an energy valley, what can be said about the energy of nuclear transformations that progress toward iron?

Nuclear Fusion

24. When two hydrogen nuclei are fused, is the mass of the product nucleus more or less than the sum of the masses of the two hydrogen nuclei?
25. For helium to release energy, should it be fissioned or fused?

Controlling Fusion

26. Where are isotopes of deuterium and tritium to be found?

RANKING

1. Assume that all of the following nuclei undergo fission into a pair of equal or nearly equal mass fragments. Using Figure 34.16 as your guide, rank from greatest to least the *reduction* in mass for these nuclei after fission.
   a. Uranium
   b. Silver
   c. Titanium
   d. Iron
2. Rank from greatest to least the *reduction* of mass per nucleon that accompanies the fusion of the following pairs of nuclei.
   a. Two hydrogen nuclei
   b. Two carbon nuclei
   c. Two aluminum nuclei
   d. Two iron nuclei

PROJECT

Write a letter to Grandpa or Grandma discussing nuclear power. Cite why uranium mines can be closed if plutonium from present nuclear warheads worldwide can be dismantled and used as fission fuel for power reactors. Cite both the ups and downs of nuclear fission power plants and explain how the comparison affects your personal view of nukes. Also explain to him or her how nuclear fission and nuclear fusion differ.

EXERCISES

1. Do today's nuclear power plants use fission, fusion, or both?
2. Why doesn't uranium ore spontaneously undergo a chain reaction?
3. Some heavy nuclei, containing even more protons than the uranium nucleus, undergo "spontaneous fission," splitting apart without absorbing a neutron. Why is spontaneous fission observed only in the heaviest nuclei?
4. Why will nuclear fission probably not be used directly for powering automobiles? How could it be used indirectly to power automobiles?
5. Why does a neutron make a better nuclear bullet than a proton?
6. Why will the escape of neutrons be proportionally less in a large piece of fissionable material than in a smaller piece?
7. A 56-kg sphere of U-235 constitutes a critical mass. If the sphere were flattened into a pancake shape, would it still be critical? Explain.
8. Which shape is likely to need more material for a critical mass, a cube or a sphere? Explain.
9. Does the average distance that a neutron travels through fissionable material before escaping increase or decrease when two pieces of fissionable material are assembled into one piece? Does this assembly increase or decrease the probability of an explosion?
10. U-235 releases an average of 2.5 neutrons per fission, while Pu-239 releases an average of 2.7 neutrons per fission. Which of these elements might you therefore expect to have the smaller critical mass?
11. Uranium and thorium occur abundantly in various ore deposits. However, plutonium could occur only in exceedingly tiny amounts in such deposits. What is your explanation?
12. Why, after a uranium fuel rod reaches the end of its fuel cycle (typically 3 years), does most of its energy come from the fissioning of plutonium?
13. If a nucleus of $^{232}_{90}Th$ absorbs a neutron and the resulting nucleus undergoes two successive beta decays (emitting electrons), what nucleus results?
14. The water that passes through the reactor core of a water-moderated fission reactor does not pass into the turbine. Instead, heat is transferred to a separate water cycle that is entirely outside the reactor. Why is this done?
15. Why is carbon better than lead as a moderator in nuclear reactors?
16. Is the mass of an atomic nucleus greater or less than the sum of the masses of the nucleons composing it? Why don't the nucleon masses add up to the total nuclear mass?
17. The energy release of nuclear fission is tied to the fact that the heaviest nuclei have about 0.1% more mass per nucleon than nuclei near the middle of the periodic table of the elements. What would be the effect on energy release if the 0.1% figure were instead 1%?
18. In what way are fission and fusion reactions similar? What are the main differences in these reactions?
19. How is chemical burning similar to nuclear fusion?
20. To predict the approximate energy release of either a fission reaction or a fusion reaction, explain how a physicist makes use of the curve in Figure 34.16 or a table of nuclear masses and the equation $E = mc^2$.
21. What nuclei will result if a U-235 nucleus, after absorbing a neutron and becoming U-236, splits into two identical fragments?
22. Heavy nuclei can be made to fuse—for instance, by firing one gold nucleus at another one. Does such a process yield energy or cost energy? Explain.
23. Light nuclei can be split. For example, a deuteron, which is a proton–neutron combination, can split into a separate proton and separate neutron. Does such a process yield energy or cost energy? Explain.
24. Which process would release energy from gold, fission or fusion? Which would release energy from carbon? From iron?
25. If uranium were to split into three segments of equal size instead of two, would more energy or less energy be released? Defend your answer in terms of Figure 34.16.
26. Mixing copper and zinc atoms produces the alloy brass. What would be produced with the fusion of copper and zinc nuclei?
27. Oxygen and hydrogen atoms combine to form water. If the nuclei in a water molecule were fused, what element would be produced?
28. If a pair of carbon atoms were fused, and the product were to emit a beta particle, what element would be produced?
29. Suppose the curve in Figure 34.16 for mass per nucleon versus atomic number had the shape of the curve in Figure 34.15. Then would nuclear fission reactions produce energy? Would nuclear fusion reactions produce energy? Defend your answers.
30. The "hydrogen magnets" in Figure 34.20 weigh more when apart than when combined. What would be the basic difference if the fictitious example instead consisted of "nuclear magnets" half as heavy as uranium?
31. In a nuclear fission reaction, which has more mass, the initial uranium or its products?
32. In a nuclear fusion reaction, which has more mass, the initial hydrogen isotopes or the fusion products?
33. Which produces more energy, the fissioning of a single uranium nucleus or the fusing of a pair of deuterium nuclei? The fissioning of a gram of uranium or the

fusing of a gram of deuterium? (Why do your answers differ?)

34. Why is there, unlike fission fuel, no limit to the amount of fusion fuel that can be safely stored in one locality?
35. If a fusion reaction produces no appreciable radioactive isotopes, why does a hydrogen bomb produce significant radioactive fallout?
36. List at least two major potential advantages of power production by fusion rather than by fission.
37. Sustained nuclear fusion has yet to be achieved and remains a hope for abundant future energy. Yet the energy that has always sustained us has been the energy of nuclear fusion. Explain.
38. Explain how radioactive decay has always warmed Earth from the inside and how nuclear fusion has always warmed Earth from the outside.
39. The world has never been the same since the discovery of electromagnetic induction and its applications to electric motors and generators. Speculate and list some of the worldwide changes that are likely to follow the advent of successful fusion reactors.
40. Discuss, and make a comparison of, pollution by conventional fossil-fuel power plants and nuclear-fission power plants. Consider thermal pollution, chemical pollution, and radioactive pollution.
41. Ordinary hydrogen is sometimes called a perfect fuel, both because of its almost unlimited supply on Earth and because, when it burns, harmless water is the product of the combustion. So why don't we abandon fission and fusion energies, not to mention fossil-fuel energy, and just use hydrogen?
42. If U-238 splits into two even pieces, and each piece emits an alpha particle, what elements are produced?
43. The energy of fission is mainly in the kinetic energy of its products. What becomes of this energy in a commercial power reactor?
44. Fermi's original reactor was just "barely" critical because the natural uranium that he used contained less than 1% of the fissionable isotope U-235 (half-life 713 million years). What if, in 1942, Earth had been 9 billion years old instead of 4.5 billion years old. Would Fermi have been able to make a reactor go critical with natural uranium?
45. U-235 has a half-life of about 700 million years. What does this say about the likelihood of fission power on Earth 1 billion years from now?

PROBLEMS

1. The kiloton, which is used to measure the energy released in an atomic explosion, is equal to 4.2×10^{12} J (approximately the energy released in the explosion of 1000 tons of TNT). Recalling that 1 kilocalorie of energy raises the temperature of 1 kg of water by 1°C and that 4184 joules is equal to 1 kilocalorie, show that 4.0×10^{8} kilograms of water (nearly half a million tons) can be heated through 50°C by a 20-kiloton atomic bomb.
2. The isotope of lithium used in a hydrogen bomb is Li-6, whose nucleus contains three protons and three neutrons. When a Li-6 nucleus absorbs a neutron, a nucleus of the heaviest hydrogen isotope, tritium, is produced. What is the other product of this reaction? Which of these two products fuels the explosive reaction?
3. An important fusion reaction in both hydrogen bombs and controlled-fusion reactors is the "DT reaction," in which a deuteron and a triton (nuclei of heavy hydrogen isotopes) combine to form an alpha particle and a neutron with the release of much energy. Use momentum conservation to explain why the neutron resulting from this reaction receives about 80% of the energy, while the alpha particle gets only about 20%.

CHAPTER 34 ONLINE RESOURCES

PhysicsPlace.com

Interactive Figures

- 34.11, 34.16, 34.18

Tutorial

- Nuclear Physics

Video

- Plutonium

Quizzes

Flashcards

Links

PART SEVEN MULTIPLE-CHOICE PRACTICE EXAM

Choose the BEST answer to the following.

1. The neutrons in an atom are normally found
   (a) inside the nucleus. (b) outside the nucleus. (c) Either of these. (d) Neither of these.
2. Spectral lines of the elements are
   (a) chaotic. (b) ordered. (c) positioned by amplitude. (d) in phase.
3. The energy of an emitted photon is related to its
   (a) frequency. (b) polarization. (c) amplitude. (d) direction.
4. The discrete orbits of electrons is best understood when modeled by
   (a) high-speed particles. (b) particles on springs. (c) waves. (d) photons.
5. From quantum mechanics we learn that a radioactive nucleus is governed by
   (a) Newton's laws. (b) probability. (c) certainty. (d) no laws at all.
6. Radioactivity has been around on Earth since the
   (a) middle of the 1900s.
   (b) Industrial Revolution.
   (c) advent of medical technology.
   (d) Earth formed.
7. Which of these can NOT be deflected by electrical or magnetic means?
   (a) Alpha rays. (b) Beta rays. (c) Gamma rays. (d) All can.
8. Which type of radiation from cosmic sources predominates on the inside of high-flying commercial airplanes?
   (a) Alpha. (b) Beta. (c) Gamma. (d) None of these.
9. In the atomic nucleus, electrical forces tend to
   (a) hold particles together. (b) push particles apart. (c) produce orbital motion. (d) charge particles.
10. When food is exposed to gamma radiation, the food
    (a) becomes slightly radioactive.
    (b) doesn't become radioactive.
    (c) will spoil faster.
    (d) should be avoided.
11. Most of the radiation in Earth's biosphere is
    (a) natural background radiation.
    (b) the result of military activities.
    (c) from nuclear power plants.
    (d) in the form of cosmic rays.
12. Carbon-14 is primarily produced by cosmic radiation in the
    (a) atmosphere.
    (b) food we eat.
    (c) Earth's interior.
    (d) fallout of nuclear bomb tests.
13. A radioactive sample has a half-life of 1 hour. Starting with 1.000 gram of it at noon, how much remains at 3:00 PM?
    (a) 0.50 g. (b) 0.25 g. (c) 0.125 g. (d) 0.0625 g.
14. When an element ejects an alpha particle, the mass number of the resulting element
    (a) reduces by 2. (b) reduces by 4. (c) increases by 2. (d) increases by 4.
15. When an element ejects an alpha particle, the atomic number of the resulting element
    (a) reduces by 2. (b) reduces by 4. (c) increases by 2. (d) increases by 4.
16. When an element ejects a beta particle, the atomic number of that element
    (a) reduces by 1. (b) increases by 1. (c) reduces by 2. (d) increases by 2.
17. A certain element emits 1 alpha particle, and its products then emit 2 beta particles in succession. The atomic number of the resulting element is changed by
    (a) zero. (b) minus 1. (c) minus 2. (d) plus 1.
18. When a nucleus of uranium-238 emits an alpha particle, left behind is
    (a) thorium-242. (b) thorium-238. (c) thorium-234. (d) radium-214.
19. When a proton is plucked from an atomic nucleus, there is a decrease in
    (a) charge. (b) energy. (c) mass. (d) None of these.
20. When small pieces of material are assembled into a larger piece, the combined surface area
    (a) greatly increases. (b) slightly increases. (c) decreases. (d) is unchanged.
21. Chain reactions in a fission reactor are caused by
    (a) kinetic energy. (b) energy conversion. (c) mass conversion. (d) ejected neutrons.
22. A common nuclear fission reactor
    (a) heats water.
    (b) generates electricity directly.
    (c) gets energy from nothing.
    (d) is a major polluter of the atmosphere.
23. Compared with the mass of a uranium atom undergoing fission, the combined masses of the products after fission are
    (a) less. (b) more. (c) the same. (d) zero.
24. When energy is released by the process of fusion, the total mass of the material after the event is
    (a) less. (b) the same. (c) more. (d) zero.
25. Which process would release energy from gold, fission or fusion? From carbon?
    (a) Gold: fission; carbon: fusion
    (b) Gold: fusion; carbon: fission
    (c) Gold: fission; carbon: fission
    (d) Gold: fusion; carbon: fusion
26. If an iron nucleus split in two, its fission fragments would have
    (a) less mass per nucleon.
    (b) more mass per nucleon.
    (c) the same mass per nucleon.
    (d) either more or less mass per nucleon.
27. Which of these three elements has the most mass *per* nucleon?
    (a) Hydrogen. (b) Iron. (c) Uranium. (d) Same in each.
28. In both fission and fusion, energy is released while mass
    (a) decreases.
    (b) remains unchanged; is conserved.
    (c) increases.
    (d) may decrease or increase.
29. In either a fission event or a fusion event, a quantity that remains unchanged is the
    (a) kinetic energy. (b) mass. (c) number of nucleons. (d) binding of nucleons.
30. The equation that most underlies energy release in nuclear events is
    (a) $E = hf$. (b) $E = 1/2\ mv^2$. (c) $E = Fd$. (d) $E = mc^2$.

After you have made thoughtful choices, and discussed them with your friends, find the answers on page 681.

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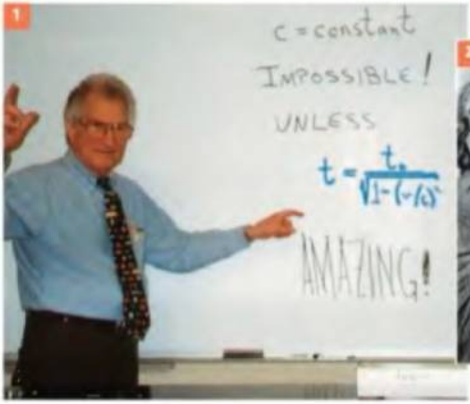
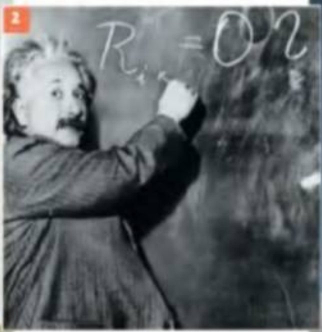
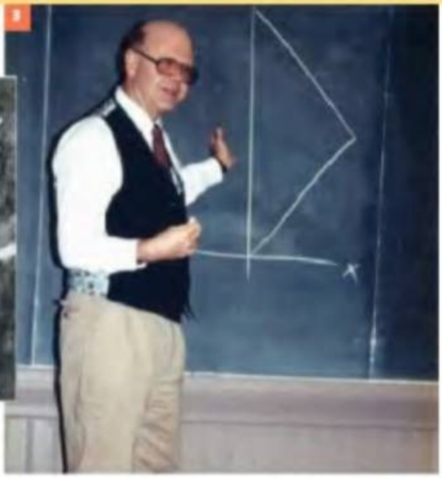
Part Eight
Relativity

Before the advent of Special Relativity, people thought the stars were beyond human reach. But distance is relative—it depends on motion. In a frame of reference moving almost as fast as light, distance contracts and time stretches enough to allow future astronauts access to the stars and beyond! We *are* like Evan's chickie on opening page 1, at the verge of a whole new beginning. Newton's physics got us to the moon; Einstein's physics points us to the stars. We live at an exciting time!

35 Special Theory of Relativity







1 Ken Ford, former CEO of the American Institute of Physics, brings the beauty of relativity to his high school students. 2 The twentieth-century's greatest scientist and one of its favorite human beings. 3 Edwin F. Taylor, co-author of several relativity books, gestures at a diagram showing two paths between a starting gun and crossing the finish line. One path is straight, one round-trip. The round-trip twin returns home younger than the lazy stay-at-home twin, an astonishing result showing Einstein's key idea that time between two events depends on the path taken between them.

Albert Einstein was born in Ulm, Germany, on March 14, 1879. According to popular legend, he was a slow child and learned to speak at a much later age than average; his parents feared for a while that he might be mentally retarded. Yet his elementary school records show that he was remarkably gifted in mathematics, physics, and playing the violin. He rebelled, however, at the practice of education by regimentation and rote and was expelled just as he was preparing to drop out at the age of 15. Largely because of business reasons, his family moved to Italy. Young Einstein renounced his German citizenship and went to live with family friends in Switzerland. There, two years younger than the normal age, he was allowed to take the entrance examinations for the renowned Swiss Federal Institute of Technology in Zurich. But because of difficulties with the French language, he did not pass the examination. He spent a year at a Swiss preparatory school in Aarau, where he was "promoted with protest in French." He tried the entrance exam again at Zurich and passed.

As an eager young student of physics in the 1890s, Albert Einstein was troubled by a difference between Newton's laws of mechanics and Maxwell's laws of electromagnetism. Newton's laws were independent of the state of motion of an observer; Maxwell's laws were not—or so it seemed. Someone at rest and someone in motion would find that the *same* laws of mechanics apply to a moving object being studied, but they would find that *different* laws of electricity and magnetism apply to a moving charge being studied. Newton's laws suggest that there is no such thing as absolute motion; only relative motion matters. But Maxwell's laws seemed to suggest that motion is absolute.

In a celebrated 1905 paper titled "On the Electrodynamics of Moving Bodies," written when he was 26, Einstein showed that Maxwell's laws can, after all, like Newton's laws, be interpreted as being independent of the state of motion of an observer—but at a cost! The cost of achieving this unified view of nature's laws is a total revolution in how we understand space and time.

Einstein showed that, as the forces between electric charges are affected by motion, the very measurements of space and time are also affected by motion. All measurements of space and time depend on relative motion. For example, the length of a rocket ship poised on its launching pad and the ticks of clocks within are found to change when the ship is set into motion at high speed. It has always been common sense that we change our position in space when we move, but Einstein flouted common sense and stated that, in moving, we also change our rate of proceeding into the future—time itself is altered. Einstein went on to show that a consequence of the interrelationship between space and time is an interrelationship between mass and energy, given by the famous equation $E = mc^2$.

These are the ideas that make up this chapter—the ideas of special relativity—ideas so remote from your everyday experience that understanding them requires stretching your mind. It will be enough to become acquainted with these ideas, so be patient with yourself if you don't understand them right away. Perhaps in some future era, when high-speed interstellar space travel is commonplace, your descendants will find that relativity makes common sense.

Motion Is Relative

Recall from Chapter 3 that whenever we talk about motion, we must always specify the vantage point from which motion is being observed and measured. For example, a person who walks along the aisle of a moving train may be walking at a speed of 1 kilometer per hour relative to his seat but at 60 kilometers per hour relative to the railroad station. We call the place from which motion is observed and measured a **frame of reference.** An object may have different velocities relative to different frames of reference.

To measure the speed of an object, we first choose a frame of reference and pretend that we are in that frame of reference standing still. Then we measure the speed with which the object moves relative to us—that is, relative to the frame of reference. In the foregoing example, if we measure from a position of rest within the train, the speed of the walking person is 1 kilometer per hour. If we measure from a position of rest on the ground, the speed of the walking person is 60 kilometers per hour. But the ground is not really still, for Earth spins like a top about its polar axis. Depending on how near the train is to the equator, the speed of the walking person may be as much as 1600 kilometers per hour relative to a frame of reference at the center of Earth. And the center of Earth is moving relative to the Sun. If we place our frame of reference on the Sun, the speed of the person walking in the train, which is on the orbiting Earth, is nearly 110,000 kilometers per hour. And the Sun is not at rest, for it orbits the center of our galaxy, which moves with respect to other galaxies.

MICHELSON–MORLEY EXPERIMENT

Isn't there some reference frame that is still? Isn't space itself still, and can't measurements be made relative to still space? In 1887, the American physicists A. A. Michelson and E. W. Morley attempted to answer these questions by performing an experiment that was designed to measure the motion of Earth through space. Because light travels in waves, it was then assumed that something in space vibrates—a mysterious something called *ether,* thought to fill all space and to serve as a frame of reference attached to space itself. These physicists used a very sensitive apparatus

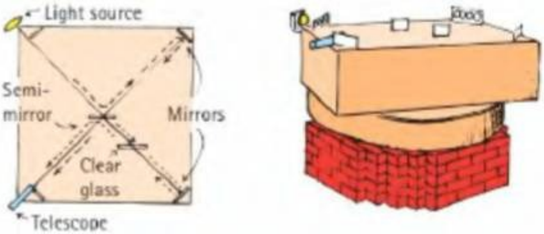


FIGURE 35.1
The Michelson–Morley interferometer, which splits a light beam into two parts and then recombines them to form an interference pattern after they have traveled different paths. Rotation was accomplished in their experiment by floating a massive sandstone slab in mercury. This schematic diagram shows how the half-silvered mirror splits the beam into two rays. The clear glass assured that both rays traverse the same amount of glass. In the actual experiment, four mirrors were placed at each corner to lengthen the paths.

called an *interferometer* to make their observations (Figure 35.1). In this instrument, a beam of light from a monochromatic source was separated into two beams with paths at right angles to each other; these were reflected and recombined to show whether there was any difference in average speed over the two back-and-forth paths. The interferometer was set with one path parallel to the motion of Earth in its orbit; then either Michelson or Morley carefully watched for any changes in average speed as the apparatus was rotated to put the other path parallel to the motion of Earth. The interferometer was sensitive enough to measure the difference in the round-trip times of light going with and against Earth's orbital velocity of 30 kilometers per second and going back and forth across Earth's path through space. But no changes were observed. None. Something was wrong with the sensible idea that the speed of light measured by a moving receiver should be its usual speed in a vacuum, c, plus or minus the contribution from the motion of the source or receiver. Many repetitions and variations of the Michelson–Morley experiment by many investigators showed the same null result. This was one of the puzzling facts of physics when the 20th century opened.

One interpretation of the bewildering result was suggested by the Irish physicist G. F. FitzGerald, who proposed that the length of the experimental apparatus shrank in the direction in which it was moving by just the amount required to counteract the presumed variation in the speed of light. The needed "shrinkage factor," $\sqrt{1 - v^2/c^2}$ was worked out by the Dutch physicist Hendrik A. Lorentz. This arithmetical factor accounted for the discrepancy, but neither FitzGerald nor Lorentz had a suitable theory for why this was so. Interestingly, the same factor was derived by Einstein in his 1905 paper, where he showed it to be the shrinkage factor of space itself, not just of matter in space.

How much the Michelson–Morley experiment influenced Einstein, if at all, is unclear. In any event, Einstein advanced the idea that the speed of light in free space is the same in all reference frames, an idea that was contrary to the classical ideas of space and time. Speed is a ratio of distance through space to a corresponding interval of time. For the speed of light to be a constant, the classical idea that space and time are independent of each other had to be rejected. Einstein saw that space and time are linked, and, with simple postulates, he developed a profound relationship between the two.

Postulates of the Special Theory of Relativity

Einstein saw no need for the ether. Gone with the stationary ether was the notion of an absolute frame of reference. All motion is relative, not to any stationary hitching post in the universe, but to arbitrary frames of reference. A rocket ship cannot measure its speed with respect to empty space but only with respect to other objects. If, for example, rocket ship A drifts past rocket ship B in empty space, spaceman A and spacewoman B will each observe the relative motion, and, from this observation, each will be unable to determine who is moving and who is at rest, if either.

This is a familiar experience to a passenger on a train who looks out his window and sees the train on the next track moving by his window. He is aware only of the relative motion between his train and the other train and cannot tell which train is moving. He may be at rest relative to the ground and the other train may be moving, or he may be moving relative to the ground and the other train may be at rest, or they both may be moving relative to the ground. The important point here is that, if you were in a train with no windows, there would be no way to determine whether the train was moving with uniform velocity or was at rest. This is the first of Einstein's postulates of the special theory of relativity:

All laws of nature are the same in all uniformly moving frames of reference.

On a jet airplane going 700 kilometers per hour, for example, coffee pours as it does when the plane is at rest; if we swing a pendulum in the moving plane, it swings as it would if the plane were at rest on the runway. There is no physical experiment that we can perform, even with light, to determine our state of uniform motion. The laws of physics within the uniformly moving cabin are the same as those in a stationary laboratory.

FIGURE 35.2
The speed of light is measured to be the same in all frames of reference.

Any number of experiments can be devised to detect accelerated motion, but none can be devised, according to Einstein, to detect a state of uniform motion. Therefore, absolute motion has no meaning. It would be very peculiar if the laws of mechanics varied for observers moving at different speeds. It would mean, for example, that a pool player on a smoothly moving ocean liner would have to adjust her style of play to the speed of the ship, or even to the season as Earth varies in its orbital speed about the Sun. It is our common experience that no such adjustment is necessary. And, according to Einstein, this same insensitivity to motion extends to electromagnetism. No experiment, mechanical or electrical or optical, has ever revealed absolute motion. That is what the first postulate of relativity means.

One of the questions that Einstein, as a youth, asked himself was, "What would a light beam look like if you traveled along beside it?" According to classical physics, the beam would be at rest to such an observer. The more Einstein thought about this, the more convinced he became that one could not move with a light beam. He finally came to the conclusion that, no matter how fast two observers might be moving relative to each other, each of them would measure the speed of a light beam passing them to be 300,000 kilometers per second. This was the second postulate in his special theory of relativity:

The speed of light in free space has the same measured value for all observers, regardless of the motion of the source or the motion of the observer; that is, the speed of light is a constant.

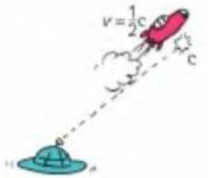


FIGURE 35.3
The speed of a light flash emitted by the space station is measured to be c by observers on both the space station and the rocket ship.

To illustrate this statement, consider a rocket ship departing from the space station shown in Figure 35.3. A flash of light traveling at 300,000 km/s, or c, is emitted from the station. Regardless of the velocity of the rocket, an observer in the rocket sees the flash of light pass her at the same speed, c. If a flash is sent to the station from the moving rocket, observers on the station will measure the speed of the flash to be c. The speed of light is measured to be the same regardless of the speed of the source or receiver. *All* observers who measure the speed of light will find it has the same value, c. The more you think about this, the more you think it doesn't make sense. We will see that the explanation has to do with the relationship between space and time.

Simultaneity

An interesting consequence of Einstein's second postulate occurs with the concept of **simultaneity.** We say that two events are simultaneous if they occur at the same time. Consider, for example, a light source in the exact center of the

FIGURE 35.4
From the point of view of the observer who travels with the compartment, light from the source travels equal distances to both ends of the compartment and therefore strikes both ends simultaneously.

compartment of a rocket ship (Figure 35.4). When the light source is switched on, light spreads out in all directions at speed c. Because the light source is equidistant from the front and back ends of the compartment, an observer inside the compartment finds that light reaches the front end at the same instant it reaches the back end. This occurs whether the ship is at rest or moving at constant velocity. The events of hitting the back end and hitting the front end occur *simultaneously* for this observer within the rocket ship.

But what about an outside observer who views the same two events in another frame of reference—say, from a planet not moving with the ship? For that observer, these same two events are *not* simultaneous. As light travels out from the source, this observer sees the ship move forward, so the back of the compartment moves toward the beam while the front moves away from it. The beam going to the back of the compartment, therefore, has a shorter distance to travel than the beam going forward (Figure 35.5). Since the speed of light is the same in both directions, this outside observer sees the event of light hitting the back of the compartment *before* seeing the event of light hitting the front of the compartment. (Of course, we are making the assumption that the observer can discern these slight differences.) A little thought will show that an observer in another rocket ship that passes the ship in the opposite direction would report that the light reaches the front of the compartment first.

FIGURE 35.5
The events of light striking the front and back of the compartment are not simultaneous from the point of view of an observer in a different frame of reference. Because of the ship's motion, light that strikes the back of the compartment doesn't have as far to go and strikes sooner than light that strikes the front of the compartment.

Two events that are simultaneous in one frame of reference need not be simultaneous in a frame moving relative to the first frame.

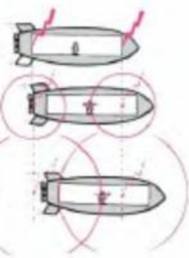
This nonsimultaneity of events in one frame that are simultaneous in another is a purely relativistic result—a consequence of light always having the same speed for all observers.

CHECK POINT

1. How is the nonsimultaneity of hearing thunder *after* seeing lightning similar to relativistic nonsimultaneity?
2. Suppose that the observer standing on a planet in Figure 35.5 sees a pair of lightning bolts simultaneously strike the front and rear ends of the compartment in the high-speed rocket ship. Will the lightning strikes be simultaneous to an observer in the middle of the compartment in the rocket ship? (We assume here that an observer can detect any slight differences in time for light to travel from the ends to the middle of the compartment.)

Check Your Answers

1. It isn't! The duration between hearing thunder and seeing lightning has nothing to do with moving observers or relativity. In such a case, you simply make corrections for the time the signals (sound and light) take to reach you. The relativity of simultaneity is a genuine discrepancy between observations made by observers in relative motion, and not simply a disparity between different travel times for different signals.
2. No; an observer in the middle of the compartment will see the lightning that hits the front end of the compartment before seeing the lightning that hits the rear end. This is shown in positions (a), (b), and (c) to the left. In (a), we see both lightning bolts striking the ends of the compartment simultaneously, according to the outside observer. In position (b), light from the front lightning bolt reaches the observer within the rocket ship. Slightly later, in (c), light from the rear lightning bolt reaches this observer.

(a)
(b)
(c)


Spacetime

When we look up at the stars, we realize that we are actually looking backward in time. The stars we see farthest away are the stars we are seeing longest ago. The more we think about this, the more apparent it becomes that space and time must be intimately tied together.

The space we live in is three-dimensional; that is, we can specify the position of any location in space with three dimensions. For example, these dimensions could be north–south, east–west, and up–down. If we are at the corner of a rectangular room and wish to specify the position of any point in the room, we can do this with three numbers. The first would be the number of meters the point is along a line joining the side wall and the floor; the second would be the number of meters the point is along a line joining the adjacent back wall and the floor; and the third would be the number of meters the point lies above the floor or along the vertical line joining the walls at the corner. Physicists speak of these three lines as the *coordinate axes* of a reference frame (Figure 35.6). Three numbers—the distances along the x axis, the y axis, and the z axis—will specify the position of a point in space.

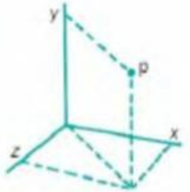


FIGURE 35.6

Point P can be specified with three numbers: the distances along the x axis, the y axis, and the z axis.

We also use three dimensions to specify the size of objects. A box, for example, is described by its length, width, and height. But the three dimensions do not give a complete picture. There is a fourth dimension—time. The box was not always a box of given length, width, and height. It began as a box only at a certain point in time, on the day it was made. Nor will it always be a box. At any moment, it may be crushed, burned, or otherwise destroyed. So the three dimensions of space are a valid description of the box only during a certain specified period of time. We cannot speak meaningfully about space without implying time. Things exist in **spacetime.** Each object, each person, each planet, each star, each galaxy exists in what physicists call "the spacetime continuum."

FIGURE 35.7

All space and time measurements of light are unified by c.

Two side-by-side observers at rest relative to each other share the same reference frame. Both would agree on measurements of space and time intervals between given events, so we say they share the same realm of spacetime. If there is relative motion between them, however, the observers will not agree on these measurements of space and time. At ordinary speeds, differences in their measurements are imperceptible, but, at speeds near the speed of light—so-called relativistic speeds—the differences are appreciable. Each observer is in a different realm of spacetime, and one observer's measurements of space and time differ from the measurements of another observer in some other realm of spacetime. The measurements differ not haphazardly but in such a way that each observer will always measure the same ratio of space and time for light: the greater the measured distance in space, the greater the measured interval of time. This constant ratio of space and time for light, c, is the unifying factor between different realms of spacetime and is the essence of Einstein's second postulate.

Time Dilation

Let's examine the notion that time can be stretched. Imagine that we are somehow able to observe a flash of light bouncing to and fro between a pair of parallel mirrors, like a ball bouncing to and fro between a floor and ceiling. If the distance between the mirrors is fixed, then the arrangement constitutes a *light clock*, because the back-and-forth trips of the flash take equal time intervals (Figure 35.8). Suppose this light clock is inside a transparent, high-speed spaceship. An observer who travels along with the ship and watches the light clock

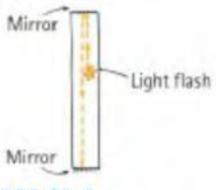


FIGURE 35.8

A light clock. A flash of light will bounce up and down between parallel mirrors and "tick off" equal intervals of time.

Clockwatching on a Trolley Car Ride

Pretend you are Einstein at the turn of the 20th century, riding in a trolley car moving away from a huge clock in the village square. The clock reads 12 noon. To say it reads 12 noon is to say that light that carries the information "12 noon" is reflected by the clock and travels toward you along your line of sight. If you suddenly move your head to the side, the light carrying the information, instead of meeting your eye, continues past, presumably out into space. Out there, an observer who *later* receives the light says, "Oh, it's 12 noon on Earth now." But, from your point of view, it's now later than that. You and the distant observer see 12 noon at different times. You wonder more about this idea. If the trolley car traveled as fast as the light, then the trolley car would keep up with the light's information that says "12 noon." Traveling at the speed of light, then, tells you it's always 12 noon at the village square. In other words, time at the village square is frozen!

If the trolley car is not moving, you see the village square clock move into the future at the rate of 60 s/min; if you move at the speed of light, you see seconds on the clock taking infinite time. These are the two extremes. What's in between? How would the advance of the clock's hands be viewed as you move at speeds less than the speed of light?

A little thought will show that you will receive the message "1 o'clock" anywhere from 60 minutes to an infinity of time after you receive the message "12 noon," depending on what your speed is between the extremes of zero and the speed of light. From your high-speed (but less than *c*) frame of reference, you see all events taking place in the reference frame of the clock (which is Earth) as happening in slow motion. If you reverse direction and travel at high speed back toward the clock, you'll see all events taking place in the clock's reference frame as being speeded up. When you return and are once again sitting in the square, will the effects of going and coming compensate each other? Amazingly, no! Time will be stretched. The wristwatch you were wearing the whole time and the village clock will disagree. This is time dilation.

(Figure 35.9a) sees the flash reflecting straight up and down between the two mirrors, just as it would if the spaceship were at rest. This observer sees no unusual effects. Note that because the observer is in the ship moving along with it, there is no relative motion between the observer and the light clock; we say that the observer and the clock share the same reference frame in spacetime.

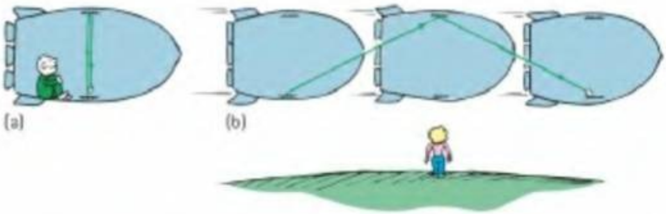


FIGURE 35.9

INTERACTIVE FIGURE

(a) An observer moving with the spaceship observes the light flash moving vertically between the mirrors of the light clock.
(b) An observer who sees the moving ship pass by observes the flash moving along a diagonal path.

Suppose now that we are standing on the ground as the spaceship whizzes by us at a high speed—say, half the speed of light. Things are quite different from our reference frame, for we do not see the light path as being simple up-and-down motion. Because each flash moves horizontally while it moves vertically between the two mirrors, we see the flash follow a diagonal path. Notice in Figure 35.9b that from our earthbound frame of reference, the flash travels a *longer distance* as it makes one round-trip between the mirrors, considerably longer than the distance it travels in the reference frame of the observer riding along with the ship. Because the speed of light is the same in all reference frames (Einstein's second postulate), the flash must travel for a correspondingly longer time between the mirrors in our frame than in the reference frame of the onboard observer. This follows from the definition of speed—distance divided by time. *The longer diagonal distance must be divided by a* *correspondingly longer time interval to yield an unvarying value for the speed of light.* This stretching out of time is called **time dilation.**

We have considered a light clock in our example, but the same is true for any kind of clock. All clocks run more slowly when moving than when at rest. Time dilation has to do not with the mechanics of clocks, but with the nature of time itself.

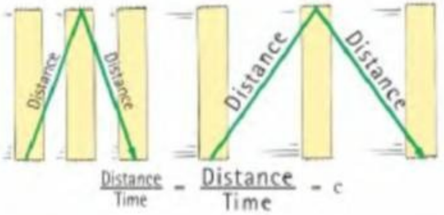


FIGURE 35.10

INTERACTIVE FIGURE

The longer distance covered by the light flash in following the longer diagonal path on the right must be divided by a correspondingly longer time interval to yield an unvarying value for the speed of light.

The relationship of time dilation for different frames of reference in spacetime can be derived from Figure 35.10 with simple geometry and algebra.[1] The relationship between the time t_0 (call it the *proper time*) in the frame of reference moving with the clock and the time t measured in another frame of reference (call it the *relative time*) is

$$t = \frac{t_0}{\sqrt{1 - \frac{v^2}{c^2}}}$$

[1]The light clock is shown in three successive positions in the figure below. The diagonal lines represent the path of the light flash as it starts from the lower mirror at position 1, moves to the upper mirror at position 2, and then back to the lower mirror at position 3. Distances on the diagram are marked ct, vt, and ct_0, which follows from the fact that the distance traveled by a uniformly moving object is equal to its speed multiplied by the time.

The symbol t_0 represents the time it takes for the flash to move between the mirrors, as measured from a frame of reference fixed to the light clock. This is the time for straight up or down motion. The speed of light is c, and the path of light is seen to move a vertical distance ct_0. This distance between mirrors is at right angles to the motion of the light clock and is the same in both reference frames.

The symbol t represents the time it takes the flash to move from one mirror to the other, as measured from a frame of reference in which the light clock moves with speed v. Because the speed of the flash is c and the time it takes to go from position 1 to position 2 is t, the diagonal distance traveled is ct. During this time t, the clock (which travels horizontally at speed v) moves a horizontal distance vt from position 1 to position 2.

As the figure shows, these three distances make up a right triangle in which ct is the hypotenuse and ct_0 and vt are legs. A well-known theorem of geometry, the Pythagorean Theorem, states that the square of the hypotenuse is equal to the sum of the squares of the two legs. If we apply this formula to the figure, we obtain:

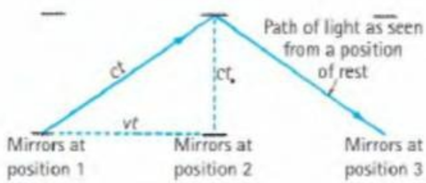
$$c^2t^2 = c^2t_0^2 + v^2t^2$$

$$c^2t^2 - v^2t^2 = c^2t_0^2$$

$$t^2[1 - (v^2/c^2)] = t_0^2$$

$$t^2 = \frac{t_0^2}{1 - (v^2/c^2)}$$

$$t = \frac{t_0}{\sqrt{1 - (v^2/c^2)}}$$



where v represents the speed of the clock relative to the outside observer (the same as the relative speed of the two observers) and c is the speed of light. The quantity

$$\sqrt{1-\frac{v^2}{c^2}}$$

is the same factor used by Lorentz to explain length contraction. We call the inverse of this quantity the *Lorentz factor*, γ (gamma). That is,

$$\gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$$

Then we can express the time dilation equation more simply as

$$t = \gamma t_0$$

Let's look at the terms in γ. Some mental tinkering will show that γ is always greater than 1 for any speed v greater than zero. Note that, since speed v is always less than c, the ratio v/c is always less than 1; likewise for v^2/c^2. Can you see it follows that γ is greater than 1? Now consider the case where $v = 0$. This ratio v^2/c^2 is 0, and for everyday speeds, where v is negligibly small compared to c, it's practically 0. Then $1 - v^2/c^2$ has a value of 1, as has $\sqrt{1-v^2/c^2}$, which makes $\gamma = 1$. Then we find $t = t_0$—time intervals appear the same in both reference frames. For higher speeds, v/c is between 0 and 1, and $1 - v^2/c^2$ is less than 1; likewise, $\sqrt{1-v^2/c^2}$. This makes γ greater than 1, so t_0 multiplied by a factor greater than 1 produces a value greater than t_0—an elongation—a dilation of time.

FIGURE 35.11
A plot of the Lorentz factor γ as a function of speed.

To consider some numerical values, assume that v is 50% the speed of light. Then we substitute $0.5c$ for v in the time-dilation equation and, after some arithmetic, find that $\gamma = 1.15$; so $t = 1.15t_0$. This means that if we viewed a clock on a spaceship traveling at half the speed of light, we would see the second hand take 1.15 minutes to make a revolution, whereas an observer riding with the clock would see it take 1 minute. If the spaceship passes us at 87% the speed of light, $\gamma = 2$ and $t = 2t_0$. We would measure time events on the spaceship taking twice the usual intervals, for the hands of a clock on the ship would turn only half as fast as those on our own clock. Events on the ship would seem to take place in slow motion. At 99.5% the speed of light, $\gamma = 10$ and $t = 10t_0$; we would see the second hand of the spaceship's clock take 10 minutes to sweep through a revolution requiring 1 minute on our clock.

To put these figures another way, at $0.995c$, the moving clock would appear to run a tenth of our rate; it would tick only 6 seconds while our clock ticks 60 seconds. At $0.87c$, the moving clock ticks at half rate and shows 30 seconds to our 60 seconds; at $0.50c$, the moving clock ticks 1/1.15 as fast and ticks 52 seconds to our 60 seconds. Moving clocks run slow.

FIGURE 35.12
When we see the rocket at rest, we see it traveling at the maximum rate in time: 24 hours per day. When we see the rocket traveling at close to the maximum rate through space (the speed of light), we see its time practically standing still.

Nothing is unusual about a moving clock itself; it is simply ticking to the rhythm of a different time. The faster a clock moves, the slower it appears to run as viewed by an observer not moving with the clock. If it were possible to make a clock fly by us at the speed of light, the clock would not appear to be running at all. We would measure the interval between ticks to be infinite. The clock would be ageless! But one thing *does* move at the speed of light—light itself. So photons never age. There is no passage of time for a photon. Photons are truly ageless.

If a person whizzing past us were to check a clock in our reference frame, he would find our clock to be running as slowly as we would find his to be. Each would conclude that the other's clock runs slow. There is really no contradiction here, for it is physically impossible for two observers in relative motion to refer to one and the same realm of spacetime. The measurements made in one realm of spacetime need not agree with the measurements made in another realm of spacetime. The measurement that all observers always agree on, however, is the speed of light.

Time dilation has been confirmed in the laboratory innumerable times with particle accelerators. The lifetimes of fast-moving radioactive particles increase as the speed goes up, and the amount of increase is just what Einstein's equation predicts. Time dilation has been confirmed also for not-so-fast motion. In 1971, to test Einstein's theory, four cesium-beam atomic clocks were twice flown on regularly scheduled commercial jet flights around the world, once eastward and once westward, to test Einstein's theory of relativity with macroscopic clocks. The clocks indicated different times after their round-trips. Relative to the atomic time scale of the U.S. Naval Observatory, the observed time differences, in billionths of a second, were in accord with Einstein's prediction. Now, with atomic clocks orbiting Earth as part of the Global Positioning System, adjustments for the effects of time dilation are essential in order to use signals from the clocks to pinpoint locations on Earth.

This all seems very strange to us only because it is not our common experience to deal with measurements made at relativistic speeds or atomic-clock-type measurements at ordinary speeds. The theory of relativity does not make common sense. But common sense, according to Einstein, is that layer of prejudices laid down in the mind prior to the age of 18. If we had spent our youth zapping through the universe in high-speed spaceships, we would probably be quite comfortable with the results of relativity.

fyi

- The Global Positioning System (GPS) takes account of the time dilation of orbiting atomic clocks. Otherwise, your GPS receiver would badly miss your location.

CHECK POINT

1. If you were moving in a spaceship at a high speed relative to Earth, would you notice a difference in your pulse rate? In the pulse rate of the people back on Earth?
2. Will observers A and B agree on measurements of time if A moves at half the speed of light relative to B? If both A and B move together at half the speed of light relative to Earth?
3. Does time dilation mean that time really passes more slowly in moving systems or only that it seems to pass more slowly?

Check Your Answers

1. There would be no relative speed between you and your pulse because the two share the same frame of reference. Therefore, you would notice no relativistic effects in your pulse. There would be, however, a relativistic effect between you and people back on Earth. You would find their pulse rate to be slower than normal (and they would find your pulse rate to be slower than normal). Relativity effects are always attributed to the other guy.
2. When A and B move relative to each other, each observes a slowing of time in the other's frame of reference. So they do not agree on measurements of time. When they are moving in unison, they share the same frame of reference and agree on measurements of time. They see each other's time as passing normally, and they each see events on Earth in the same slow motion.
3. The slowing of time in moving systems is not merely an illusion resulting from motion. Time really does pass more slowly in a moving system relative to one at relative rest, as we shall see in the next section. Read on!

The Twin Trip

A dramatic illustration of time dilation is provided by identical twins, one an astronaut who takes a high-speed round-trip journey in the galaxy while the other stays home on Earth. When the traveling twin returns, he is younger than the stay-at-home twin. How much younger depends on the relative speeds involved.

FIGURE 35.13

The traveling twin does not age as fast as the stay-at-home twin.

If the traveling twin maintains a speed of 50% the speed of light for 1 year (according to clocks aboard the spaceship), 1.15 years will have elapsed on Earth. If the traveling twin maintains a speed of 87% the speed of light for a year, then 2 years will have elapsed on Earth. At 99.5% the speed of light, 10 Earth years would pass in one spaceship year. At this speed, the traveling twin would age a single year while the stay-at-home twin would age 10 years.

fyi

- Cosmonaut Sergei Avdeyev spent more than two years orbiting Earth in the *Mir* spacecraft, and, due to time dilation, he is today two-hundredths of a second younger than he would be if he'd never been in space!

One question often arises: Since motion is relative, why doesn't the effect work equally well the other way around? Why wouldn't the traveling twin return to find his stay-at-home twin younger than himself? We will show that, from the frames of reference of both the earthbound twin and traveling twin, it is the earthbound twin who ages more. First, consider a spaceship hovering at rest relative to Earth. Suppose the spaceship sends brief, regularly spaced flashes of light to the planet (Figure 35.14). Some time will elapse before the flashes get to the planet, just as 8 minutes elapse before sunlight gets to Earth. The light flashes will encounter the receiver on the planet at speed c. Since there is no relative motion between the sender and receiver, successive flashes will be received as frequently as they are sent. For example, if a flash is sent from the ship every 6 minutes, then, after some initial delay, the receiver will receive a flash every 6 minutes. With no motion involved, there is nothing unusual about this.

FIGURE 35.14

When no motion is involved, the light flashes are received as frequently as the spaceship sends them.

When motion is involved, the situation is quite different. It is important to note that the speed of the flashes will still be c, no matter how the ship or receiver may move. How frequently the flashes are seen, however, very much depends on the relative motion involved. When the ship travels toward the receiver, the receiver sees the flashes more frequently. This happens not only because time is altered due to motion but mainly because each succeeding flash has less distance to travel as the ship gets closer to the receiver. If the spaceship emits a flash every 6 minutes, the flashes will be seen at intervals of less than 6 minutes. Suppose the ship is traveling fast enough for the flashes to be seen twice as frequently. Then they are seen at intervals of 3 minutes (Figure 35.15).

If the ship recedes from the receiver at the same speed and still emits flashes at 6-minute intervals, these flashes will be seen half as frequently by the receiver—that is, at 12-minute intervals (Figure 35.16). This is mainly because each suc-

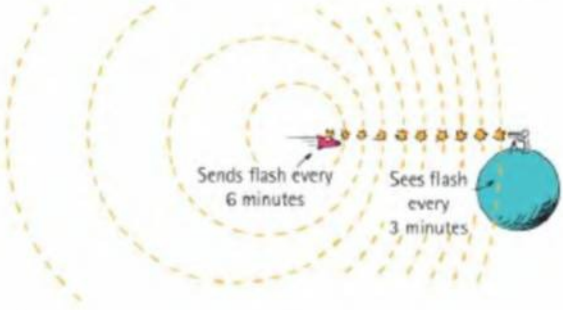


FIGURE 35.15

When the sender moves toward the receiver, the flashes are seen more frequently.

ceeding flash has a longer distance to travel as the ship gets farther away from the receiver.

The effect of moving away is just the opposite of moving closer to the receiver. So if the flashes are received twice as frequently when the spaceship is approaching (6-minute flash intervals are seen every 3 minutes), they are received half as frequently when it is receding (6-minute flash intervals are seen every 12 minutes).[2]

This means that, if two events are separated by 6 minutes according to the spaceship clock, flashes will be seen to be separated by 12 minutes when the spaceship recedes and by only 3 minutes when the ship is approaching.

FIGURE 35.16

When the sender moves away from the receiver, the flashes are spaced farther apart and are seen less frequently.

[2]This reciprocal relationship (halving and doubling of frequencies) is a consequence of the constancy of the speed of light and can be illustrated with the following example: Suppose that a sender on Earth emits flashes 3 min apart to a distant observer on a planet that is at rest relative to Earth. The observer, then, sees a flash every 3 min. Now suppose a second observer travels in a spaceship between Earth and the planet at a speed great enough to allow him to see the flashes half as frequently—6 min apart. This halving of frequency occurs for a speed of recession of $0.6c$. We can see that the frequency will double for a speed of approach of $0.6c$ by supposing that the spaceship emits its own flash every time it sees an Earth flash—that is, every 6 min. How does the observer on the distant planet see these flashes? Since Earth flashes and the spaceship flashes travel together at the same speed, c, the observer will see not only Earth flashes every 3 min but the spaceship flashes every 3 min as well. So, although a person on the spaceship emits flashes every 6 min, the observer sees them every 3 min at twice the emitting frequency. So, for a speed of recession where frequency appears halved, frequency appears doubled for the same speed of approach. If the ship were traveling faster so that the frequency of recession were 1/3 or 1/4 as much, then the frequency of approach would be threefold or fourfold, respectively. This reciprocal relationship does not hold for waves that require a medium. In the case of sound waves, for example, a speed that results in a doubling of emitting frequency for approach produces 2/3 (not 1/2) the emitting frequency for recession. So the relativistic Doppler effect differs from the one we experience with sound.

CHECK POINT

1. If the spaceship emits an initial "starting gun" signal followed by a flash every 6 min for an hour, how many flashes will be emitted?
2. The ship sends equally spaced flashes every 6 min while approaching the receiver at constant speed. Will these flashes be equally spaced when they encounter the receiver?
3. If the receiver sees these flashes at 3-min intervals, how much time will elapse between the initial signal and the last flash (in the frame of reference of the receiver)?

Check Your Answers

1. The ship will emit a total of 10 flashes in 1 h, since (60 min)/(6 min) = 10 (11 if the initial signal is counted).
2. Yes; as long as the ship moves at constant speed, the equally spaced flashes will be seen equally spaced but more frequently. (If the ship accelerated while sending flashes, then they would not be seen at equally spaced intervals.)
3. Thirty minutes, since the 10 flashes are coming every 3 min.

Let's apply this doubling and halving of flash intervals to the twins. Suppose the traveling twin recedes from the earthbound twin at the same high speed for 1 hour and then quickly turns around and returns in 1 hour. Follow this line of reasoning with the help of Figure 35.17. The traveling twin takes a round trip of 2 hours, according to all clocks aboard the spaceship. This trip will not be seen to take 2 hours from the Earth frame of reference, however. We can see this with the help of the flashes from the ship's light clock.

As the ship recedes from Earth, it emits a flash of light every 6 minutes. These flashes are received on Earth every 12 minutes. During the hour of going away from

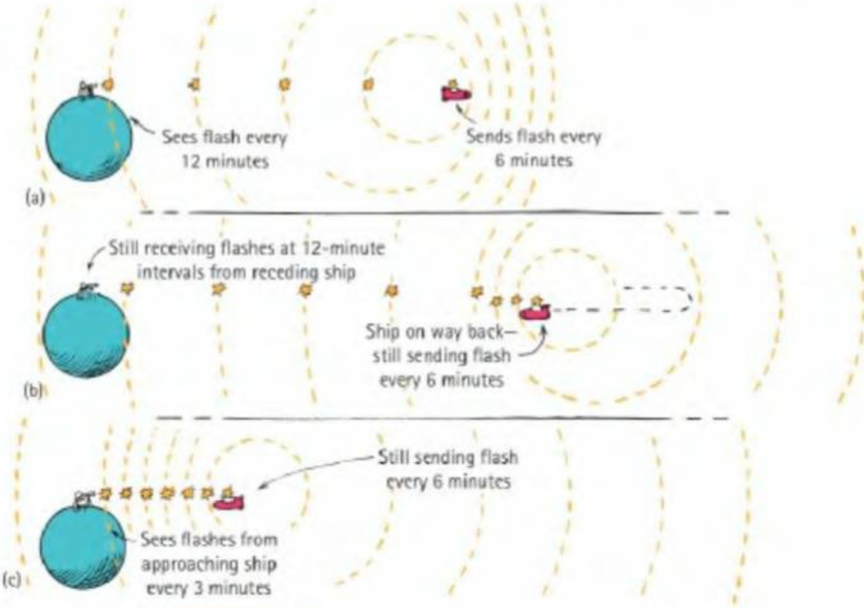


FIGURE 35.17

The spaceship emits flashes every 6 min during a 2-h trip. During the first hour, it recedes from Earth. During the second hour, it approaches Earth.

Earth, a total of 10 flashes are emitted (after the "starting gun" signal). If the ship departs from Earth at noon, clocks aboard the ship read 1 PM when the tenth flash is emitted. What time will it be on Earth when this tenth flash reaches Earth? The answer is 2 PM. Why? Because the time it takes Earth to receive 10 flashes at 12-minute intervals is $10 \times (12 \text{ min})$, or 120 min ($= 2$ h).

Suppose the spaceship is somehow able to turn around "on a dime" (in a negligibly short time) and return at the same high speed. During the hour of return, it emits 10 more flashes at 6-min intervals. These flashes are received every 3 minutes on Earth, so all 10 flashes come in 30 minutes. A clock on Earth will read 2:30 PM when the spaceship completes its 2-hour trip. We see that the earthbound twin has aged half an hour more than the twin aboard the spaceship!

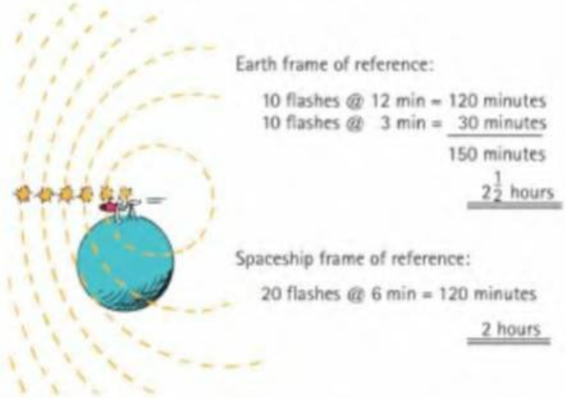


FIGURE 35.18
The trip that takes 2 h in the frame of reference of the spaceship takes 2 1/2 h in Earth's frame of reference.

The result is the same from either frame of reference. Consider the same trip again, only this time with flashes emitted from Earth at regularly spaced 6-minute intervals in Earth time. From the frame of reference of the receding spaceship, these flashes are received at 12-minute intervals (Figure 35.19a). This means that 5 flashes are seen by the spaceship during the hour of receding from Earth. During

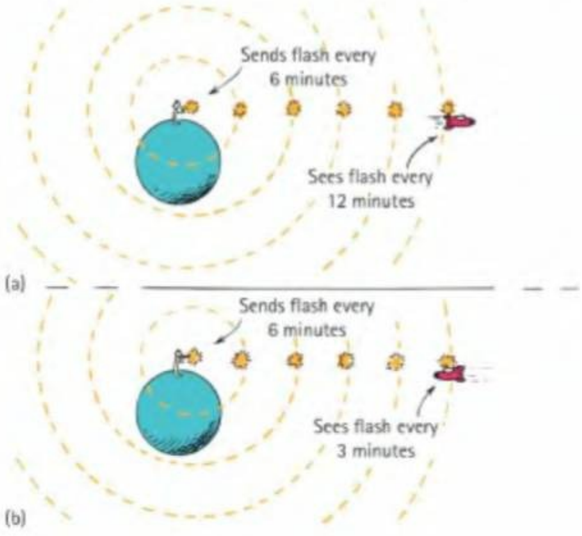


FIGURE 35.19
Flashes sent from Earth at 6-min intervals are seen at 12-min intervals by the ship when it recedes and at 3-min intervals when it approaches.

the spaceship's hour of approaching, the light flashes are seen at 3-minute intervals (Figure 35.19b), so 20 flashes will be seen.

So we see that the spaceship receives a total of 25 flashes during its 2-hour trip. According to clocks on Earth, however, the time it took to emit the 25 flashes at 6-minute intervals was 25 × (6 min), or 150 min (=2.5 h). This is shown in Figure 35.20.

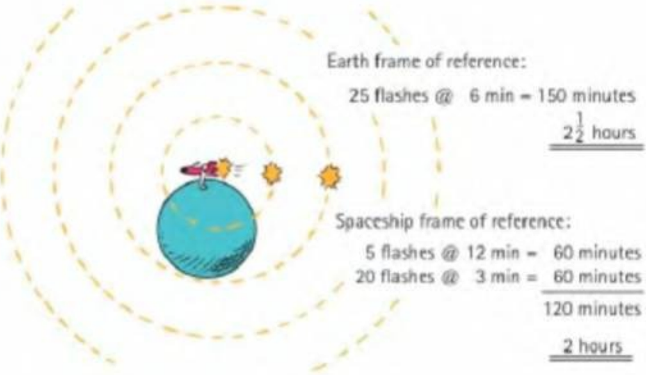


FIGURE 35.20
A time interval of 2 1/2 h on Earth is seen to take 2 h in the spaceship's frame of reference.

So both twins agree on the same results, with no dispute as to who ages more. While the stay-at-home twin remains in a single reference frame, the traveling twin has experienced two different frames of reference, separated by the acceleration of the spaceship in turning around. The spaceship has in effect experienced two different realms of time, while Earth has experienced a still different but single realm of time. The twins can meet again at the same place in space only at the expense of time.

CHECK POINT

Since motion is relative, can't we say as well that the spaceship is at rest and the Earth moves, in which case the twin on the spaceship ages more?

Check Your Answer

No, not unless Earth then undergoes the turnaround and returns, as our spaceship did in the twin-trip example. The situation is not symmetrical, for one twin remains in a single reference frame in spacetime during the trip while the other makes a distinct change of reference frame, as evidenced by the acceleration in turning around.

Addition of Velocities

Most people know that if you walk at 1 km/h along the aisle of a train that moves at 60 km/h, your speed relative to the ground is 61 km/h if you walk in the same direction as the moving train and 59 km/h if you walk in the opposite direction. What most people know is *almost* correct. Taking special relativity into account, one's speeds are *very nearly* 61 km/h and 59 km/h, respectively.

For everyday objects in uniform (nonaccelerating) motion, we ordinarily combine velocities by the simple rule

$$V = v_1 + v_2$$

But this rule does not apply to light, which always has the same velocity, c. Strictly speaking, the above rule is an approximation of the relativistic rule for adding velocities. We'll not treat the long derivation but simply state the rule:

$$V = \frac{v_1 + v_2}{1 + \frac{v_1 v_2}{c^2}}$$

The numerator of this formula makes common sense. But this simple sum of two velocities is altered by the second term in the denominator, which is significant only when both v_1 and v_2 are nearly c.

As an example, consider a spaceship moving away from you at a velocity of $0.5c$. It fires a rocket that thrusts in the same direction, also away from you, at a speed of $0.5c$ relative to itself. How fast does the rocket move relative to you? The nonrelativistic rule would say that the rocket moves at the speed of light in your reference frame. But, in fact,

$$V = \frac{0.5c + 0.5c}{1 + \frac{0.25c^2}{c^2}} = \frac{c}{1.25} = 0.8c$$

which illustrates another consequence of relativity: No material object can travel as fast as, or faster than, light.

Suppose that the spaceship instead fires a pulse of laser light in its direction of travel. How fast does the pulse move in your frame of reference?

$$V = \frac{0.5c + c}{1 + \frac{0.5c^2}{c^2}} = \frac{1.5c}{1.5} = c$$

No matter what the relative velocities between two frames, light moving at c in one frame will be seen to be moving at c in any other frame. If you try chasing light, you can never catch it.

Space Travel

One of the old arguments against the possibility of human interstellar travel was that our life span is too short. It was argued, for example, that the star nearest Earth (after the Sun), Alpha Centauri, is 4 light-years away, and a round-trip even at the speed of light would require 8 years.[3] And even a speed-of-light voyage to the center of our galaxy, 25,000 light-years distant, would require 25,000 years. But these arguments fail to take into account time dilation. Time for a person on Earth and time for a person in a high-speed spaceship are not the same.

A person's heart beats to the rhythm of the realm of spacetime in which it finds itself. And one realm of spacetime seems the same as any other to the heart, but not to an observer who stands outside the heart's frame of reference. For example, astronauts traveling at 99% of c could go to the star Procyon (10.4 light-years distant) and back in 21 Earth years. Because of time dilation, however, only 3 years would pass for the astronauts. This is what all their clocks would tell them—and, biologically, they would be only 3 years older. It would be the space officials greeting them on their return who would be 21 years older!

At higher speeds, the results are even more impressive. At a speed of 99.99% of c, travelers could travel a distance of slightly more than 70 light-years in a single year

[3] A light-year is the distance light travels in 1 year, 9.46×10^{12} km.

FIGURE 35.21

From the Earth frame of reference, light takes 25,000 years to travel from the center of our Milky Way galaxy to our solar system. From the frame of reference of a high-speed spaceship flying outward from the galactic center toward Earth, the trip takes less time. If a frame of reference could be attached to the light itself, the travel time could be reduced to zero.

of their own time; at 99.999% of c, this distance would be pushed appreciably farther than 200 light-years. A 5-year trip for them would take them farther than light travels in 1000 Earth-time years!

Present technology does not permit such journeys. Getting enough propulsive energy and shielding against radiation are both prohibitive problems. Spaceships traveling at relativistic speeds would require billions of times the energy used to put a space shuttle into orbit. Even some kind of interstellar ramjet that scooped up interstellar hydrogen gas for burning in a fusion reactor would have to overcome the enormous retarding effect of scooping up the hydrogen at high speeds. And the space travelers would encounter interstellar particles just as if they had a large particle accelerator pointed at them. No way of shielding such intense particle bombardment for prolonged periods of time is presently known. For the present, interstellar space travel must be relegated to science fiction. Not because of scientific fantasy, but simply because of the impracticality of space travel. Traveling close to the speed of light in order to take advantage of time dilation is completely consistent with the laws of physics.

We can see into the past, but we cannot go into the past. For example, we experience the past when we look at the night skies. The starlight impinging on our eyes left those stars dozens, hundreds, even millions of years ago. What we see is the stars as they were long ago. We are thus eyewitnesses to ancient history—and can only speculate about what may have happened to the stars in the interim.

If we are looking at light that left a star, say, 100 years ago, then it follows that any sighted beings in that solar system are seeing us by light that left *here* 100 years ago and that, further, if they possessed super telescopes, they might very well be able to eyewitness earthly events of a century ago—the aftermath of the American Civil War, for instance. They would see our past, but they would still see events in a forward direction: they would see our clocks running clockwise.

We can speculate about the possibility that time might just as well move counterclockwise into the past as clockwise into the future. Why is it, we might ask, that in space we can move forward or back, left or right, up or down, but we can move only in one direction through time? Quite interestingly, the mathematics of elementary-particle interactions permits "time reversal," although there are some particle interactions that slightly favor one direction in time. Hypothetical particles that can move both faster than light and backward in time are called *tachyons*. In any case, for the complex organism called a human being, time has only one direction.[4]

This conclusion is blithely ignored in a limerick that is a favorite with scientist types:

There was a young lady named Bright
Who traveled much faster than light.
She departed one day
In a relative way
And returned on the previous night.

Even with our heads fairly well into relativity, we may still unconsciously cling to the idea that there is an absolute time and compare all these relativistic effects to it—recognizing that time changes this way and that way for this speed and that speed, yet feeling that there still is some basic or absolute time. We may tend to think that the time we experience on Earth is fundamental and that other times are not. This is understandable: We're earthlings. But the idea is confining. From the point of view of observers elsewhere in the universe, we may be moving at relativistic speeds; they see us living in slow motion. They may see us living lifetimes a hundred times as long as theirs, just as with super telescopes we would see them living lifetimes a hundredfold longer than ours. There is no universally standard time—none.

If traveling backward in time were possible, wouldn't we have tourists from the future?

[4] It has been speculated that if we moved backward through time, we wouldn't know it, for then we would remember our future and would think it was our past!

Century Hopping

Let's push our science fiction to a possible time in the future when the prohibitive problems of energy supplies and of radiation have been overcome and space travel is a routine experience. People will have the option of taking a trip and returning to any future century of their choosing. For example, one might depart from Earth in a high-speed spaceship in the year 2100, travel for 5 years or so, and return in the year 2500. One could live among the earthlings of that period for a while and depart again to try out the year 3000 for style.

People could keep jumping into the future with some expense of their own time—but they could not trip into the past. They could never return to the same era on Earth to which they had bade farewell. Time, as we know it, travels one way—forward. Here on Earth, we move constantly into the future at the steady rate of 24 hours per day. An astronaut leaving on a deep-space voyage must live with the fact that, upon return, much more time will have elapsed on Earth than the astronaut has subjectively and physically experienced during the voyage. The credo of all star travelers, whatever their physiological condition, will be permanent farewell.

We think of time and then we think of the universe. We think of the universe and we wonder about what went on before the universe began. We wonder about what will happen if the universe ceases to exist in time. But the concept of time applies to events and entities within the universe, not to the universe as a whole. Time is "in" the universe; the universe is not "in" time. Without the universe, there is no time; no before, no after. Likewise, space is "in" the universe; the universe is not "in" a region of space. There is no space "outside" the universe. Spacetime exists within the universe. Think about that!

Length Contraction

As objects move through spacetime, space as well as time changes. In a nutshell, space is contracted, making the objects look shorter when they move by us at relativistic speeds. This **length contraction** was first proposed by the physicist George F. FitzGerald and mathematically expressed by another physicist, Hendrik A. Lorentz (mentioned earlier). Whereas these physicists hypothesized that matter contracts, Einstein saw that what contracts is space itself. Nevertheless, because Einstein's formula is the same as Lorentz's, we call the effect the *Lorentz contraction:*

FIGURE 35.22
The Lorentz contraction. The meterstick is measured to be half as long when traveling at 87% of the speed of light relative to the observer.

$$L = L_0\sqrt{1 - \frac{v^2}{c^2}}$$

where v is the relative velocity between the observed object and the observer, c is the speed of light, L is the measured length of the moving object, and L_0 is the measured length of the object at rest.[5]

Suppose that an object is at rest so that $v = 0$. When we substitute $v = 0$ in the Lorentz equation, we find $L = L_0$, as we would expect. When we substitute various large values of v in the Lorentz equation, we begin to see the calculated L get smaller and smaller. At 87% of c, an object would be contracted to half its original length. At 99.5% of c, it would contract to one-tenth its original length. If the object were somehow able to move at c, its length would be zero. This is one of the reasons we say that the speed of light is the upper limit for the speed of any moving object. Another limerick popular with the science heads is this one:

[5]We can express this as $L = \frac{1}{\gamma}L_0$. Where $\frac{1}{\gamma}$ is always 1 or less (because γ is always 1 or greater). Note that we do not explain how the length-contraction equation or other equations come about. We simply state equations as "guides to thinking" about the ideas of special relativity.

There was a young fencer named Fisk,
Whose thrust was exceedingly brisk.
So fast was his action
The Lorentz contraction
Reduced his rapier to a disk.

Time dilation: Moving clocks run slowly. Length contraction: Moving objects are shorter (in the direction of motion).

As Figure 35.23 indicates, contraction takes place only in the direction of motion. If an object is moving horizontally, no contraction takes place vertically.

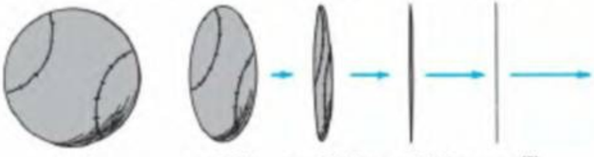


FIGURE 35.23
As speed increases, length in the direction of motion decreases. Lengths in the perpendicular direction do not change.

Length contraction should be of considerable interest to space voyagers. The center of our Milky Way galaxy is 25,000 light-years away. Does this mean that if we traveled in that direction at the speed of light, it would take 25,000 years to get there? From an Earth frame of reference, yes; but to the space voyagers, decidedly not! At the speed of light, the 25,000 light-year distance would be contracted to no distance at all. The imagined space voyagers would arrive there instantly!

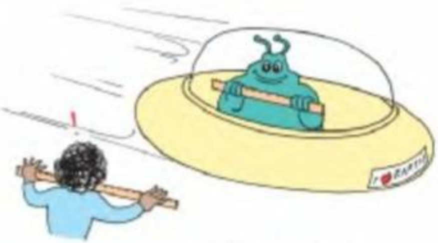


FIGURE 35.24
INTERACTIVE FIGURE
In the frame of reference of our meterstick, its length is 1 m. Observers in a moving frame see *our* metersticks contracted, while we see *their* metersticks contracted. The effects of relativity are always attributed to "the other guy."

For hypothetical travel near the speed of light, length contraction and time dilation are just two faces of the same phenomenon. If astronauts go so fast that they find the distance to the nearest star to be just 1 light-year instead of the 4 light-years measured from Earth, they make the trip in a little more than 1 year. But observers back on Earth say that the clocks aboard the spaceship have slowed so much that they tick off only 1 year in 4 years of Earth time. Both agree on what happens: The astronauts are only a little more than a year older when they reach the star. One set of observers say it's because of length contraction; the other set say it's because of time dilation. Both are right.

If space voyagers are ever able to boost themselves to relativistic speeds, they will find distant parts of the universe drawn closer by space contraction, while observers back on Earth will see the astronauts covering more distance because they age more slowly.

CHECK POINT

A rectangular billboard in space has the dimensions 10 m × 20 m. How fast, and in what direction with respect to the billboard, would a space traveler have to pass for the billboard to appear square?

Check Your Answer

The space traveler would have to travel at $0.87c$ in a direction parallel to the longer side of the board.

Relativistic Momentum

Recall our study of momentum in Chapter 6. We learned that the change of momentum mv of an object is equal to the impulse Ft applied to it: $Ft = \Delta mv$, or, $Ft = \Delta p$, where $p = mv$. If you apply more impulse to an object that is free to move, the object acquires more momentum. Double the impulse, and the momentum doubles. Apply 10 times the impulse, and the object gains 10 times as much momentum. Does this mean that momentum can increase without any limit? The answer is *yes*. Does this mean that speed can also increase without any limit? The answer is *no!* Nature's speed limit for material objects is c.

To Newton, infinite momentum would mean infinite mass or infinite speed. But not so in relativity. Einstein showed that a new definition of momentum is required. It is

$$p = \gamma mv$$

where γ is the Lorentz factor (recall that γ is always 1 or greater). This generalized definition of momentum is valid in all uniformly moving reference frames. *Relativistic momentum* is larger than mv by a factor of γ. For everyday speeds much less than c, γ is nearly equal to 1, so p is nearly equal to mv. Newton's definition of momentum is valid at low speeds. At higher speeds, γ grows dramatically, and so does relativistic momentum. As speed approaches c, γ approaches infinity! No matter how close to c an object is pushed, it would still require infinite impulse to give it the last bit of speed needed to reach c—clearly impossible. Hence we see that no body with mass can be pushed to the speed of light, much less beyond it.

Subatomic particles are routinely pushed to nearly the speed of light. The momenta of such particles may be thousands of times more than the Newtonian expression mv predicts. Classically, the particles behave as if their masses increase with speed. Einstein initially favored this interpretation and later changed his mind to keep mass a constant, a property of matter that is the same in all frames of reference. So it is γ that changes with speed, not mass. The increased momentum of a high-speed particle is evident in the increased "stiffness" of its trajectory. The more momentum it has, the "stiffer" is its trajectory and the harder it is to deflect.

We see this when a beam of electrons is directed into a magnetic field. Charged particles moving in a magnetic field experience a force that deflects them from their normal paths. For small momentum, the path curves sharply. For large momentum, there is greater stiffness and the path curves only a little (Figure 35.26). Even though one particle may be moving only a little faster than another one—say, 99.9% of the speed of light instead of 99% of the speed of light—its momentum will be considerably greater and it will follow a straighter path in the magnetic field. This stiffness must be compensated for in circular accelerators like cyclotrons and synchrotrons, where momentum dictates the radius of curvature. In the linear accelerator shown in Figure 35.25, the particle beam travels in a straight-line path and momentum changes don't produce deviations from a straight-line path. Deviations occur when the beam of electrons is bent at the exit port by magnets, as indicated in Figure 35.26. Whatever the type of particle accelerator, physicists working with subatomic particles every day verify the correctness of the relativistic definition of momentum and the speed limit imposed by nature.

To summarize, we see that, as the speed of an object approaches the speed of light, its momentum approaches infinity—which means there is no way that the speed of light can be reached. There is, however, at least one thing that reaches the speed of light—light itself! But the photons of light are massless, and the equations that apply to them are different. Light travels always at the same speed. So, interestingly, a material particle can never be brought to the speed of light, and light can never be brought to rest.

FIGURE 35.25

The Stanford Linear Accelerator is 3.2 km (2 mi) long. But to electrons moving through it at 0.99999999995c, the accelerator is only 3.2 cm long. The electrons start their journey in the foreground, and they smash into targets, or are otherwise studied, in the experimental areas beyond the freeway (near the top of the photo).

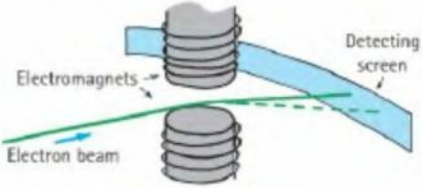


FIGURE 35.26

If the momentum of the electrons were equal to the Newtonian value mv, the beam would follow the dashed line. But because the relativistic momentum γmv is greater, the beam follows the "stiffer" trajectory shown by the solid line.

Mass, Energy, and $E = mc^2$

Einstein linked not only space and time but also mass and energy. A piece of matter, even at rest and not interacting with anything else, has an "energy of being." This is called its *rest energy*. Einstein concluded that it takes energy to make mass and that energy is released if mass disappears. The amount of energy E is related to the amount of mass m by the most celebrated equation of the 20th century:

$$E = mc^2$$

The c^2 is the conversion factor between energy units and mass units. Because of the large magnitude of c, a small mass corresponds to an enormous quantity of energy.[6]

FIGURE 35.27

Saying that a power plant delivers 90 million megajoules of energy to its consumers is equivalent to saying that it delivers 1 gram of energy to its consumers, because mass and energy are equivalent.

Recall from the previous chapter that tiny decreases of nuclear mass in both nuclear fission and nuclear fusion produce enormous releases of energy, all in accord with $E = mc^2$. To the general public, $E = mc^2$ is synonymous with nuclear energy. If we were to weigh a fully fueled nuclear power plant, then weigh it again a week later, we'd find it weighs slightly less—about 1 gram less for every kilogram of fuel that underwent fission in that week. Part of the fuel's mass has been converted to energy. Now, interestingly enough, if we were to weigh a coal-burning power plant and all the coal and oxygen it consumes in a week, and then weigh it again with all the carbon dioxide and other combustion products that came out during the week, we'd also find it all weighs slightly less. Again, mass has been converted to energy. About 1 part in a billion has been converted. Get this: If both plants produce the same amount of energy, the mass change will be the same for both—whether energy is released by nuclear or chemical mass conversion makes no difference. The chief difference lies in the amount of energy released in each individual reaction and the amount of mass involved. Fissioning of a single uranium nucleus releases 10 million times as much energy as the combustion of carbon to produce a single carbon dioxide molecule. Hence, a few truckloads of uranium fuel will power a fission plant while a coal-burning plant consumes many hundred car trainloads of coal.

When we strike a match, phosphorus atoms in the match head rearrange themselves and combine with oxygen in the air to form new molecules. The resulting molecules have very slightly less mass than the separate phosphorus and oxygen molecules. From a mass standpoint, the whole is slightly less than the sum of its parts, by amounts that escape our notice. For all chemical reactions that give off energy, there is a corresponding decrease in mass of about 1 part in a billion.

FIGURE 35.28

In 1 second, 4.5 million tons of mass are converted to radiant energy in the Sun. The Sun is so massive, however, that in 1 million years only 1 ten-millionth of the Sun's mass will have been converted to radiant energy.

For nuclear reactions, a decrease in mass by 1 part in a thousand can be directly measured by a variety of devices. This decrease of mass in the Sun by the process of thermonuclear fusion bathes the solar system with radiant energy and nourishes life. The present stage of thermonuclear fusion in the Sun has been going on for the past 5 billion years, and there is sufficient hydrogen fuel for fusion to last another 5 billion years. It is nice to have such a big Sun!

The equation $E = mc^2$ is not restricted to chemical and nuclear reactions. A change in energy of any object at rest is accompanied by a change in its mass. The filament of a lightbulb energized with electricity has more mass than when it is turned off. A hot cup of tea has more mass than the same cup of tea when cold. A wound-up spring clock has more mass than the same clock when unwound. But these examples involve incredibly small changes in mass—far too small to be measured. Even the much larger changes of mass in radioactive change were not

[6]When c is in meters per second and m is in kilograms, then E will be in joules. If the equivalence of mass and energy had been understood long ago when physics concepts were first being formulated, there would probably be no separate units for mass and energy. Furthermore, with a redefinition of space and time units, c could equal 1, and $E = mc^2$ would simply be $E = m$.

measured until after Einstein predicted the mass–energy equivalence. Now, however, mass-to-energy and energy-to-mass conversions are measured routinely.

Consider a coin with a mass of 1 g. You'd expect 2 of the same coins to have a mass of 2 g, 10 coins to have a mass of 10 g, and 1,000 coins piled in a box to have a mass of 1 kg. Not so if the coins attract or repel each other. Suppose, for example, that each coin carries a negative electric charge so that each coin repels all other coins. Then forcing them together in the box takes work. This work adds to the mass of the collection. So a box containing 1,000 negatively charged coins has more than 1 kg of mass. If, on the other hand, the coins all attracted one another (as nucleons in the nucleus attract one another), it takes work to separate them; then a box of 1,000 coins would have a mass less than 1 kg. So the mass of an object is not necessarily equal to the sum of the masses of its parts, as we know from measuring the masses of nuclei. The effect would be dramatically enormous if we could deal with bare charged particles. If we could force together a number of electrons whose masses add separately to 1 g into a 10-cm-diameter sphere, the collection would have a mass of 40 billion kg! The equivalence of mass and energy is indeed profound.

Before physicists came to understand that the electron is a fundamental particle with no measurable radius, some speculated that it had a certain size and that its mass is merely a measure of how much work was required to compress its charge to that size.[7]

In ordinary units of measurement, the speed of light c is a large quantity and its square is even larger—hence a small amount of mass stores a large amount of energy. The quantity c^2 is a "conversion factor." It converts the measurement of mass to the measurement of equivalent energy. Or it is the ratio of rest energy to mass; $E/m = c^2$. Its appearance in either form of this equation has nothing to do with light and nothing to do with motion. The magnitude of c^2 is 90 quadrillion (9×10^{16}) J/kg. One kilogram of matter has an "energy of being" equal to 90 quadrillion J. Even a speck of matter with a mass of only 1 mg has a rest energy of 90 billion J.

The equation $E = mc^2$ is more than a formula for the conversion of mass into other kinds of energy, or vice versa. It states even more: that energy and mass are the *same thing*. Mass is congealed energy. If you want to know how much energy is in a system, measure its mass. For an object at rest, its energy *is* its mass. Energy, like mass, exhibits inertia. Shake a massive object back and forth; it is energy itself that is hard to shake.

$E = mc^2$ says that energy and mass are related. Mass is congealed energy.

The first evidence for the conversion of radiant energy to mass was provided in 1932 by the American physicist Carl Anderson. He discovered the *positron* by the track it left in a cloud chamber. The positron is the *antiparticle* of the electron, equal in mass and spin to the electron but opposite in charge. When a high-frequency photon comes close to an atomic nucleus, it can create an electron and a positron together as a pair, thus creating mass. The created particles fly apart. The positron is not part of normal matter because it lives such a short time. As soon as it encounters an electron, the pair is annihilated, sending out two gamma rays in the process. Then mass is converted back to radiant energy.[8]

[7] San Francisco Sidewalk Astronomer John Dobson speculates that, just as a clock becomes more massive when we do work on it by winding it against the resistance of its spring, the mass of the entire universe is nothing more than the energy that has gone into winding it up against mutual gravitation. In this view, the mass of the universe is equivalent to the work done in spreading it out.

[8] Recall that the energy of a photon is $E = hf$ and that the mass energy of a particle is $E = mc^2$. High-frequency photons routinely convert their energy to mass when they produce pairs of particles in nature—and in accelerators, where the processes can be observed. Why pairs? Mainly because that's the only way the conservation of charge is not violated. So, when an electron is created, an antiparticle positron is created also. Equating the two equations, $hf = 2mc^2$, where m is the mass of a particle (or antiparticle), we see the minimum frequency of a gamma ray for the production of a particle pair is $f = 2mc^2/h$.

CHECK POINT

Can we look at the equation $E = mc^2$ in another way and say that matter transforms into pure energy when it is traveling at the speed of light squared?

Check Your Answer

No, no, no! Matter cannot be made to move at the speed of light, let alone the speed of light squared (which is not a speed!). The equation $E = mc^2$ simply means that energy and mass are "two sides of the same coin."

The Correspondence Principle

We introduced the correspondence principle in Chapter 32. Recall that it states that any new theory or any new description of nature must agree with the old where the old gives correct results. If the equations of special relativity are valid, they must correspond to those of classical mechanics when speeds much less than the speed of light are considered.

How nice that Einstein's equations for time, length, and momentum correspond to their classical expressions for everyday speeds.

The relativity equations for time, length, and momentum are

$$t = \frac{t_0}{\sqrt{1 - \frac{v^2}{c^2}}} = \gamma t_0$$

$$L = L_0\sqrt{1 - \frac{v^2}{c^2}} = L_0/\gamma$$

$$p = \frac{mv}{\sqrt{1 - \frac{v^2}{c^2}}} = \gamma mv$$

Note that these equations each reduce to Newtonian values for speeds that are very small compared with c. Then the ratio v^2/c^2 is very small and, for everyday speeds, may be taken to be zero. The relativity equations become

$$t = \frac{t_0}{\sqrt{1 - 0}} = t_0$$

$$L = L_0\sqrt{1 - 0} = L_0$$

$$p = \frac{mv}{\sqrt{1 - 0}} = mv$$

So, for everyday speeds, the momentum, length, and time of moving objects are essentially unchanged. The equations of special relativity hold for all speeds, although they differ appreciably from classical equations only for speeds near the speed of light.

Einstein's theory of relativity has raised many philosophical questions. What, exactly, is time? Can we say that it is nature's way of seeing to it that everything does not all happen at once? And why does time seem to move in one direction? Has it always moved *forward*? Are there other parts of the universe in which time moves *backward*? Is it likely that our three-dimensional perception of a four-dimensional world is only a beginning? Could there be a fifth dimension? A sixth dimension? A seventh dimension? And, if so, what would the nature of these dimensions be? Perhaps these unanswered questions will be answered by the physicists of tomorrow. How exciting!

SUMMARY OF TERMS

Frame of reference A vantage point (usually a set of coordinate axes) with respect to which position and motion may be described.

Postulates of the special theory of relativity (1) All laws of nature are the same in all uniformly moving frames of reference. (2) The speed of light in free space has the same measured value regardless of the motion of the source or the motion of the observer; that is, the speed of light is a constant.

Simultaneity Occurring at the same time. Two events that are simultaneous in one frame of reference need not be simultaneous in a frame moving relative to the first frame.

Spacetime The four-dimensional continuum in which all events take place and all things exist: Three dimensions are the coordinates of space, and the fourth is time.

Time dilation The slowing of time as a result of speed.

Length contraction The contraction of space in an observer's direction of motion as a result of speed.

REVIEW QUESTIONS

Motion Is Relative

1. If you walk at 1 km/h down the aisle of a train that moves at 60 km/h, what is your speed relative to the ground?
2. In the previous question, is your approximate speed relative to the Sun as you walk down the aisle of the train slightly more or very much more?

Michelson–Morley Experiment

3. What hypothesis did G. F. FitzGerald make to explain the findings of Michelson and Morley?
4. What classical idea about space and time was rejected by Einstein?

Postulates of the Special Theory of Relativity

5. Cite two examples of Einstein's first postulate.
6. Cite one example of Einstein's second postulate.

Simultaneity

7. Inside the moving compartment of Figure 35.4, light travels a certain distance to the front end and a certain distance to the back end of the compartment. How do these distances compare as seen in the frame of reference of the moving rocket?
8. How do the distances in Question 7 compare as seen in the frame of reference of an observer on a stationary planet?

Spacetime

9. How many coordinate axes are usually used to describe three-dimensional space? What does the fourth dimension measure?
10. Under what condition will you and a friend share the same realm of spacetime? When will you not share the same realm?
11. What is special about the ratio of the distance traveled by a flash of light and the time the light takes to travel this distance?

Time Dilation

12. Time is required for light to travel along a path from one point to another. If this path is seen to be longer because of motion, what happens to the time it takes for light to travel this longer path?
13. What do we call the "stretching out" of time?
14. What is an algebraic expression for the Lorentz factor γ (gamma)? Why is γ never less than 1?
15. How do measurements of time differ for events in a frame of reference that moves at 50% the speed of light relative to us? At 99.5% the speed of light relative to us?
16. What is the evidence for time dilation?

The Twin Trip

17. When a flashing light approaches you, each flash that reaches you has a shorter distance to travel. What effect does this have on how frequently you receive the flashes?
18. When a flashing light source approaches you, does the speed of light or the frequency of light—or both—increase?
19. If a flashing light source moves toward you fast enough so that the duration between flashes is half as long, how long will be the duration between flashes if the source is moving away from you at the same speed?
20. How many frames of reference does the stay-at-home twin experience in the twin trip? How many frames of reference does the traveling twin experience?

Addition of Velocities

21. What is the maximum value of v_1v_2/c^2 in an extreme situation? What is the smallest value?
22. Is the relativistic rule

$$V = \frac{v_1 + v_2}{1 + \frac{v_1 v_2}{c^2}}$$

consistent with the fact that light can have only one speed in all uniformly moving reference frames?

Space Travel

23. What two main obstacles prevent us from traveling today throughout the galaxy at relativistic speeds?
24. What is the universal standard of time?

Length Contraction

25. How long would a meterstick appear to be if it were traveling like a properly thrown spear at 99.5% the speed of light?
26. How long would the meterstick in the previous question appear to be if it were traveling with its length perpendicular to its direction of motion? (Why is your answer different from your answer to the previous question?)
27. If you were traveling in a high-speed rocket ship, would metersticks on board appear to you to be contracted? Defend your answer.

Relativistic Momentum

28. What would be the momentum of an object pushed to the speed of light?
29. When a beam of charged particles moves through a magnetic field, what is the evidence that particles in the beam have momenta greater than the value mv?

Mass, Energy, and $E = mc^2$

30. Compare the amount of mass converted to energy in nuclear reactions and in chemical reactions.
31. How does the energy from the fissioning of a single uranium nucleus compare with the energy from the combustion of a single carbon atom?
32. Does the equation $E = mc^2$ apply only to nuclear and chemical reactions?
33. What is the evidence for $E = mc^2$ in cosmic-ray investigations?

The Correspondence Principle

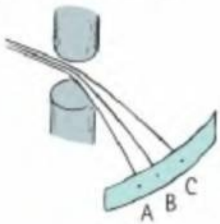
34. How does the correspondence principle relate to special relativity?
35. Do the relativity equations for time, length, and momentum hold true for everyday speeds? Explain.

PROJECT

Text Grandma and explain how Einstein's theories of relativity concern the fast and the big—that relativity is not only "out there" but that it affects this world. Tell her how these ideas stimulate your quest for more knowledge about the universe. Impress Grandma by proper use of the words *there*, *they're*, and *their* in your text.

RANKING

1. Electrons are fired at different speeds through a magnetic field and are bent from their straight-line paths to hit the detector at the points shown. Rank the speeds of the electrons from highest to lowest.



2. To an Earth observer, metersticks on three spaceships are seen to have these lengths. Rank the speeds of the spaceships relative to Earth from highest to lowest.

EXERCISES

1. The idea that force causes acceleration doesn't seem strange. This and other ideas of Newtonian mechanics are consistent with our everyday experience. But the ideas of relativity do seem odd and more difficult to grasp. Why is this?
2. If you were in a smooth-riding train with no windows, could you sense the difference between uniform motion and rest? Between accelerated motion and rest? Explain how you could make such a distinction with a bowl filled with water.
3. A person riding on the roof of a freight train throws a ball forward. (a) Neglecting air drag and relative to the ground, is the ball moving faster or slower when the train is moving than when it is standing still? (b) Relative to the

freight car, is the ball moving faster or slower when the train is moving than when the train is standing still?

4. Suppose instead that the person riding on top of the freight car shines a searchlight beam in the direction in which the train is traveling. Compare the speed of the light beam relative to the ground when the train is at rest and when it is in motion. How does the behavior of the light beam differ from the behavior of the ball in Exercise 3?
5. Why did Michelson and Morley at first consider their experiment a failure? (Have you ever encountered other examples where failure has to do not with the lack of ability, but with the impossibility of the task?)
6. When you drive down the highway, you are moving through space. What else are you moving through?
7. In Chapter 26, we learned that light travels more slowly in glass than in air. Does this contradict Einstein's second postulate?
8. Astronomers view light coming from distant galaxies moving away from Earth at speeds greater than 10% the speed of light. How fast does this light meet the telescopes of the astronomers?
9. Does special relativity allow *anything* to travel faster than light? Explain.
10. When a light beam approaches you, its frequency is greater and its wavelength less. Does this contradict the postulate that the speed of light cannot change? Defend your answer.
11. The beam of light from a laser on a rotating turntable casts into space. At some distance, the beam moves across space faster than c. Why does this not contradict relativity?
12. Can an electron beam sweep across the face of a cathode-ray tube at a speed greater than the speed of light? Explain.
13. Consider the speed of the point where scissors blades meet when the scissors are closed. The closer the blades are to being closed, the faster the point moves. The point could, in principle, move faster than light. Likewise for the speed of the point where an ax meets wood when the ax blade meets the wood not quite horizontally; the contact point travels faster than the ax. Similarly, a pair of laser beams that are crossed and moved toward being parallel produce a point of intersection that can move faster than light. Why do these examples not contradict special relativity?
14. If two lightning bolts hit exactly the same place at exactly the same time in one frame of reference, is it possible that observers in other frames will see the bolts hitting at different times or at different places?
15. Event A occurs before event B in a certain frame of reference. How could event B occur before event A in some other frame of reference?
16. Suppose that the lightbulb in the rocket ship in Figures 35.4 and 35.5 is closer to the front than to the rear of the compartment so that the observer in the ship sees the light reaching the front before it reaches the back. Is it still possible that the outside observer will see the light reaching the back first?
17. The speed of light is a speed limit in the universe—at least for the four-dimensional universe we comprehend. No material particle can attain or surpass this limit even when a continuous, unremitting force is exerted on it. What evidence supports this?
18. Since there is an upper limit on the speed of a particle, does it follow that there is also an upper limit on its momentum, and, therefore, on its kinetic energy? Explain.
19. Light travels a certain distance in, say, 20,000 years. How is it possible that an astronaut, traveling slower than light, could go as far in 20 years of her life as light travels in 20,000 years?
20. Is it possible in principle for a human being who has a life expectancy of 70 years to make a round-trip journey to a part of the universe thousands of light-years distant? Explain.
21. A twin who makes a long trip at relativistic speeds returns younger than her stay-at-home twin sister. Could she return before her twin sister was born? Defend your answer.
22. Is it possible for a son or daughter to be biologically older than his or her parents? Explain.
23. If you were in a rocket ship traveling away from Earth at a speed close to the speed of light, what changes would you note in your pulse? In your volume? Explain.
24. If you were on Earth monitoring a person in a rocket ship traveling away from Earth at a speed close to the speed of light, what changes would you note in his pulse? In his volume? Explain.
25. Due to length contraction, you see people in a spaceship passing by you as being slightly narrower than they normally appear. How do these people view you?
26. Because of time dilation, you observe the hands of your friend's watch to be moving slowly. How does your friend view your watch—as running slowly, running rapidly, or neither?
27. Does the equation for time dilation show dilation occurring for all speeds, whether slow or fast? Explain.
28. If you lived in a world where people regularly traveled at speeds near the speed of light, why would it be risky to make a dental appointment for 10:00 AM next Thursday?
29. How do the measured densities of a body compare at rest and in motion?
30. If stationary observers measure the shape of a passing object to be exactly circular, what is the shape of the object according to observers on board the object, traveling with it?
31. The formula relating speed, frequency, and wavelength of electromagnetic waves, $v = f\lambda$, was known before relativity was developed. Relativity has not changed this equation, but it has added a new feature to it. What is that feature?
32. Light is reflected from a moving mirror. How is the reflected light different from the incident light, and how is it the same?
33. As a meterstick moves past you, your measurements show its momentum to be twice its classical momentum and its length to be 1 m. In what direction is the stick pointing?
34. In the preceding exercise, if the stick is moving in a direction along its length (like a properly thrown spear), how long will you measure its length to be?
35. If a high-speed spaceship appears shrunken to half its normal length, how does its momentum compare with the classical formula $p = mv$?
36. How can the momentum of a particle increase by 5% with only a 1% increase in speed?

37. The 2-mile linear accelerator at Stanford University in California "appears" to be less than a meter long to the electrons that travel in it. Explain.
38. Electrons end their trip in the Stanford accelerator with an energy thousands of times greater than their initial rest energy. In theory, if you could travel with them, would you notice an increase in their energy? In their momentum? In your moving frame of reference, what would be the approximate speed of the target they are about to hit?
39. Two safety pins, identical except that one is latched and one is unlatched, are placed in identical acid baths. After the pins are dissolved, what, if anything, is different about the two acid baths?
40. A chunk of radioactive material encased in an idealized, perfectly insulating blanket gets warmer as its nuclei decay and release energy. Does the mass of the radioactive material and the blanket change? If so, does it increase or decrease?
41. The electrons that illuminate the screen in the picture tube of yesterday's TV sets travel at nearly one-fourth the speed of light and possess nearly 3% more energy than hypothetical nonrelativistic electrons traveling at the same speed. Does this relativistic effect tend to increase or decrease the electric bill?
42. Muons are elementary particles that are formed high in the atmosphere by the interactions of cosmic rays with atomic nuclei up there. Muons are radioactive and have average lifetimes of about two-millionths of a second. Even though they travel at almost the speed of light, very few should be detected at sea level after traveling through the atmosphere—at least according to classical physics. Laboratory measurements, however, show that muons in great number do reach Earth's surface. What is the explanation?
43. How might the idea of the correspondence principle be applied outside the field of physics?
44. What does the equation $E = mc^2$ mean?
45. According to $E = mc^2$, how does the amount of energy in a kilogram of feathers compare with the amount of energy in a kilogram of iron?
46. Does a fully charged flashlight battery weigh more than the same battery when dead? Defend your answer.
47. When we look out into the universe, we see into the past. John Dobson, founder of the San Francisco Sidewalk Astronomers, says that we cannot even see the backs of our own hands *now*—in fact, we can't see anything *now*. Do you agree? Explain.
48. One of the fads of the future might be "century hopping," where occupants of high-speed spaceships would depart from Earth for several years and return centuries later. What are the present-day obstacles to such a practice?
49. Is the statement by the philosopher Kierkegaard that "Life can only be understood backwards; but it must be lived forwards" consistent with the theory of special relativity?
50. Make up four multiple-choice questions, one each that would check a classmate's understanding of (a) time dilation, (b) length contraction, (c) relativistic momentum, and (d) $E = mc^2$.

PROBLEMS

Recall, from this chapter, that the factor gamma (γ) governs both time dilation and length contraction, where

$$\gamma = \frac{1}{\sqrt{1 - \left(\frac{v^2}{c^2}\right)}}$$

When you multiply the time in a moving frame by γ, you get the longer (dilated) time in your fixed frame. When you divide the length in a moving frame by γ, you get the shorter (contracted) length in your fixed frame.

1. Consider a high-speed rocket ship equipped with a flashing light source. If the frequency of flashes seen on an approaching ship is twice what it was when the ship was a fixed distance away, by how much is the period (time interval between flashes) changed? Is this period constant for a constant relative speed? For accelerated motion? Defend your answer.
2. A starship passes Earth at 80% of the speed of light and sends a drone ship forward at half the speed of light relative to itself. Show that the drone travels at 93% the speed of light relative to Earth.
3. Pretend that the starship in the previous problem is somehow traveling at c with respect to Earth and it fires a drone forward at speed c with respect to itself. Use the equation for the relativistic addition of velocities to show that the speed of the drone with respect to Earth is still c.
4. A passenger on an interplanetary express bus traveling at $v = 0.99c$ takes a 5-minute catnap, according to her watch. Show that her catnap from the vantage point of a fixed planet lasts 35 minutes.
5. According to Newtonian mechanics, the momentum of the bus in the preceding problem is $p = mv$. According to relativity, it is $p = \gamma mv$. How does the actual momentum of the bus moving at $0.99c$ compare with the momentum it would have if classical mechanics were valid? How does the momentum of an electron traveling at $0.99c$ compare with its classical momentum?
6. The bus in the previous problems is 70 feet long, according to its passengers and driver. Show that its length is seen as slightly less than 10 feet from a vantage point on a fixed planet.
7. If the bus in Problem 4 were to slow to a "mere" 10% of the speed of light, show that you would measure the passenger's catnap to last slightly more than 5 minutes.
8. If the bus driver in Problem 4 decided to drive at 99.99% of the speed of light in order to gain some time, show that you'd measure the length of the bus to be a little less than 1 foot.

9. Assume that rocket taxis of the future move about the solar system at half the speed of light. For a 1-hour trip as measured by a clock in the taxi, a driver is paid 10 stellars. The taxi-driver's union demands that pay be based on Earth time instead of taxi time. If their demand is met, show that the new payment for the same trip would be 11.5 stellars.

10. The fractional change of reacting mass to energy in a fission reactor is about 0.1%, or 1 part in a thousand. For each kilogram of uranium that undergoes fission, how much energy is released? If energy costs 3 cents per megajoule, how much is this energy worth in dollars?

CHAPTER 35 ONLINE RESOURCES

PhysicsPlace.com

Interactive Figures

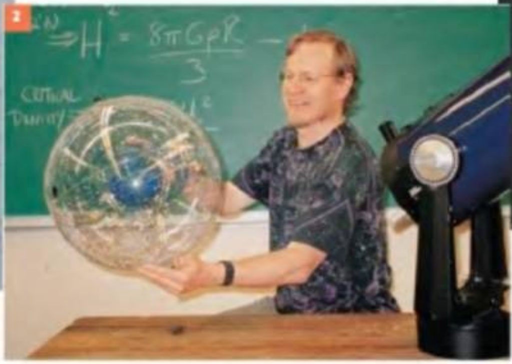
- 35.9, 35.10, 35.24

Quizzes

Flashcards

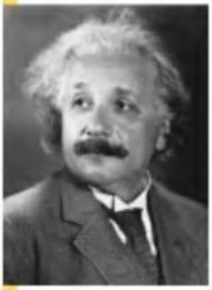
Links

36 General Theory of Relativity



1 When your Global Positioning System (GPS) unit tells you where you are, thank Einstein. 2 Richard Crowe kicks off a lecture on general relativity with a celestial sphere. 3 When he and other astrophysicists make measurements of far-off galactic events, they also thank Einstein.

When Einstein was a young student he cut many lectures, preferring to study on his own, and in 1900 he succeeded in passing his examinations by cramming with the help of a friend's meticulous notes. He said later of this, ". . . after I had passed the final examination, I found the consideration of any scientific problem distasteful to me for an entire year." During this year he became a citizen of Switzerland; he accepted a temporary summer teaching position and tutored two young high school students. He advised their father, a high school teacher himself, to remove the boys from school, where, he maintained, their natural curiosity was being destroyed. Einstein's job as a tutor was short-lived.



It was not until two years after graduation that he got a steady job, as a patent examiner at the Swiss Patent Office in Berne. Einstein held this position for over seven years. He found the work rather interesting, sometimes stimulating his scientific imagination, but mainly freeing him of financial worries while providing time to ponder the problems in physics that puzzled him.

With no academic connections whatsoever, and with essentially no contact with other physicists, he laid out the main lines along which 20th-century theoretical physics has developed. In 1905, at the age of 26, he earned his Ph.D. in physics and published four major papers. The first was on the quantum theory of light, including an explanation of the photoelectric effect, for which he won the 1921 Nobel Prize in Physics. The second paper was on the statistical aspects of molecular theory and Brownian motion, a proof for the existence of atoms. His third and most famous paper was on special relativity. In a follow-up fourth paper he presented the famous $E = mc^2$.

Then came ten years of intense work, leading in 1915 to the **general theory of relativity** in which Einstein presented a new theory of gravitation that included Newton's theory as a special case. These trailblazing papers have greatly affected the course of modern physics.

Einstein's concerns were not limited to physics. He lived in Berlin during World War I and denounced the German militarism of his time. He publicly expressed his deeply felt conviction that warfare should be abolished and an international organization founded to govern disputes between nations. In 1933, while Einstein was visiting the United States, Hitler came to power. Einstein spoke out against Hitler's racial and political policies and resigned his position at the University of Berlin. No longer safe in Germany, Einstein came to the United States and accepted a research position at the Institute for Advanced Study in Princeton, New Jersey.

In 1939, one year before Einstein became an American citizen, and after German scientists fissioned the uranium atom, he was urged by several prominent Hungarian-American scientists to write the famous letter to President Roosevelt pointing out the scientific possibilities of a nuclear bomb. Einstein was a pacifist, but the thought of Hitler developing such a bomb prompted his action. The outcome was the development of the first nuclear bomb, which, ironically, was detonated on Japan after the fall of Germany.

Einstein believed that the universe is indifferent to the human condition and stated that if humanity were to continue, it must create a moral order. He intensely advocated world peace through nuclear disarmament. Nuclear bombs, Einstein remarked, had changed everything but our way of thinking.

Science philosopher C. P. Snow, who was acquainted with Einstein, in a review of *The Born–Einstein Letters, 1916–1955*, says this of him: "Einstein was the most powerful mind of the twentieth century, and one of the most powerful that ever lived. He was more than that. He was a man of enormous weight of personality, and perhaps most of all, of normal stature . . . I have met a number of people whom the world calls great; of these, he was by far, by an order of magnitude, the most impressive. He was—despite the warmth, the humanity, the touch of the comedian—the most different from other men."

Einstein was more than a great scientist; he was a man of unpretentious disposition with a deep concern for the welfare of his fellow beings. The choice of Einstein as the person of the century by *Time* magazine at the end of the 1900s was most appropriate—and noncontroversial.

Reference Frames—Nonaccelerated and Accelerated

Recall that Einstein postulated, in 1905, that no observation made inside an enclosed chamber could determine whether the chamber is at rest or moving with constant velocity; that is, no mechanical, electrical, optical, or any other physical measurement that one could perform inside a closed compartment in a smoothly riding train traveling along a straight track (or in an airplane flying through still air with the window curtains drawn) could possibly give any information as to whether the train was moving or at rest (or whether the plane was airborne or at rest on the runway). But if the track were not smooth and straight (or if the air were turbulent), the situation would be entirely different: Uniform motion would give way to accelerated motion, which would be easily noticed. Einstein's conviction that the laws of nature should be expressed in the same form in every frame of reference, accelerated as well as nonaccelerated, was the primary motivation that led him to the general theory of relativity.

fyi

- Special relativity is "special" in the sense that it deals with uniformly moving reference frames—ones that aren't accelerated. General relativity is "general" and deals also with accelerating reference frames. The general theory of relativity presents a new theory of gravity.

FIGURE 36.1

Everything is weightless on the inside of a nonaccelerating spaceship far away from gravitational influences.

Principle of Equivalence

Long before there were real spaceships, Einstein could imagine himself in a vehicle far away from gravitational influences. In such a spaceship at rest or in uniform motion relative to the distant stars, he and everything within the ship would float freely; there would be no "up" and no "down." But, when the rocket motors were turned on and the ship accelerated, things would be different; phenomena similar to gravity would be observed. The wall adjacent to the rocket motors would push up against any occupants and become the floor, while the opposite wall would become the

FIGURE 36.2

When the spaceship accelerates, an occupant inside feels "gravity."

ceiling. Occupants in the ship would be able to stand on the floor and even jump up and down. If the acceleration of the spaceship were equal to *g*, the occupants could well be convinced the ship was not accelerating but was at rest on the surface of Earth.

To examine this new "gravity" in an accelerating spaceship, let's consider the consequence of dropping two balls inside the spaceship, one ball of wood and the other of lead. When the balls are released, they continue to move upward side by side with the velocity the ship had at the moment of release. If the ship were moving at *constant velocity* (zero acceleration), the balls would remain suspended in the same place because they and the ship move the same distance in any given time interval. But because the ship is accelerating, the floor moves upward faster than the balls, with the result that the floor soon catches up with the balls (Figure 36.3). Both balls, regardless of their mass, meet the floor at the same time. Remembering Galileo's demonstration at the Leaning Tower of Pisa, occupants of the ship might be prone to attribute their observations to the force of gravity.

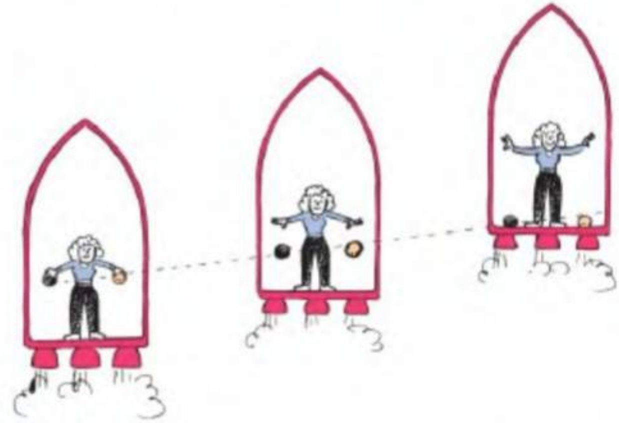


FIGURE 36.3

To an observer inside the accelerating ship, a lead ball and a wood ball appear to fall together when released.

The two interpretations of the falling balls are equally valid, and Einstein incorporated this equivalence, or impossibility of distinguishing between gravitation and acceleration, in the foundation of his general theory of relativity. The **principle of equivalence** states that observations made in an accelerated reference frame are indistinguishable from observations made in a Newtonian gravitational field. This equivalence would be interesting but not revolutionary if it could be applied only to mechanical phenomena, but Einstein went further and stated that the principle holds for all natural phenomena; it holds for optical and all electromagnetic phenomena as well.

An incorrect hypothesis, rightly treated, can sometimes produce more new useful information than unguided observation.

CHECK POINT

If you drop a ball inside a spaceship at rest on a launching pad, you'll see it accelerate to the floor. Far away from Earth, how else could you see the ball do the same?

Check Your Answer

You could also see the ball accelerate to the floor if your spaceship accelerated at *g*.

Bending of Light by Gravity

A ball thrown sideways in a stationary spaceship in a gravity-free region will follow a straight-line path relative both to an observer inside the ship and to a stationary observer outside the spaceship. But if the ship is accelerating, the floor overtakes the ball just as in our previous example. An observer outside the ship still sees a straight-line path, but to an observer in the accelerating ship, the path is curved; it is a parabola (Figure 36.4). The same holds true for a beam of light.

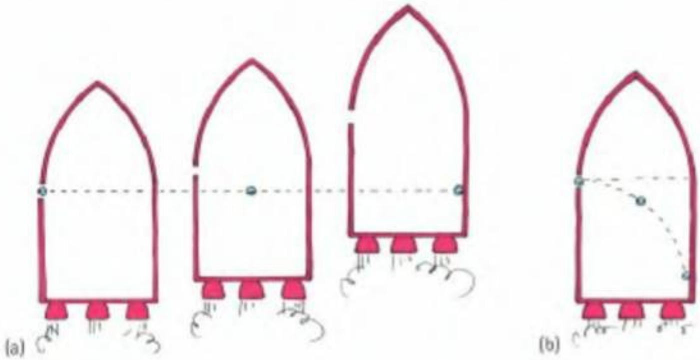


FIGURE 36.4

(a) An outside observer sees a horizontally thrown ball travel in a straight line. Because the ship is moving upward while the ball travels horizontally, the ball strikes the wall below a point opposite the window. (b) To an inside observer, the ball bends as if in a gravitational field.

Imagine that a light ray enters the spaceship horizontally through a side window, passes through a sheet of glass in the middle of the cabin, leaving a visible trace, and then reaches the opposite wall, all in a very short time. The outside observer sees that the light ray enters the window and moves horizontally along a straight line with constant velocity toward the opposite wall. But the spaceship is accelerating upward. During the time it takes for the light to reach the glass sheet, the spaceship moves up some distance, and, during the equal time for the light to continue to the far wall, the spaceship moves up a greater distance. So, to observers in the spaceship the light has followed a downward curving path (Figure 36.5). In this accelerating frame of reference, the light ray is deflected downward toward the floor, just as the thrown ball in Figure 36.4 is deflected. The curvature of the slow-moving ball is very pronounced; but if the ball were somehow thrown horizontally across the spaceship cabin at a velocity equal to that of light, its curvature would match the light ray's curvature.

Einstein actually imagined himself in elevators, certainly more common at the time than spaceships!

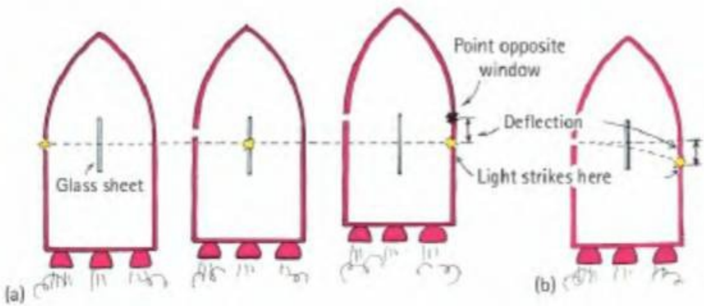


FIGURE 36.5

(a) An outside observer sees light travel horizontally in a straight line, and, like the ball in the previous figure, it strikes the wall slightly below a point opposite the window. (b) To an inside observer, the light bends as if responding to a gravitational field.

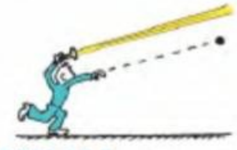


FIGURE 36.6

The trajectory of a flashlight beam is identical to the trajectory that a baseball would have if it could be "thrown" at the speed of light. Both paths curve equally in a uniform gravitational field.

An observer inside the ship feels "gravity" because of the ship's acceleration. The observer is not surprised by the deflection of the thrown ball, but might be quite surprised by the deflection of light. According to the principle of equivalence, if light is deflected by acceleration, it must be deflected by gravity. Yet how can gravity bend light? According to Newton's physics, gravitation is an interaction between masses; a moving ball curves because of the interaction between its mass and the mass of Earth. But what of light, which is pure energy and is massless? Einstein's answer was that light may be massless, but it's not "energyless." Gravity pulls on the energy of light because energy is equivalent to mass.

This was Einstein's first answer, before he fully developed the general theory of relativity. Later, he gave a deeper explanation—that light bends when it travels in a spacetime geometry that is bent. We shall see later in this chapter that the presence of mass results in the bending or warping of spacetime. The mass of Earth is too small to appreciably warp the surrounding spacetime, which is practically flat, so any such bending of light in our immediate environment is not ordinarily detected. Close to bodies of mass much greater than Earth's, however, the bending of light is large enough to detect.

Einstein predicted that starlight passing close to the Sun would be deflected by an angle of 1.75 seconds of arc—large enough to be measured. Although stars are not visible when the Sun is in the sky, the deflection of starlight can be observed during an eclipse of the Sun. (Measuring this deflection has become a standard practice at every total eclipse since the first measurements were made during the total eclipse of 1919.) A photograph of a darkened sky around the eclipsed Sun reveals the presence of the nearby bright stars. The positions of the stars are compared with those in other photographs of the same area taken at other times in the night with the same telescope. In every instance, the deflection of starlight has supported Einstein's prediction (Figure 36.7).

FIGURE 36.7

Starlight bends as it grazes the Sun. Point A shows the apparent position; point B shows the true position.

Light bends in Earth's gravitational field also—but not as much. We don't notice it because the effect is so tiny. For example, in a constant gravitational field of 1 g, a beam of horizontally directed light will "fall" a vertical distance of 4.9 m in 1 s (just as a baseball would), but it will travel a horizontal distance of 300,000 km in that time. Its curve would hardly be noticeable when you're this far from the beginning point. But if the light traveled 300,000 km in multiple reflections between idealized parallel mirrors, the effect would be quite noticeable (Figure 36.8). (Doing this would make a dandy home project for extra credit—like earning credit for a Ph.D.)

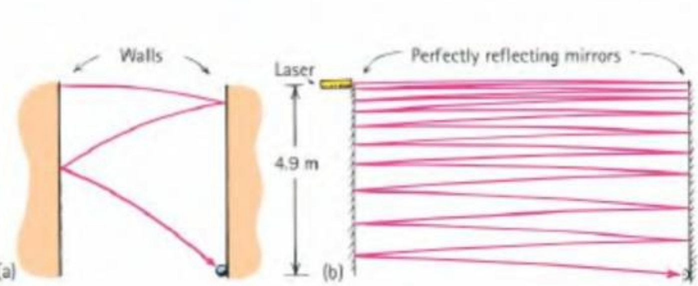


FIGURE 36.8

(a) If a ball is horizontally projected between a vertical pair of parallel walls, it will bounce back and forth and fall a vertical distance of 4.9 m in 1 s. (b) If a horizontal beam of light is directed between a vertical pair of perfectly parallel ideal mirrors, it will reflect back and forth and fall a vertical distance of 4.9 m in 1 s. The number of back-and-forth reflections is overly simplified in the diagram; if the mirrors were 300 km apart, for example, 1000 reflections would occur in 1 s.

CHECK POINT

1. Whoa! We learned previously that the pull of gravity is an interaction between masses. And we learned that light has no mass. Now we say that light can be bent by gravity. Isn't this a contradiction?
2. Why do we not notice the bending of light in our everyday environment?

Check Your Answers

1. There is no contradiction when the mass–energy equivalence is understood. It's true that light has no mass, but it is not "energyless." The fact that gravity deflects light is evidence that gravity pulls on the energy of light. Energy indeed is equivalent to mass!
2. Only because light travels so fast; just as, over a short distance, we do not notice the curved path of a high-speed bullet, we do not notice the curving of a light beam.

Gravity and Time: Gravitational Red Shift

According to Einstein's general theory of relativity, gravitation causes time to slow down. If you move in the direction in which the gravitational force acts—from the top of a skyscraper to the ground floor, for instance, or from the surface of Earth to the bottom of a well—time will run slower at the point you reach than at the point you left behind. We can understand the slowing of clocks by gravity by applying the principle of equivalence and time dilation to an accelerating frame of reference.

Astrophysics goes beyond describing how the sky looks by explaining how it got to be as it is.

Imagine our accelerating reference frame to be a large rotating disk. Suppose we measure time with three identical clocks, one placed on the disk at its center, a second placed on the rim of the disk, and the third at rest on the ground nearby (Figure 36.9). From the laws of special relativity, we know that the clock attached to the center, since it is not moving with respect to the ground, should run at the same rate as the clock on the ground—but not at the same rate as the clock attached to the rim of the disk. The clock at the rim is in motion with respect to the ground and should therefore be observed to be running more slowly than the ground clock—and therefore more slowly than the clock at the center of the disk. Although the clocks on the disk are attached to the same frame of reference, they do not run synchronously; the outer clock runs slower than the inner clock.

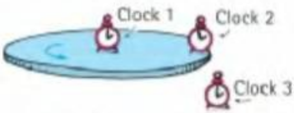


FIGURE 36.9
Clocks 1 and 2 are on an accelerating disk, and clock 3 is at rest in an inertial frame. Clocks 1 and 3 run at the same rate, while clock 2 runs slower. From the point of view of an observer at clock 3, clock 2 runs slow because it is moving. From the point of view of an observer at clock 1, clock 2 runs slow because it is at a lower potential (it would take work to move it from the edge to the center).

An observer on the rotating disk and an observer at rest on the ground both see the same difference in clock rates between themselves and the clock on the rim. Interpretations of the difference for the two observers are not the same, however. To the observer on the ground, the slower rate of the clock on the rim is due to its motion. But, to an observer on the rotating disk, the disk clocks are not in motion with respect to each other; instead, a centrifugal force acts on the clock at the rim, while no such force acts on the clock at the center. The observer on the disk is likely to conclude that the centrifugal force has something to do with the slowing of time. He notices that as he moves in the direction of the centrifugal force, outward from the center to the edge of the disk, time is slowed. By applying the principle of equivalence, which says that any effect of acceleration can be duplicated by gravity, we must conclude that as we move in the direction in which a gravitational force acts, time will also be slowed.

This slowing down will apply to all "clocks," whether physical, chemical, or biological. An executive working on the ground floor of a tall city skyscraper will age more slowly than her twin sister working on the top floor. The difference is very small, only a few millionths of a second per decade, because, by cosmic standards, the distance is small and the gravitation is weak. For larger differences in gravitation,

FIGURE 36.10

If you move from a distant point down to the surface of Earth, you move in the direction in which the gravitational force acts—toward a location where clocks run more slowly. A clock at the surface of Earth runs slower than a clock farther away.

such as between the surface of the Sun and the surface of Earth, the differences in time are larger (although still tiny). A clock at the surface of the Sun should run measurably slower than a clock at the surface of Earth. Years before he completed his general relativity theory, Einstein suggested a way to measure this when he formulated the principle of equivalence in 1907.

All atoms emit light at specific frequencies characteristic of the vibrational rate of electrons within the atom. Every atom is therefore a "clock," and a slowing down of atomic vibration indicates the slowing down of such clocks. An atom on the Sun should emit light of a lower frequency (slower vibration) than light emitted by the same element on Earth. Since red light is at the low-frequency end of the visible spectrum, a lowering of frequency shifts the color toward the red. This effect is called the **gravitational red shift.** The gravitational red shift is observed in light from the Sun, but various disturbing influences prevent accurate measurements of this tiny effect. It wasn't until 1960 that an entirely new technique, using gamma rays from radioactive atoms, permitted incredibly precise and confirming measurements of the gravitational slowing of time between the top and bottom floors of a laboratory building at Harvard University.[1]

So measurements of time depend not only on relative motion, as we learned in the last chapter, but also on gravity. In special relativity, time dilation depends on the *speed* of one frame of reference relative to another one. In general relativity, the gravitational red shift depends on the *location* of one point in a gravitational field relative to another one. As viewed from Earth, a clock will be measured to tick more slowly on the surface of a star than on Earth. If the star shrinks, its surface moves inward to ever-stronger gravity, which causes time on its surface to slow down more and more. We would measure longer intervals between the ticks of the star clock. But if we made our measurements of the star clock from the star itself, we would notice nothing unusual about the clock's ticking.

Suppose, for example, that an indestructible volunteer stands on the surface of a giant star that begins collapsing. We, as outside observers, will note a progressive slowing of time on the clock of our volunteer as the star surface recedes to regions of stronger gravity. The volunteer himself, however, does not notice any differences in his own time. He is viewing events within his own frame of reference, and he notices nothing unusual. As the collapsing star proceeds toward becoming a black hole and time proceeds normally from the viewpoint of the volunteer, we on the outside perceive time for the volunteer as approaching a complete stop; we see him frozen in time with an infinite duration between the ticks of his clock or the beats of his heart. From our view, his time stops completely. The gravitational red shift, instead of being a tiny effect, is dominating.

We can understand the gravitational red shift from another point of view—in terms of the gravitational force acting on photons. As a photon flies from the surface of a star, it is "retarded" by the star's gravity. It loses energy (but not speed). Since a photon's frequency is proportional to its energy, its frequency decreases as its energy decreases. When we observe the photon, we see that it has lower frequency than what it would if it had been emitted by a less-massive source. Its time has been slowed, just like the ticking of a clock is slowed. In the case of a black hole, a photon is unable to escape at all. It loses all its energy and all its frequency in the attempt. Its frequency is gravitationally red-shifted to zero, consistent with our observation that the rate at which time passes on a collapsing star approaches zero.

The Global Positioning System (GPS) must take account of the effect of gravity as well as speed on orbiting atomic clocks. Because of gravity, clocks run faster in orbit. Because of speed, they run slower. The effects vary during each elliptical orbit and they don't cancel. When your GPS unit tells you exactly where you are, thank Einstein.

[1]In the late 1950s, shortly after Einstein's death, the German physicist Rudolph Mössbauer discovered an important effect in nuclear physics that provides an extremely accurate method of using atomic nuclei as atomic clocks. The *Mössbauer effect,* for which its discoverer was awarded the Nobel Prize, has many practical applications. In late 1959, Robert Pound and Glen Rebka at Harvard University conceived an application that was a test for general relativity and performed the confirming experiment.

It is important to note the relativistic nature of time both in special relativity and in general relativity. In both theories, there is no way that you can extend the duration of your own existence. Others moving at different speeds or in different gravitational fields may attribute a great longevity to you, but your longevity is seen from *their* frame of reference, never from your own. Changes in time are always attributed to "the other guy."

CHECK POINT

Will a person at the top of a skyscraper age more than or less than a person at ground level?

Check Your Answer

More—going from the top of the skyscraper to the ground is going in the direction of the gravitational force, so it is going to a place where time runs more slowly.

Gravity and Space: Motion of Mercury

From the special theory of relativity, we know that measurements of space and time undergo transformations when motion is involved. Likewise with the general theory: Measurements of space differ in different gravitational fields—for example, close to and far away from the Sun.

Planets orbit the Sun and stars in elliptical orbits and move periodically into regions farther from the Sun and closer to the Sun. Einstein directed his attention to the varying gravitational fields experienced by the planets orbiting the Sun and found that the elliptical orbits of the planets should *precess* (Figure 36.11)—independently of the Newtonian influence of other planets. Near the Sun, where the effect of gravity on time is the greatest, the rate of precession should be the greatest; and far from the Sun, where time is less affected, any deviations from Newtonian mechanics should be virtually unnoticeable.

FIGURE 36.11
A precessing elliptical orbit.

Mercury, the planet nearest the Sun, is in the strongest part of the Sun's gravitational field. If the orbit of any planet exhibits a measurable precession, it should be Mercury, and the fact that the orbit of Mercury does precess—above and beyond effects attributable to the other planets—had been a mystery to astronomers since the early 1800s. Careful measurements showed that Mercury's orbit precesses about 574 seconds of arc per century. Perturbations by the other planets were found to account for all but 43 seconds of arc per century. Even after all known corrections due to possible perturbations by other planets had been applied, the calculations of physicists and astronomers failed to account for the extra 43 seconds of arc. Either Venus was extra massive or a never-discovered other planet (called Vulcan) was pulling on Mercury. And then came the explanation of Einstein, whose general relativity field equations applied to Mercury's orbit predict an extra 43 seconds of arc per century!

The mystery of Mercury's orbit was solved, and a new theory of gravity was recognized. Newton's law of gravitation, which had stood as an unshakable pillar of science for more than two centuries, was found to be a special limiting case of Einstein's more general theory. If the gravitational fields are comparatively weak, Newton's law turns out to be a good approximation of the new law—enough so that Newton's law, which is easier to work with mathematically, is the law that today's space scientists use most of the time.

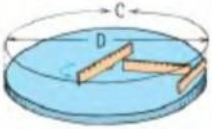


FIGURE 36.12
A measuring stick along the edge of the rotating disk appears contracted, while a measuring stick farther in and moving more slowly is not contracted as much. A measuring stick along a radius is not contracted at all. When the disk is not rotating, $C/D = \pi$; but, when the disk is rotating, C/D is not equal to π and Euclidean geometry is no longer valid. Likewise in a gravitational field.

Gravity, Space, and a New Geometry

We can begin to understand that measurements of space are altered in a gravitational field by again considering the accelerated frame of reference of our rotating disk. Suppose that we measure the circumference of the outer rim with a measuring stick. Recall the Lorentz contraction from special relativity: The measuring stick will appear contracted to any observer not moving along with the stick, while the dimensions of an identical measuring stick moving much more slowly near the center will be nearly unaffected (Figure 36.12). All distance measurements along a *radius* of the rotating disk should be completely unaffected by motion, because motion is perpendicular to the radius. Since only distance measurements parallel to and around the circumference are affected, the ratio of circumference to diameter when the disk is rotating is no longer the fixed constant π (3.14159 . . .) but is a variable depending on angular speed and the diameter of the disk.

According to the principle of equivalence, the rotating disk is equivalent to a stationary disk with a strong gravitational field near its edge and a progressively weaker gravitational field toward its center. Measurements of distance, then, will depend on the strength of gravitational field (or, more exactly, for relativity buffs, on gravitational potential), even if no relative motion is involved. Gravity causes space to be non-Euclidean; the laws of Euclidean geometry taught in high school are no longer valid when applied to objects in the presence of strong gravitational fields.

The standard model of cosmology assumes a flat universe dominated by dark matter and dark energy that formed by rapid inflation from its hot, dense origins.

The familiar rules of Euclidean geometry pertain to various figures you can draw on a flat surface. The ratio of the circumference of a circle to its diameter is equal to π; all the angles in a triangle add up to 180°; the shortest distance between two points is a straight line. The rules of Euclidean geometry are valid in flat space; but if you draw these figures on a curved surface, like a sphere or a saddle-shaped object, the Euclidean rules no longer hold (Figure 36.13). If you measure the sum of the angles for a triangle in space, you call the space flat if the sum is equal to 180°, spherelike or positively curved if the sum is larger than 180°, and saddlelike or negatively curved if it is less than 180°.

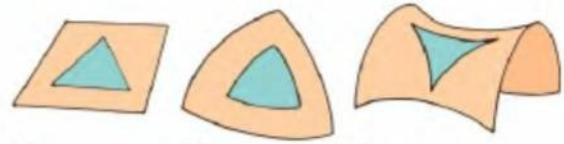


FIGURE 36.13
The sum of the angles of a triangle depends on which kind of surface the triangle is drawn on. (a) On a flat surface, the sum is 180°. (b) On a spherical surface, the sum is greater than 180°. (c) On a saddle-shaped surface, the sum is less than 180°.

Of course, the lines forming the triangles in Figure 36.13 are not all "straight" from a three-dimensional view, but they are the "straightest," or *shortest*, distances between two points if we are confined to the curved surface. These lines of shortest distance are called *geodesic* lines or simply **geodesics.**

The path of a light beam follows a geodesic. Suppose three experimenters on Earth, Venus, and Mars measure the angles of a triangle formed by light beams traveling between these three planets. The light beams bend when passing the Sun, resulting in the sum of the three angles being larger than 180° (Figure 36.14). So the space around the Sun is positively curved. The planets that orbit the Sun travel along four-dimensional geodesics in this positively curved spacetime. Freely falling objects, satellites, and light rays all travel along geodesics in four-dimensional spacetime.

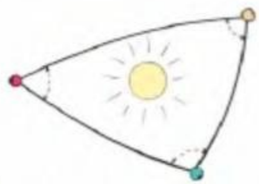


FIGURE 36.14
The light rays joining the three planets form a triangle. Since light passing near the Sun bends, the sum of the angles of the resulting triangle is greater than 180°.

"Small" parts of the universe are certainly curved. What about the universe as a whole? Recent study of the low-temperature radiation in space that is a remnant of the Big Bang suggests that the universe is flat. If it were open-ended like the saddle in Figure 36.13c, it would extend forever and beams of light that started out parallel would diverge. If it were closed like the spherical surface in Figure 36.13b, beams of light that started out parallel would eventually cross and circle back to their starting point. In such a universe, if you could look infinitely into space through an ideal telescope, you would see the back of your own head (after waiting patiently for enough billions of years)! In our actual flat universe, parallel beams of light remain parallel and will never return.

General relativity calls for a new geometry: Rather than space simply being a region of nothingness, space is a flexible medium that can bend and twist. How it bends and twists describes a gravitational field. General relativity is a geometry of curved, four-dimensional spacetime.[2] The mathematics of this geometry is too formidable to present here. The essence, however, is that the presence of mass produces the curvature, or *warping*, of spacetime. Conversely, a curvature of spacetime shows that mass must be present. Instead of visualizing gravitational forces between masses, we abandon altogether the notion of force and instead think of masses responding in their motion to the warping of the spacetime they inhabit. It is the bumps, depressions, and warpings of geometrical spacetime that *are* the phenomena of gravity.

We cannot visualize the four-dimensional bumps and depressions in spacetime because we are three-dimensional beings. We can get a glimpse of this warping by considering a simplified analogy in two dimensions: a heavy ball resting on the middle of a waterbed. The more massive the ball, the greater it dents or warps the two-dimensional surface. A marble rolled across the bed, but far from the ball, will roll in a relatively straight-line path, whereas a marble rolled near the ball will curve as it rolls across the indented surface. If the curve closes upon itself, its shape resembles an ellipse. The planets that orbit the Sun similarly travel along four-dimensional geodesics in the warped spacetime about the Sun.

Gravitational Waves

Every object has mass and therefore warps the surrounding spacetime. When an object undergoes a change in motion, the surrounding warp moves in order to readjust to the new position. These readjustments produce ripples in the overall geometry of spacetime. This is similar to moving a ball that rests on the surface of a waterbed. A disturbance ripples across the waterbed surface in waves; if we move a more massive ball, then we get a greater disturbance and the production of even stronger waves. Similarly for spacetime in the universe. Similar ripples travel outward from a gravitational source at the speed of light and are **gravitational waves.**

Any accelerating object produces a gravitational wave. In general, the more massive the object and the greater its acceleration, the stronger the resulting gravitational wave. But even the strongest waves produced by ordinary astronomical events are extremely weak—the weakest known in nature. For example, the gravitational waves emitted by a vibrating electric charge are a trillion trillion trillion times weaker than the electromagnetic waves emitted by the same charge. Detecting gravitational waves is enormously difficult, and no confirmed detection has occurred to

[2]Don't be discouraged if you cannot visualize four-dimensional spacetime. Einstein himself often told his friends, "Don't try. I can't do it either." Perhaps we are not too different from the great thinkers of Galileo's time who couldn't think of a moving Earth!

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- One of general relativity's predictions is a subtle twisting of spacetime around a massive spinning object. A test for this "frame-dragging" effect would be predictable tiny changes in the orientations of satellite orbits and orbiting gyroscopes. Researchers in 2004 found such confirming evidence.

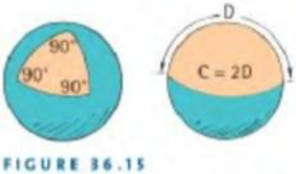

FIGURE 36.15

The geometry of the curved surface of Earth differs from the Euclidean geometry of flat space. Note, in the globe on the left, that the sum of the angles for an equilateral triangle in which each side equals 1/4 Earth's circumference is clearly greater than 180°. The globe on the right shows Earth's circumference is only twice its diameter instead of 3.14 times its diameter. Euclidean geometry is also invalid in curved space.

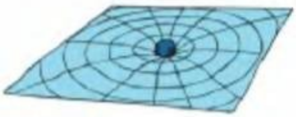

FIGURE 36.16

A two-dimensional analogy of four-dimensional warped spacetime. Spacetime near a star is curved in a way similar to the surface of a waterbed when a heavy ball rests on it.

fyi

- Researchers in 2005 confirmed predictions of energy losses due to gravitational waves emitted by the double-pulsar system PSR J0737-3039A/B over a 3-year period. Yay, Einstein!

Space is stretching out, carrying the galaxies with it. Visible light in the early universe has stretched out now to be relatively long-wavelength microwave radiation.

date. Recently completed wave detectors are expected to detect gravitational waves from supernovae, which may radiate away as much as 0.1% of their mass as gravitational waves, and perhaps from even more cataclysmic events, such as colliding black holes.

As weak as they are, gravitational waves are everywhere. Shake your hand back and forth—you have just produced a gravitational wave. It is not very strong, but it exists.

Newtonian and Einsteinian Gravitation

When Einstein formulated his new theory of gravitation, he realized that if his theory is valid, his field equations must reduce to Newtonian equations for gravitation in the weak-field limit. He showed that Newton's law of gravitation is a special case of the broader theory of relativity. Newton's law of gravitation is still an accurate description of most of the interactions between bodies in the solar system and beyond. From Newton's law, one can calculate the orbits of comets and asteroids and even predict the existence of undiscovered planets. Even today, when computing the trajectories of space probes to the Moon and planets, only ordinary Newtonian theory is used. This is because the gravitational field of these bodies is very weak, and, from the viewpoint of general relativity, the surrounding spacetime is essentially flat. But for regions of more intense gravitation, where spacetime is more appreciably curved, Newtonian theory cannot adequately account for various phenomena—such as the precession of Mercury's orbit close to the Sun and, in the case of stronger fields, the gravitational red shift and other apparent distortions in measurements of space and time. These distortions reach their limit in the case of a star that collapses to a black hole, where spacetime completely folds over on itself. Only Einsteinian gravitation reaches into this domain.

We saw, in Chapter 32, that Newtonian physics is linked at one end with quantum theory, whose domain is the very light and very small—tiny particles and atoms. And now we have seen that Newtonian physics is linked at the other end with relativity theory, whose domain is the very massive and very large. We do not see the world the way the ancient Egyptians, Greeks, or Chinese did. It is unlikely that people in the future will see the universe as we do. Our view of the universe may be quite limited, and perhaps filled with misconceptions, but it is most likely clearer than the views of others before us. Our view today stems from the findings of Copernicus, Galileo, Newton, and, more recently, Einstein—findings that were often opposed on the grounds that they diminished the importance of humans in the universe. In the past, being important meant having risen above nature—being apart from nature. We have expanded our vision since then by enormous effort, painstaking observation, and an unrelenting desire to comprehend our surroundings. Seen from today's understanding of the universe, we find our importance in being very much a part of nature, not apart from it. We are the part of nature that is becoming more and more conscious of itself.

If a learner's first course in physics is enjoyable, the rigor of a second course will be welcome and meaningful.

SUMMARY OF TERMS

General theory of relativity The second of Einstein's theories of relativity, which relates gravity to the properties of space and time.

Principle of equivalence Because observations made in an accelerated frame of reference are indistinguishable from observations made in a gravitational field, any effect produced by gravity can be duplicated by accelerating a frame of reference.

Gravitational red shift The lengthening of the waves of electromagnetic radiation escaping from a massive object.

Geodesic The shortest path between two points in various models of space.

Gravitational wave A gravitational disturbance, generated by an accelerating mass, that propagates through spacetime.

REVIEW QUESTIONS

Reference Frames—Nonaccelerated and Accelerated

1. What is the principal difference between the theory of special relativity and the theory of general relativity?

Principle of Equivalence

2. In a spaceship accelerating at *g*, far from Earth's gravity, how does the motion of a dropped ball compare with the motion of a ball dropped at Earth's surface?
3. Exactly what is *equivalent* in the principle of equivalence?

Bending of Light by Gravity

4. Compare the bending of the paths of baseballs and photons by a gravitational field.
5. Why must the Sun be eclipsed to measure the deflection of starlight passing near the Sun?

Gravity and Time: Gravitational Red Shift

6. What is the effect of strong gravitation on measurements of time?
7. Which runs slower, a clock at the top of the tallest skyscraper in Chicago or a clock on the shore of Lake Michigan?
8. How does the frequency of a particular spectral line observed in sunlight compare with the frequency of that line observed from a source on Earth?
9. If we view events occurring on a star that is collapsing to become a black hole, do we see time speeded up or slowed down?

Gravity and Space: Motion of Mercury

10. Of all the planets, why is Mercury the best candidate for finding evidence of the relationship between gravitation and space?
11. In what kind of gravitational field are Newton's laws valid?

Gravity, Space, and a New Geometry

12. A measuring stick placed along the circumference of a rotating disk will appear contracted, but if it is oriented along a radius, it will not. Explain.
13. The ratio of circumference to diameter for measured circles on a disk equals π when the disk is at rest, but not when the disk is rotating. Explain.
14. What effect does mass have on spacetime?

Gravitational Waves

15. What occurs in the surrounding space when a massive object undergoes a change in its motion?
16. A star 10 light-years away explodes and produces gravitational waves. How long will it take these waves to reach Earth?
17. Why are gravitational waves so difficult to detect?

Newtonian and Einsteinian Gravitation

18. Does Einstein's theory of gravitation invalidate Newton's theory of gravitation? Explain.
19. Is Newtonian physics adequate to get a rocket to the Moon?
20. How does Newtonian physics link with quantum theory and relativity theory?

EXERCISES

1. What is different about the reference frames that apply to special relativity and to general relativity?
2. An astronaut awakes in her closed capsule, which actually sits on the Moon. Can she tell whether her weight is the result of gravitation or of accelerated motion? Explain.
3. Provide a classical explanation for an astronaut in an orbiting spacecraft experiencing no net force (as measured by a weighing scale), even though the astronaut is in the grips of Earth gravity.
4. An astronaut is provided a "gravity" when the spaceship's engines are activated to accelerate the ship. This requires the use of fuel. Is there a way to accelerate and provide "gravity" without the sustained use of fuel? Explain, perhaps using ideas from Chapter 8.
5. In a spaceship far from the reaches of gravity, under what conditions could you feel as if the spaceship were stationary on Earth's surface?
6. In his famous novel *Journey to the Moon*, Jules Verne stated that occupants in a spaceship would shift their orientation from up to down when the ship crossed the point where the Moon's gravitation became greater than Earth's. Is this correct? Defend your answer.
7. What happens to the separation distance between two people if they both walk north at the same rate from two locations on Earth's equator? And just for fun, where in the world is a step in every direction a step south?
8. We readily note the bending of light by reflection and refraction, but why are we not aware of the bending of light by gravity?
9. Light *does* bend in a gravitational field. Why is this bending not taken into consideration by surveyors who use laser beams as straight lines?
10. Why do we say that light travels in straight lines? Is it strictly accurate to say that a laser beam provides a perfectly straight line for purposes of surveying? Explain.
11. Your friend says that light passing the Sun is bent whether or not Earth experiences a solar eclipse. Do you agree or disagree, and why?
12. In 2004, when Mercury passed between the Sun and Earth, sunlight was not appreciably bent as it passed Mercury. Why?
13. A setting Sun is seen as distorted on Earth, but not by astronauts on the Moon. What causes this distortion (and why could this question have been asked back in Chapter 28)?

14. At the end of 1 s, a horizontally fired bullet drops a vertical distance of 4.9 m from its otherwise straight-line path in a gravitational field of 1 *g*. By what distance would a beam of light drop from its otherwise straight-line path if it traveled in a uniform field of 1 *g* for 1 s? For 2 s?
15. Light changes its energy when it "falls" in a gravitational field. This change in energy is not evidenced by a change in speed, however. What is the evidence for this change in energy?
16. Would we notice a slowing down or speeding up of a clock if we carried it to the bottom of a very deep well?
17. If we witness events occurring on the Moon, where gravitation is weaker than on Earth, would we expect to see a gravitational red shift or a gravitational blue shift? Explain.
18. Armed with highly sensitive detection equipment, you are in the front of a railroad car that is accelerating forward. Your friend at the rear of the car shines green light toward you. Do you find the light to be red-shifted (lowered in frequency), blue-shifted (increased in frequency), or neither? Explain. (*Hint:* Think in terms of the principle of equivalence. What is your accelerating railroad car equivalent to?)
19. Why will the gravitational field intensity increase on the surface of a shrinking star?
20. Will a clock at the equator run slightly faster or slightly slower than an identical clock at one of Earth's poles?
21. Do you age faster at the top of mountain or at sea level?
22. Splitting hairs, should a person who worries about growing old live at the top or at the bottom of a tall apartment building?
23. Which would run slower, a clock at the center of a rotating space habitat or one at the edge? Or would there be no difference?
24. Prudence and Charity are twins raised at the center of a rotating kingdom. Charity goes to live at the edge of the kingdom for a time and then returns home. Which twin is older when they rejoin? (Ignore any time-dilation effects associated with travel to and from the edge.)
25. Splitting hairs, if you shine a beam of colored light to a friend above in a high tower, will the color of light your friend receives be the same color you send? Explain.
26. Is light emitted from the surface of a massive star red-shifted or blue-shifted by gravity?
27. From our frame of reference on Earth, objects slow to a stop as they approach black holes in space because time gets infinitely stretched by the strong gravity near the black hole. If astronauts accidentally falling into a black hole tried to signal back to Earth by flashing a light, what kind of "telescope" would we need to detect the signals?
28. Would an astronaut falling into a black hole see the outside universe red-shifted or blue-shifted?
29. How can we "observe" a black hole if neither matter nor radiation can escape from it?
30. Should it be possible in principle for a photon to circle a very massive star?
31. Why does the gravitational attraction between the Sun and Mercury vary? Would it vary if the orbit of Mercury were perfectly circular?
32. Your friend whimsically says that at the North Pole, a step in any direction is a step south. Do you agree?
33. In the astronomical triangle shown in Figure 36.14, with sides defined by light paths, the sum of the interior angles is more than 180°. Is there any astronomical triangle whose interior angles sum to less than 180°?
34. Do binary stars (double-star systems that orbit about a common center of mass) radiate gravitational waves? Why or why not?
35. Given the possible sources of gravitational waves in the universe, would you expect them to have short wavelengths or long?
36. Based on what you know about the emission and absorption of electromagnetic waves, suggest how gravitational waves are emitted and how they are absorbed. (Scientists seeking to detect gravitational waves must arrange for them to be absorbed.)
37. Comparing Einstein's and Newton's theories of gravitation, how can the correspondence principle be applied?
38. Current findings suggest that the universe is flat. What is an implication of this finding?
39. Make up a multiple-choice question to check a classmate's understanding of the principle of equivalence.
40. Make up a multiple-choice question to check a classmate's understanding of the effect of gravity on time.

CHAPTER 36 ONLINE RESOURCES

PhysicsPlace.com

Quizzes

Links

Flashcards

PART EIGHT MULTIPLE-CHOICE PRACTICE EXAM

Choose the BEST answer to the following:

1. What Einstein discovered about space and time is that they
   (a) are separate entities.
   (b) are parts of one whole.
   (c) follow an inverse-square law.
   (d) are special to space travelers.
2. In his special theory of relativity, Einstein stated that the laws of physics are
   (a) different in different situations.
   (b) common sense applied to microscopic and macroscopic things.
   (c) the same in all frames of reference.
   (d) the same in all uniformly moving frames of reference.
3. Einstein's second postulate tells us that the speed of light
   (a) depends on one's frame of reference.
   (b) is a constant in all frames of reference.
   (c) provides accurate clocks.
   (d) slows in a transparent medium.
4. When we speak of time dilation, we mean that time
   (a) compresses with speed.
   (b) stretches with speed.
   (c) is a constant at all speeds.
   (d) is related to space.
5. If you travel at high speed, then compared with your friends who "stay at home," you are
   (a) older.
   (b) younger.
   (c) no younger nor no older.
   (d) longer.
6. Clocks on a fast-moving spaceship whizzing past Earth appear to run slow when viewed from
   (a) inside the spaceship.
   (b) Earth.
   (c) Both of these.
   (d) Neither of these.
7. If you were to travel at a speed close to that of the speed of light, you could notice that your own
   (a) mass changes.
   (b) pulse decreases.
   (c) Both of these.
   (d) Neither of these.
8. As a blinking light source approaching you gains in speed, you see the frequency of flashes
   (a) increase.
   (b) decrease.
   (c) remain unchanged.
   (d) None of these.
9. At very high speeds, an object appears to an observer at rest to be
   (a) shorter in the direction of travel.
   (b) shrunken in all directions.
   (c) shorter in the direction perpendicular to travel.
   (d) longer in all directions.
10. Compared with the Newtonian momentum $p = mv$, the momentum of an object traveling at great speed is
    (a) greater.
    (b) less.
    (c) the same.
    (d) dependent on rest mass.
11. Relativity equations for time, length, and momentum hold true for
    (a) everyday low speeds.
    (b) relativistic speeds.
    (c) Both of these.
    (d) Neither of these.
12. To say that $E = mc^2$ is to say that energy
    (a) increases as the speed of light squared.
    (b) is twice as much as the speed of light.
    (c) and mass are equivalent.
    (d) equals mass traveling at the speed of light squared.
13. According to the correspondence principle,
    (a) new theory must agree with old theory where they overlap.
    (b) Newton's mechanics is as valid as Einstein's mechanics.
    (c) relativity equations apply to high speeds while Newton's equations apply to low speeds.
    (d) special relativity and general relativity are two sides of the same coin.
14. Things that are equivalent according to the equivalence principle are
    (a) space and time.
    (b) a traveling twin and a stay-at-home twin.
    (c) gravity and acceleration.
    (d) mass and energy.
15. According to general relativity,
    (a) mass distorts spacetime.
    (b) gravity affects clocks.
    (c) light can't escape from a black hole.
    (d) All of these.
16. According to four-dimensional geometry, the angles of a triangle add to 180°
    (a) always.
    (b) sometimes.
    (c) never.
    (d) on planet Earth only.
17. General relativity predicts that
    (a) light leaving the Sun is slowed by gravity.
    (b) light passing the Sun is deflected.
    (c) a clock on the Sun's surface runs faster than on Earth.
    (d) All of these.
18. If a star that is 20 light-years from Earth explodes, gravitational waves from the explosion would reach Earth in
    (a) less than 20 years.
    (b) 20 years.
    (c) more than 20 years.
    (d) None of these.

After you have made thoughtful choices, and discussed them with your friends, find the answers on page 681.

EPILOGUE

I hope you've enjoyed *Conceptual Physics* and will value your knowledge of physics as a worthwhile component of your general education. Viewing physics as a study of the rules of nature can contribute to your sense of wonder and enhance the way you see the physical world—knowing that so much in nature is interconnected, with seemingly diverse phenomena often following the same basic rules. How intriguing that the rules governing a falling apple also apply to a space station orbiting Earth, that a sky's redness at sunset is connected to its blueness at midday, or that the link between electricity and magnetism reveals the nature of light.

The value of science is more than its applications to fast cars, iPods, computers, and other products of technology. Its greatest value lies in its methods of understanding and investigating nature—that hypotheses are framed so that they are capable of being disproved and experiments are designed so that their results can be reproduced by others. Science is more than a body of knowledge. It is a way of thinking.

But even now many, if not most, people hardly give a thought to science. Too many people around the world believe that all relevant knowledge is to be found in one or another sacred book. To such people, the answers to any questions of nature are to be found not in experimentation, but in the established written word. Once answers are found in the sacred text, there is no further investigation. Where there is no investigation, there is no science. Science becomes moot. Questioning and openness to new ideas stop.

This kind of thinking can get in the way of solving environmental problems, feeding ever more people, and finding cures for disease and other forms of human misery. Certitude ruled in the Dark Ages, and it may rule again. The beginning pages of this book cited the burning down of the Great Library of Alexandria by people who presumably were certain in their world view, people threatened by the heretical writing in the Great Library. Could it happen again—on a larger scale?

It is hard to imagine an end to the human adventure, but an end is painfully possible. This adventure started eons ago with specks of living matter making their appearance on this tiny planet orbiting an undistinguished star among countless other stars in one of billions of galaxies. Some of the specks replicated themselves, and the replicas replicated themselves ad infinitum—but with variations appearing in all the niches of ever-changing environments. Four hundred million years ago, before mammals, there were fish. Then came amphibians and then reptiles. In the struggle of species survival, trillions upon trillions of life forms passed their genetic traits on to their offspring, sometimes here and there making adaptive changes. After a long and prodigious ascent, some 200,000 years ago, humans emerged. We should not ignore the sacrifices of the innumerable lives that brought us to where we are. We should celebrate this long and astounding journey of life—for we are the benefactors. In my view, just as science is more fascinating than science fiction, the modern story of the ascent of humans is more beautiful than the legends written in sacred books.

Science offers a means of establishing our origins and shaping our future—at a time when the potential for world calamity has never been greater. Denial of overpopulation (the elephant in the room), indifference of the powerful to human suffering, energy greed, and forms of fanaticism devoted to terror, even nuclear terror, beset our age. Science offers the *tools* to save ourselves. The *will* is ours to find.

Fortunately, more and more people are finding the will and employing scientific tools to address the societal issues that threaten our survival. Growing numbers of imaginative, knowledgeable, caring people are focusing their intellectual and emotional energies to help solve global problems. Awareness of the urgency is growing. Earth is the home we all share. Science is needed to protect and preserve this home and to care for its billions of human occupants.

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Appendix A

ON MEASUREMENT AND UNIT CONVERSIONS

Two major systems of measurement prevail in the world today: the *United States Customary System* (USCS, formerly called the British system of units), used in the United States of America and formerly in Burma, and the *Système International* (SI) (known also as the international system and as the metric system), used everywhere else. Each system has its own standards of length, mass, and time. The units of length, mass, and time are sometimes called the *fundamental units* because, once they are selected, other quantities can be measured in terms of them.

TABLE A.1

SI Units

Quantity	Unit	Symbol
Length	meter	m
Mass	kilogram	kg
Time	second	s
Force	newton	N
Energy	joule	J
Current	ampere	A
Temperature	kelvin	K

United States Customary System

Based on the British Imperial System, the USCS is familiar to everyone in the United States. It uses the foot as the unit of length, the pound as the unit of weight or force, and the second as the unit of time. The USCS is presently being replaced by the international system—rapidly in science and technology and some sports (track and swimming), but so slowly in other areas and in some specialties it seems the change may never come. For example, we will continue to buy seats on the 50-yard line. We remember camera film in millimeters and compact discs in inches.

For measuring time, there is no difference between the two systems except that in pure SI the only unit is the second (s, not sec) with prefixes; but in general, minute, hour, day, year, and so on, with two or more lettered abbreviations (h, not hr), are accepted in the USCS.

Systéme International

During the 1960 International Conference on Weights and Measures held in Paris, the SI units were defined and given status. Table A.1 shows SI units and their symbols. SI is based on the *metric system*, originated by French scientists after the French Revolution in 1791. The orderliness of this system makes it useful for scientific work, and it is used by scientists all over the world. The metric system branches into two systems of units. In one of these the unit of length is the meter, the unit of mass is the kilogram, and the unit of time is the second. This is called the *meter-kilogram-second* (mks) system and is preferred in physics. The other branch is the *centimeter-gram-second* (cgs) system, which, because of its smaller values, is favored in chemistry. The cgs and mks units are related to each other as follows: 100 centimeters equal 1 meter; 1000 grams equal 1 kilogram. Table A.2 shows several units of length related to each other.

One major advantage of a metric system is that it uses the decimal system, in which all units are related to smaller or larger units by dividing or multiplying by 10. The prefixes shown in Table A.3 are commonly used to show the relationship among units.

TABLE A.2

Conversions Between Different Units of Length

Unit of Length	Kilometer	Meter	Centimeter	Inch	Foot	Mile
1 kilometer	= 1	1000	100,000	39,370	3280.84	0.62140
1 meter	= 0.00100	1	100	39.370	3.28084	6.21×10^{-4}
1 centimeter	$= 1.0 \times 10^{-5}$	0.0100	1	0.39370	0.032808	6.21×10^{-6}
1 inch	$= 2.54 \times 10^{-5}$	0.02540	2.5400	1	0.08333	1.58×10^{-5}
1 foot	$= 3.05 \times 10^{-4}$	0.30480	30.480	12	1	1.89×10^{-4}
1 mile	= 1.60934	1609.34	160,934	63,360	5280	1

TABLE A.3
Some Prefixes

Prefix	Definition
micro-	One-millionth: a microsecond is one-millionth of a second
milli-	One-thousandth: a milligram is one-thousandth of a gram
centi-	One-hundredth: a centimeter is one-hundredth of a meter
kilo-	One thousand: a kilogram is 1000 grams
mega-	One million: a megahertz is 1 million hertz
giga-	One billion: a gigahertz is 1 billion hertz

METER

The standard of length of the metric system orginally was defined in terms of the distance from the north pole to the equator. This distance was thought at the time to be close to 10,000 kilometers. One ten-millionth of this, the meter, was carefully determined and marked by means of scratches on a bar of platinum-iridium alloy. This bar is kept at the International Bureau of Weights and Measures in France. The standard meter in France has since been calibrated in terms of the wavelength of light—it is 1,650,763.73 times the wavelength of orange light emitted by the atoms of the gas krypton-86. The meter is now defined as being the length of the path traveled by light in a vacuum during a time interval of 1/299,792,458 of a second.

KILOGRAM

The standard unit of mass, the kilogram, is a block of platinum–iridium alloy, also preserved at the International Bureau of Weights and Measures located in France (Figure A.1). The kilogram equals 1000 grams. A gram is the mass of 1 cubic centimeter (cc) of water at a temperature of 4°C. (The standard pound is defined in terms of the standard kilogram; the mass of an object that weighs 1 pound is equal to 0.4536 kilogram.)


FIGURE A.1
The standard kilogram.

SECOND

The official unit of time for both the USCS and the SI is the second. Until 1956, it was defined in terms of the mean solar day, which was divided into 24 hours. Each hour was divided into 60 minutes and each minute into 60 seconds. Thus, there were 86,400 seconds per day, and the second was defined as 1/86,400 of the mean solar day. This proved unsatisfactory because the rate of rotation of Earth is gradually becoming slower. In 1956, the mean solar day of the year 1900 was chosen as the standard on which to base the second. In 1964, the second was officially defined as the time taken by a cesium-133 atom to make 9,192,631,770 vibrations.

NEWTON

One newton is the force required to accelerate 1 kilogram at 1 meter per second per second. This unit is named after Sir Isaac Newton.

JOULE

One joule is equal to the amount of work done by a force of 1 newton acting over a distance of 1 meter. In 1948, the joule was adopted as the unit of energy by the International Conference on Weights and Measures. Therefore, the specific heat of water at 15°C is now given as 4185.5 joules per kilogram Celsius degree. This figure is always associated with the mechanical equivalent of heat—4.1855 joules per calorie.

AMPERE

The ampere is defined as the intensity of the constant electric current that, when maintained in two parallel conductors of infinite length and negligible cross section and placed 1 meter apart in a vacuum, would produce between them a force equal to 2×10^{-7} newton per meter length. In our treatment of electric current in this text, we have used the not-so-official but easier-to-comprehend definition of the ampere as being the rate of flow of 1 coulomb of charge per second, where 1 coulomb is the charge of 6.25×10^{18} electrons.

KELVIN

The fundamental unit of temperature is named after the scientist William Thomson, Lord Kelvin. The kelvin is defined to be 1/273.15 the thermodynamic temperature of the triple point of water (the fixed point at which ice, liquid water, and water vapor coexist in equilibrium). This definition was adopted in 1968 when it was decided to change the name *degree Kelvin* (°K) to *kelvin* (K). The temperature of melting ice at atmospheric pressure is 273.15 K. The temperature at which the vapor pressure of pure water is equal to standard atmospheric pressure is 373.15 K (the temperature of boiling water at standard atmospheric pressure).

AREA

The unit of area is a square that has a standard unit of length as a side. In the USCS, it is a square with sides that are each 1 foot in length, called 1 square foot and written 1 ft^2. In the international system, it is a square with sides that are 1 meter in length, which makes a unit of area of 1 m^2. In the cgs system it is 1 cm^2. The area of a given surface is specified by the number of square feet, square meters, or square centimeters that would fit into it. The area of a rectangle equals the base times the height. The area of a circle is equal to πr^2, where $\pi = 3.14$ and r is the radius of the circle. Formulas for the surface areas of other objects can be found in geometry textbooks.

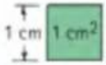


FIGURE A.2
Unit square.

VOLUME

The volume of an object refers to the space it occupies. The unit of volume is the space taken up by a cube that has a standard unit of length for its edge. In the USCS, one unit of volume is the space occupied by a cube 1 foot on an edge and is called 1 cubic foot, written 1 ft^3. In the metric system it is the space occupied by a cube with sides of 1 meter (SI) or 1 centimeter (cgs). It is written 1 m^3 or 1 cm^3 (or cc). The volume of a given space is specified by the number of cubic feet, cubic meters, or cubic centimeters that will fill it.

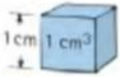


FIGURE A.3
Unit volume.

In the USCS, volumes can also be measured in quarts, gallons, and cubic inches as well as in cubic feet. There are 1728 ($12 \times 12 \times 12$) cubic inches in 1 ft^3. A U.S. gallon is a volume of 231 in^3. Four quarts equal 1 gallon. In the SI volumes are also measured in liters. A liter is equal to 1000 cm^3.

Unit Conversion

Often in science, and especially in a laboratory setting, it is necessary to convert from one unit to another. To do so, you need only multiply the given quantity by the appropriate *conversion factor.*

All conversion factors can be written as ratios in which the numerator and denominator represent the equivalent quantity expressed in different units. Because any quantity divided by itself is equal to 1, all conversion factors are equal to 1. For example, the following two conversion factors are both derived from the relationship 100 centimeters = 1 meter:

$$\frac{100 \text{ centimeters}}{1 \text{ meter}} = 1 \qquad \frac{1 \text{ meter}}{100 \text{ centimeters}} = 1$$

Because all conversion factors are equal to 1, multiplying a quantity by a conversion factor does not change the value of the quantity. What does change are the units. Suppose you measured an item to be 60 centimeters in length. You can convert this measurement to meters by multiplying it by the conversion factor that allows you to cancel centimeters.

CHECK POINT

Convert 60 centimeters to meters.

Check Your Answer

$$\underbrace{(60 \cancel{\text{ centimeters}})}_{\text{quantity in centimeters}} \underbrace{\frac{(1 \text{ meter})}{(100 \cancel{\text{ centimeters}})}}_{\text{conversion factor}} = \underbrace{0.6 \text{ meter}}_{\text{quantity in meters}}$$

To derive a conversion factor, consult a table that presents unit equalities, such as Table A.2 or on the inside back cover of this book. Then multiply the given quantity by the conversion factor, and voilà, the units are converted. Always be careful to write down your units. They are your ultimate guide, telling you what numbers go where and whether you are setting up the equation properly.

APPENDIX A ONLINE RESOURES

PhysicsPlace.com

Tutorials

- Significant Figures
- The Metric System

Appendix B

MORE ABOUT MOTION

When we describe the motion of something, we say how it moves relative to something else (Chapter 3). In other words, motion requires a reference frame (an observer, origin, and axes). We are free to choose this frame's location and to have it moving relative to another frame. When our frame of motion has zero acceleration, it is called an *inertial frame*. In an inertial frame, force causes an object to accelerate in accord with Newton's laws. When our frame of reference is accelerated, we observe fictitious forces and motions (Chapter 8). Observations from a carousel, for example, are different when it is rotating and when it is at rest. Our description of motion and force depends on our "point of view."

We distinguish between *speed* and *velocity* (Chapter 3). Speed is how fast something moves, or the time rate of change of position (excluding direction): a *scalar* quantity. Velocity includes direction of motion: a *vector* quantity whose magnitude is speed. Objects moving at constant velocity move the same distance in the same time in the same direction.

Another distinction between speed and velocity has to do with the difference between distance and net distance, or *displacement*. Speed is *distance per duration*, while velocity is *displacement per duration*. Displacement differs from distance. For example, a commuter who travels 10 kilometers to work and back travels 20 kilometers, but has "gone" nowhere. The distance traveled is 20 kilometers and the displacement is zero. Although the instantaneous speed and instantaneous velocity have the same value at the same instant, the average speed and average velocity can be very different. The average speed of this commuter's round trip is 20 kilometers divided by the total commute time—a value greater than zero. But the average velocity is zero. In science, displacement is often more important than distance. (To avoid information overload, we have not treated this distinction in the text.)

Acceleration is the rate at which velocity changes. This can be a change in speed only, a change in direction only, or both. Slowing down is often called *deceleration*.

In Newtonian space and time, space has three dimensions—length, width, and height—each with two directions. We can go, stop, and return in any of them. Time has one dimension, with two directions—past and future. We cannot stop or return, only go. In Einsteinian spacetime, these four dimensions merge (Chapter 35).

Computing Velocity and Distance Traveled on an Inclined Plane

Recall, from Chapter 2, Galileo's experiments with inclined planes. Consider a plane tilted such that the speed of a rolling ball increases at the rate of 2 meters per second each second—an acceleration of 2 m/s^2. At the instant it starts moving, its velocity is zero; and 1 second later, it is rolling at 2 m/s; at the end of the next second, 4 m/s; at the end of the next second, 6 m/s; and so on. Starting from rest, the velocity of the ball at any instant is simply

$$\text{Velocity} = \text{acceleration} \times \text{time}$$

or, in shorthand notation,

$$v = at$$

(It is customary to omit the multiplication sign, ×, when expressing relationships in mathematical form. When two symbols are written together, such as the *at* in this case, it is understood that they are multiplied.)

How fast the ball rolls is one thing; how *far* it rolls is another. To understand the relationship between acceleration and distance traveled, we must first investigate the relationship between instantaneous velocity and *average velocity*. If the ball shown in Figure B.1 starts from rest, it will roll a distance of 1 meter in the first second. Question: What will be its average speed? The answer is 1 m/s (because it covered 1 meter in the interval of 1 second). But we have seen that the *instantaneous velocity* at the end of the first second is 2 m/s. Since the acceleration is uniform, the average in any time interval is found the same way we usually find the average of any two numbers: add them and divide by 2. (Be careful not to do this when acceleration is not uniform!) So, if we add the initial speed (zero in this case) and the final speed of 2 m/s and then divide by 2, we get 1 m/s for the average velocity.

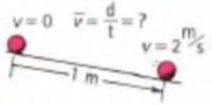


FIGURE B.1
The ball rolls 1 m down the incline in 1 s and reaches a speed of 2 m/s. Its average speed, however, is 1 m/s. Do you see why?

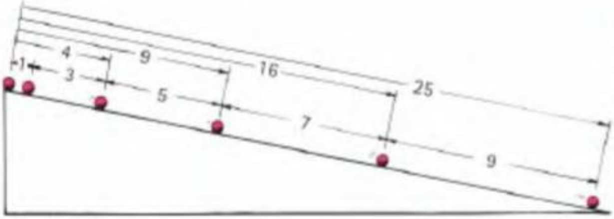


FIGURE B.2

If the ball covers 1 m during its first second, then, in each successive second, it will cover the odd-numbered sequence of 3, 5, 7, 9 m, and so on. Note that the total distance covered increases as the square of the total time.

In each succeeding second, we see the ball roll a longer distance down the same slope in Figure B.2. Note the distance covered in the second time interval is 3 meters. This is because the average speed of the ball in this interval is 3 m/s. In the next 1-second interval, the average speed is 5 m/s, so the distance covered is 5 meters. It is interesting to see that successive increments of distance increase as a *sequence of odd numbers*. Nature clearly follows mathematical rules!

CHECK POINT

During the span of the second time interval, the ball begins at 2 m/s and ends at 4 m/s. What is the *average speed* of the ball during this 1-s interval? What is its *acceleration?*

Check Your Answers

$$\text{Average speed} = \frac{\text{beginning} + \text{final speed}}{2} = \frac{2\text{ m/s} + 4\text{ m/s}}{2} = 3\text{ m/s}$$

$$\text{Acceleraion} = \frac{\text{change in velocity}}{\text{time interval}} = \frac{4\text{ m/s} - 2\text{ m/s}}{1\text{ s}} = \frac{2\text{ m/s}}{1\text{ s}} = 2\text{ m/s}^2$$

Investigate Figure B.2 carefully and note the *total* distance covered as the ball accelerates down the plane. The distances go from zero to 1 meter in 1 second, zero to 4 meters in 2 seconds, zero to 9 meters in 3 seconds, zero to 16 meters in 4 seconds, and so on in succeeding seconds. The sequence for *total distances* covered is of the *squares of the time*. We'll investigate the relationship between distance traveled and the square of the time for constant acceleration more closely in the case of free fall.

Computing Distance When Acceleration Is Constant

How far will an object released from rest fall in a given time? To answer this question, let us consider the case in which it falls freely for 3 seconds, starting at rest. Neglecting air resistance, the object will have a constant acceleration of about 10 meters per second each second (actually more like 9.8 m/s^2, but we want to make the numbers easier to follow).

$$\begin{aligned}
\text{Velocity at the } \textit{beginning} &= 0\text{ m/s} \\
\text{Velocity at the } \textit{end} \text{ of 3 seconds} &= (10 \times 3)\text{ m/s} \\
\textit{Average} \text{ velocity} &= \tfrac{1}{2} \text{ the sum of these two speeds} \\
&= \tfrac{1}{2} \times (0 + 10 \times 3)\text{ m/s} \\
&= \tfrac{1}{2} \times 10 \times 3 = 15\text{ m/s} \\
\text{Distance traveled} &= \text{average velocity} \times \text{time} \\
&= (\tfrac{1}{2} \times 10 \times 3) \times 3 \\
&= \tfrac{1}{2} \times 10 \times 3^2 = 45\text{ m}
\end{aligned}$$

We can see from the meanings of these numbers that

$$\text{Distance traveled} = \tfrac{1}{2} \times \text{acceleration} \times \text{square of time}$$

This equation is true for an object falling not only for 3 seconds but for any length of time, as long as the acceleration is constant. If we let d stand for the distance traveled, a for the acceleration, and t for the time, the rule may be written, in shorthand notation,

$$d = \tfrac{1}{2} at^2$$

This relationship was first deduced by Galileo. He reasoned that, if an object falls for, say, twice the time, it will fall with *twice the average speed*. Since it falls for *twice* the time at *twice* the average speed, it will fall *four* times as far. Similarly, if an object falls for *three* times the time, it will have an average speed *three* times as great and will fall *nine* times as far. Galileo reasoned that the total distance fallen should be proportional to the *square* of the time.

In the case of objects in free fall, it is customary to use the letter g to represent the acceleration instead of the letter a (g because acceleration is due to *gravity*). While the value of g varies slightly in different parts of the world, it is approximately equal to 9.8 m/s^2 (32 ft/s^2). If we use g for the acceleration of a freely falling object (negligible air resistance), the equations for falling objects starting from a rest position become

$$v = gt$$
$$d = \tfrac{1}{2} gt^2$$

Much of the difficulty in learning physics, like learning any discipline, has to do with learning the language—the many terms and definitions. Speed is somewhat different from velocity, and acceleration is vastly different from speed or velocity.

CHECK POINT

1. An auto starting from rest has a constant acceleration of 4 m/s^2. How far will it go in 5 s?
2. How far will an object released from rest fall in 1 s? In this case the acceleration is $g = 9.8$ m/s^2.
3. If it takes 4 s for an object to freely fall to the water when released from the Golden Gate Bridge, how high is the bridge?

Check Your Answers

1. Distance $= \frac{1}{2} \times 4 \times 5^2 = 50$ m
2. Distance $= \frac{1}{2} \times 9.8 \times 1^2 = 4.9$ m
3. Distance $= \frac{1}{2} \times 9.8 \times 4^2 = 78.4$ m

Notice that the units of measurement when multiplied give the proper units of meters for distance:

$$d = \frac{1}{2} \times 9.8 \text{ m/s}^2 \times 16\text{s}^2 = 78.4 \text{ m}$$

Mass and weight are related but are different from each other. Likewise for work, heat, and temperature. Please be patient with yourself as you find that learning the similarities and the differences among physics concepts is not an easy task.

So far our equations for speed and distance have been for starting-from-rest cases. What of objects that undergo uniform acceleration and don't start from rest? A little thought will show that

$$v = v_0 + at$$
$$d = v_0t + 1/2\, at^2$$

We've simply tacked on the initial conditions: velocity beginning with v_0 and distance traveled increased by v_0t. Common sense tells you that when acceleration is zero, these equations become

$$v = v_0$$
$$d = v_0t$$

After all, physics is applied common sense!

Appendix C

GRAPHING

Graphs: A Way to Express Quantitative Relationships

Graphs, like equations and tables, show how two or more quantities relate to each other. Since investigating relationships between quantities makes up much of the work of physics, equations, tables, and graphs are important physics tools.

Equations are the most concise way to describe quantitative relationships. For example, consider the equation $v = v_0 + gt$. It compactly describes how a freely falling object's velocity depends on its initial velocity, acceleration due to gravity, and time. Equations are nice shorthand expressions for relationships among quantities.

Tables give values of variables in list form. The dependence of v on t in $v = v_0 + gt$ can be shown by a table that lists various values v for corresponding times t. Table 3.2 on page 41 is an example. Tables are especially useful when the mathematical relationship between quantities is not known, or when numerical values must be given to a high degree of accuracy. Also, tables are handy for recording experimental data.

Graphs *visually* represent relationships between quantities. By looking at the shape of a graph, you can quickly tell a lot about how the variables are related. For this reason, graphs can help clarify the meaning of an equation or table of numbers. And, when the equation is not already known, a graph can help reveal the relationship between variables. Experimental data are often graphed for this reason.

Graphs are helpful in another way. If a graph contains enough plotted points, it can be used to estimate values between the points (interpolation) or values following the points (extrapolation).

Cartesian Graphs

The most common and useful graph in science is the *Cartesian* graph. On a Cartesian graph, possible values of one variable are represented on the vertical axis (called the *y-axis*) and possible values of the other variable are plotted on the horizontal axis (*x-axis*).

Figure C.1 shows a graph of two variables, x and y, that are *directly proportional* to each other. A direct proportionality is a type of *linear* relationship. Linear relationships have straight-line graphs—the easiest kinds of graphs to interpret. On the graph shown in Figure C.1, the continuous straight-line rise from left to right tells you that, as x increases, y increases. More specifically, it shows that y increases at a

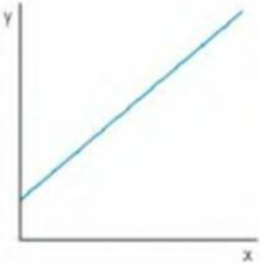


FIGURE C.1

constant rate with respect to x. As x increases, y increases. The graph of a direct proportionality often passes through the "origin"—the point at the lower left where $x = 0$ and $y = 0$. In Figure C.1, however, we see the graph begins where y has a nonzero value when $x = 0$. The value y has a "head start."

Figure C.2 shows a graph of the equation $v = v_0 + gt$. Speed v is plotted along the y-axis, and time t along the x-axis. As you can see, there is a linear relationship between v and t. Note that the initial speed is 10 m/s. If the initial speed were 0, as in dropping an object from rest, then the graph would intercept the origin, where both v and t are 0. Note that the graph originates at $v = 10$ m/s when $t = 0$, showing a 10-m/s "head start."

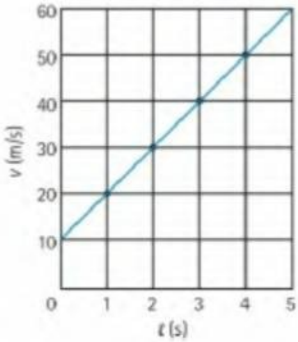


FIGURE C.2

Many physically significant relationships are more complicated than linear relationships, however. If you double the size of a room, the area of the floor increases four times; tripling the size of the room increases the floor area nine times; and so on. This is one example of a *nonlinear*

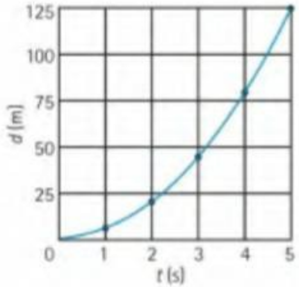


FIGURE C.3

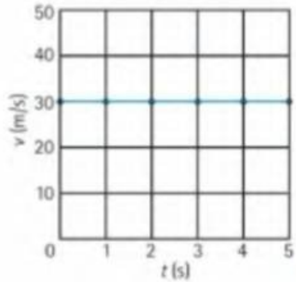


FIGURE C.5

relationship. Figure C.3 shows a graph of another nonlinear relationship: distance versus time in the equation of free fall from rest, $d = \frac{1}{2}gt^2$.

Figure C.4 shows a *radiation curve*. The *curve* (or graph) shows the rather complex nonlinear relationship between intensity I and radiation wavelength λ for a glowing object at 2000 K. The graph shows that radiation is most intense when λ equals about 1.4 μm. Which is brighter, radiation at 0.5 μm or radiation at 4.0 μm? The graph can quickly tell you that radiation at 4.0 μm is appreciably more intense.

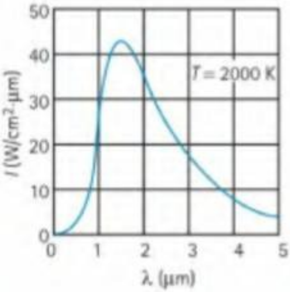


FIGURE C.4

Slope and Area Under the Curve

Quantitative information can be obtained from a graph's *slope* and the *area under the curve*. The slope of the graph in Figure C.2 represents the rate at which v increases relative to t. It can be calculated by dividing a segment Δv along the y-axis by a corresponding segment Δt along the x-axis. For example, dividing Δv of 30 m/s by Δt of 3 s gives $\Delta v/\Delta t$ = 10 m/s·s = 10 m/s^2, the acceleration due to gravity. By contrast, consider the graph in Figure C.5, which is a horizontal straight line. Its slope of zero shows zero acceleration—that is, constant speed. The graph shows that the speed is 30 m/s, acting throughout the entire 5-second interval. The rate of change, or slope, of the speed with respect to time is zero—there is no change in speed at all.

The area under the curve is an important feature of a graph because it often has a physical interpretation. For example, consider the area under the graph of v versus t shown in Figure C.6. The shaded region is a rectangle with sides 30 m/s and 5 s. Its area is 30 m/s × 5 s = 150 m. In this example, the area is the distance covered by an object moving at constant speed of 30 m/s for 5 s ($d = vt$).

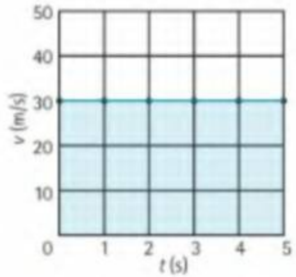


FIGURE C.6

The area need not be rectangular. The area beneath any curve of v versus t represents the distance traveled in a given time interval. Similarly, the area beneath a curve of acceleration versus time gives the change of velocity in a time interval. The area beneath a force-versus-time curve gives the change of momentum. (What does the area beneath a force-versus-distance curve give?) The nonrectangular area under various curves, including rather complicated ones, can be found by way of an important branch of mathematics—*integral calculus*.

Graphing with Conceptual Physics

You may develop basic graphing skills in the laboratory part of this course. The lab "Blind as a Bat" introduces you to graphing concepts. It also gives you a chance to work with a computer and sonic-ranging device. The lab "Trial and Error" will show you the useful technique of converting a nonlinear graph to a linear one to discover a direct proportionality. The area under the curve is the

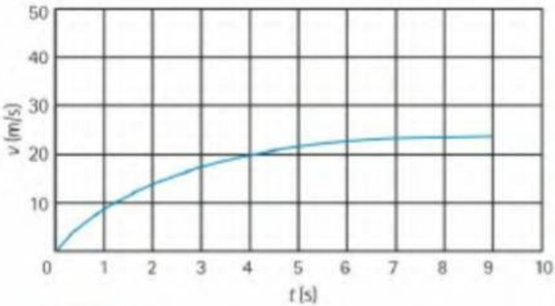


FIGURE C.7

basis of the lab experiment "Impact Speed." You will learn more about graphing in other labs as well.

You may also learn in the lab part of your *Conceptual Physics* course that computers can graph data for you. You are not being lazy when you graph your data with a software program. Instead of investing time and energy scaling the axes and plotting points, you spend your time and energy investigating the meaning of the graph, a high level of thinking!

CHECK POINT

Figure C.7 is a graphical representation of a ball dropped into a mine.

1. How long did the ball take to hit the bottom?
2. What was the ball's speed when it struck bottom?
3. What does the decreasing slope of the graph tell you about the acceleration of the ball with increasing speed?
4. Did the ball reach terminal speed before hitting the bottom of the shaft? If so, about how many seconds did it take to reach its terminal speed?
5. What is the approximate depth of the mine shaft?

Check Your Answers

1. 9 s
2. 25 m/s
3. Acceleration decreases as speed increases (due to air resistance).
4. Yes (since slope curves to zero), about 7 s.
5. Depth is about 170 m. (The area under the curve is about 17 squares, each of which represents 10 m.)

APPENDIX C ONLINE RESOURES

PhysicsPlace.com

Tutorial

- Graphing

Appendix D

MORE ABOUT VECTORS

Vectors and Scalars

A *vector* quantity is a directed quantity—one that must be specified not only by magnitude (size) but by direction as well. Recall, from Chapter 5, that velocity is a vector quantity. Other examples are force, acceleration, and momentum. In contrast, a *scalar* quantity can be specified by magnitude alone. Some examples of scalar quantities are speed, time, temperature, and energy.

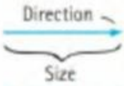


FIGURE D.1

Vector quantities may be represented by arrows. The length of the arrow tells you the magnitude of the vector quantity, and the arrowhead tells you the direction of the vector quantity. Such an arrow drawn to scale and pointing appropriately is called a *vector*.

Adding Vectors

Vectors that add together are called *component vectors*. The sum of component vectors is called a *resultant*.

To add two vectors, make a parallelogram with two component vectors acting as two of the adjacent sides (Figure D.2). (Here our parallelogram is a rectangle.) Then draw a diagonal from the origin of the vector pair; this is the resultant (Figure D.3).

FIGURE D.2

FIGURE D.3

Caution: Do not try to mix vectors! We cannot add apples and oranges, so velocity vectors combine only with velocity vectors, force vectors combine only with force vectors, and acceleration vectors combine only with acceleration vectors—each on its own vector diagram. If you ever show different kinds of vectors on the same diagram, use different colors or some other method of distinguishing the different kinds of vectors.

Finding Components of Vectors

Recall, from Chapter 5, that to find a pair of perpendicular components for a vector, first draw a dashed line through the tail of the vectors (in the direction of one of the desired components). Second, draw another dashed line through the tail end of the vector at right angles to the first dashed line. Third, make a rectangle whose diagonal is the given vector. Draw in the two components. Here we let **F** stand for "total force," **U** stand for "upward force," and **S** stand for "sideways force."

FIGURE D.4

FIGURE D.5

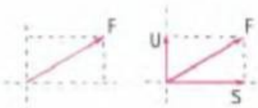


FIGURE D.6

EXAMPLES

1. Ernie Brown pushes a lawnmower and applies a force that pushes it forward and also against the ground. In Figure D.7, F represents the force applied by Ernie. We can separate this force into two components. The vector D represents the downward component, and S is the sideways component, the force that moves the lawnmower forward. If we know the magnitude and direction of the vector F, we can estimate the magnitude of the components from the vector diagram.

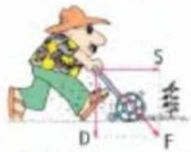


FIGURE D.7

2. Would it be easier to push or pull a wheelbarrow over a step? Figure D.8 shows the force at the wheel's center. When you push a wheelbarrow, part of the force is directed downward, which makes it harder to get over the step. When you pull, however, part of the pulling force is directed upward, which helps to lift the wheel over the step. Note that the vector diagram suggests that pushing the wheelbarrow may not get it over the step at all. Do you see that the height of the

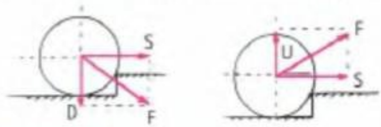


FIGURE D.8

step, the radius of the wheel, and the angle of the applied force determine whether the wheelbarrow can be pushed over the step? We see how vectors help us analyze a situation so that we can see just what the problem is!

3. If we consider the components of the weight of an object rolling down an incline, we can see why its speed depends on the angle. Note that the steeper the incline, the greater the component **S** becomes and the faster the object rolls. When the incline is vertical, **S** becomes equal to the weight, and the object attains maximum acceleration, 9.8 m/s^2. There are two more force vectors that are not shown: the normal force **N**, which is equal and oppositely directed to **D**, and the friction force **f**, acting at the barrel-plane contact.

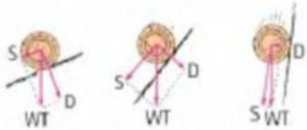


FIGURE D.9

4. When moving air strikes the underside of an airplane wing, the force of air impact against the wing may be represented by a single vector perpendicular to the plane of the wing (Figure D.10). We represent the force vector as acting midway along the lower wing surface, where the dot is, and pointing above the wing to show the direction of the resulting wind impact force. This force can be broken up into two components, one sideways and the other up. The upward component, U, is called *lift*. The sideways component, S, is called *drag*. If the aircraft is to fly at constant velocity at constant altitude, then lift must equal the weight of the aircraft and the thrust of the plane's engines must equal drag. The magnitude of lift (and drag) can be altered by changing the speed of the airplane or by changing the angle (called *angle of attack*) between the wing and the horizontal.

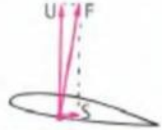


FIGURE D.10

5. Consider the satellite moving clockwise in Figure D.11. Everywhere in its orbital path, gravitational force **F** pulls it toward the center of the host planet. At position A we see **F** separated into two components: **f**, which is tangent to the path of the projectile, and **f'**, which is perpendicular to the path. The relative magnitudes of these components in comparison to the magnitude of **F** can be seen in the imaginary rectangle they compose; **f** and **f'** are the sides, and **F** is the diagonal. We see that component **f** is along the orbital path but against the direction of motion of the satellite. This force component reduces the speed of the satellite. The other component, **f'**, changes the direction of the satellite's motion and pulls it away from its tendency to go in a straight line. So the path of the satellite curves. The satellite loses speed until it reaches position B. At this farthest point from the planet (apogee), the gravitational force is somewhat weaker but perpendicular to the satellite's motion, and component **f** has reduced to zero. Component **f'**, on the other hand, has increased and is now fully merged to become **F**. Speed at this point is not enough for circular orbit, and the satellite begins to fall toward the planet. It picks up speed because the component **f** reappears and is in the direction of motion as shown in position C. The satellite picks up speed until it whips around to position D (perigee), where once again the direction of motion is perpendicular to the gravitational force, **f'** blends to full **F**, and **f** is nonexistent. The speed is in excess of that needed for circular orbit at this distance, and it overshoots to repeat the cycle. Its loss in speed in going from D to B equals its gain in speed from B to D. Kepler discovered that planetary paths are elliptical, but never knew why. Do you?

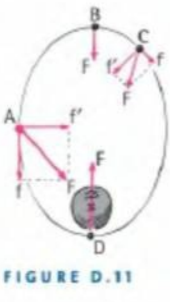


FIGURE D.11

6. Refer to the Polaroids held by Ludmila back in Chapter 29, in Figure 29.35. In the first picture (a), we see that light is transmitted through the pair of Polaroids because their axes are aligned. The emerging light can be represented as a vector aligned with the polarization axes of the Polaroids. When the Polaroids are crossed (b), no light emerges because light passing through the first Polaroid is perpendicular to the polarization axes of the second Polaroid, with no components along its axis. In the third picture (c), we see that light is transmitted when a third Polaroid is sandwiched at an angle between the crossed Polaroids. The explanation for this is shown in Figure D.12.

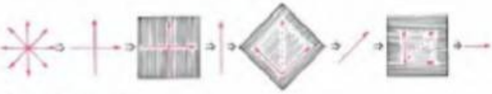


FIGURE D.12

Sailboats

Sailors have always known that a sailboat can sail downwind, in the direction of the wind. Sailors have not always known, however, that a sailboat can sail upwind, against the wind. One reason for this has to do with a feature that is common only to recent sailboats—a fin-like keel that extends deep beneath the bottom of the boat to ensure that the boat will knife through the water only in a forward (or backward) direction. Without a keel, a sailboat could be blown sideways.

Figure D.13 shows a sailboat sailing directly downwind. The force of wind impact against the sail accelerates the boat. Even if the drag of the water and all other resistance forces are negligible, the maximum speed of the boat is the wind speed. This is because the wind will not make impact against the sail if the boat is moving as fast as the wind. The wind would have no speed relative to the boat and the sail would simply sag. With no force, there is no acceleration. The force vector in Figure D.13 *decreases* as the boat travels

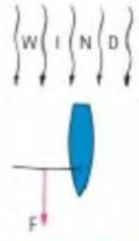


FIGURE D.13

faster. The force vector is maximum when the boat is at rest and the full impact of the wind fills the sail, and is minimum when the boat travels as fast as the wind. If the boat is somehow propelled to a speed faster than the wind (by way of a motor, for example), then air resistance against the front side of the sail will produce an oppositely directed force vector. This will slow the boat down. Hence, the boat when driven only by the wind cannot exceed wind speed.

If the sail is oriented at an angle, as shown in Figure D.14, the boat will move forward, but with less acceleration. There are two reasons for this:

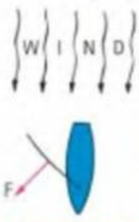


FIGURE D.14

1. The force on the sail is less because the sail does not intercept as much wind in this angular position.
2. The direction of the wind impact force on the sail is not in the direction of the boat's motion but is perpendicular to the surface of the sail. Generally speaking, whenever any fluid (liquid or gas) interacts with a smooth surface, the force of interaction is perpendicular to the smooth surface.* The boat does not move in the same direction as the perpendicular force on the sail, but is constrained to move in a forward (or backward) direction by its keel.

We can better understand the motion of the boat by resolving the force of wind impact, **F**, into perpendicular components. The important component is that which is parallel to the keel, which we label **K**, and the other component is perpendicular to the keel, which we label **T**. It is the component **K**, as shown in Figure D.15, that is responsible for the forward motion of the boat. Component **T** is a useless force that tends to tip the boat over and move it sideways. This component force is offset by the deep keel. Again, maximum speed of the boat can be no greater than wind speed.

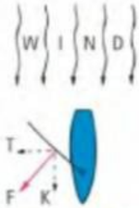


FIGURE D.15

Many sailboats sailing in directions other than exactly downwind (Figure D.16) with their sails properly oriented can exceed wind speed. In the case of a sailboat cutting across the wind, the wind may continue to make impact with the sail even after the boat exceeds wind speed. A surfer, in a similar way, exceeds the velocity of the propelling wave by angling his surfboard across the wave. Greater angles to the propelling medium (wind for the boat, water wave for the surfboard) result in greater speeds. A sailcraft can sail faster cutting across the wind than it can sailing downwind.

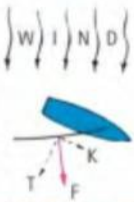


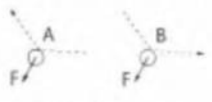
FIGURE D.16

As strange as it may seem, maximum speed for most sailcraft is attained by cutting into (against) the wind, that is, by angling the sailcraft in a direction upwind! Although a sailboat cannot sail directly upwind, it can reach a destination upwind by angling back and forth in a zigzag fashion. This is called *tacking*. Suppose the boat and sail are as shown in Figure D.17. Component K will push the boat along in a forward direction, angling into the wind. In the position shown, the boat can sail faster than the speed of the wind. This is because as the boat travels faster, the impact of wind is increased. This is similar to running in a rain that comes down at an angle. When you run into the direction of the downpour, the drops strike you harder and more frequently, but when you run away from the direction of the downpour, the drops don't strike you as hard or as frequently. In the same way, a boat sailing upwind experiences greater wind impact force, while a boat sailing downwind experiences a decreased wind impact force. In any case, the boat reaches its terminal speed when opposing forces cancel the force of wind impact. The opposing forces consist mainly of water resistance against the hull of the boat. The hulls of racing boats are shaped to minimize this resistive force, which is the principal deterrent to high speeds.

FIGURE D.17

Iceboats (sailcraft equipped with runners for traveling on ice) encounter no water resistance and can travel at several times the speed of the wind when they tack upwind. Although ice friction is nearly absent, an iceboat does not accelerate without limits. The terminal velocity of a sailcraft is determined not only by opposing friction forces but also by the change in relative wind direction. When the boat's orientation and speed are such that the wind seems to shift in direction, so the wind moves parallel to the sail rather than into it, forward acceleration ceases—at least in the case of a flat sail. In practice, sails are curved and produce an airfoil that is as important to sailcraft as it is to aircraft, as discussed in Chapter 14.

*You can do a simple exercise to see that this is so. Try bouncing a coin off another on a smooth surface, as shown. Note that the struck coin moves at right angles (perpendicular) to the contact edge. Note also that it makes no difference whether the projected coin moves along path A or path B. See your instructor for a more rigorous explanation, which involves momentum conservation.



APPENDIX D ONLINE RESOURES

PhysicsPlace.com

Tutorial

- Vectors

Appendix E

EXPONENTIAL GROWTH AND DOUBLING TIME*

One of the most important things we seem unable to perceive is the process of exponential growth. We think we understand how compound interest works, but we can't get it through our heads that a fine piece of tissue paper folded upon itself 50 times (if that were possible) would be more than 20 million kilometers thick. If we could, we could "see" why our income buys only half of what it did 4 years ago, why the price of everything has doubled in the same time, why populations and pollution proliferate out of control.**

When a quantity such as money in the bank, population, or the rate of consumption of a resource steadily grows at a fixed percent per year, we say the growth is exponential. Money in the bank may grow at 4 percent per year; electric power generating capacity in the United States grew at about 7 percent per year for the first three-quarters of the 20th century. The important thing about exponential growth is that the time required for the growing quantity to double in size (increase by 100 percent) is also constant. For example, if the population of a growing city takes 12 years to double from 10,000 to 20,000 inhabitants and its growth remains steady, in the next 12 years the population will double to 40,000, and in the next 10 years to 80,000, and so on.

There is an important relationship between the percent growth rate and its *doubling time*, the time it takes to double a quantity:†

$$\text{Doubling time} = \frac{69.3}{\text{percent growth per unit time}} \approx \frac{70}{\%}$$

So to estimate the doubling time for a steadily growing quantity, we simply divide the number 70 by the percentage growth rate. For example, the 7 percent growth rate of electric power generating capacity in the United States means that in the past the capacity had doubled every 10 years [70%/(7%/year) = 10 years]. A 2 percent growth rate for world population means the population of the world doubles every 35 years [70%/(2%/year) = 35 years]. A city planning commission that accepts what seems like a modest 3.5 percent growth rate may not realize that this means that doubling will occur in 70/3.5, or 20 years; that's double capacity for such things as water supply, sewage-treatment plants, and other municipal services every 20 years.

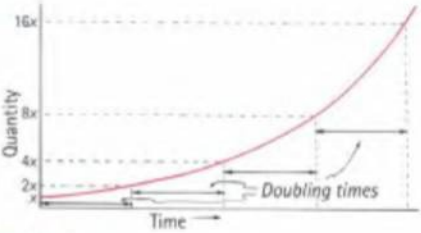


FIGURE E.1

An exponential curve. Notice that each of the successive equal time intervals noted on the horizontal scale corresponds to a doubling of the quantity indicated on the vertical scale. Such an interval is called the doubling time.

What happens when you put steady growth in a finite environment? Consider the growth of bacteria that grow by division, so that one bacterium becomes two, the two divide to become four, the four divide to become eight, and so on. Suppose the division time for a certain strain of bacteria is 1 minute. This is then steady growth—the number of bacteria grows exponentially with a doubling time of 1 minute. Further, suppose that one bacterium is put in a bottle at 11:00 A.M. and that growth continues steadily until the bottle becomes full of bacteria at 12 noon. Consider seriously the following question.

FIGURE E.2

CHECK POINT

When was the bottle half-full?

Check Your Answer

11:59 A.M.; the bacteria will double in number every minute!

*This appendix is adapted from material written by University of Colorado physics professor Albert A. Bartlett, who asserts, "The greatest shortcoming of the human race is our inability to understand the exponential function." See more on Al Bartlett on the web.

**K. C. Cole, *Sympathetic Vibrations* (New York: Morrow, 1984).

†For exponential decay we speak about half-life, the time required for a quantity to reduce to half its value. This case is treated in Chapter 33.

TABLE E.1

The Last Minutes in the Bottle

Time	Part Full (%)	Part Empty
11:54 A.M.	1/64 (1.5%)	63/64
11:55 A.M.	1/32 (3%)	31/32
11:56 A.M.	1/16 (6%)	15/16
11:57 A.M.	1/8 (12%)	7/8
11:58 A.M.	1/4 (25%)	3/4
11:59 A.M.	1/2 (50%)	1/2
12:00 noon	full (100%)	none

TABLE E.2

Effects of the Discovery of Three New Bottles

Time	Effect
11:58 A.M.	Bottle 1 is 1/4 full
11:59 A.M.	Bottle 1 is 1/2 full
12:00 noon	Bottle 1 is full
12:01 P.M.	Bottles 1 and 2 are both full
12:02 P.M.	Bottles 1, 2, 3, and 4 are all full

It is startling to note that at 2 minutes before noon the bottle was only 1/4 full. Table E.1 summarizes the amount of space left in the bottle in the last few minutes before noon. If you were an average bacterium in the bottle, at which time would you first realize that you were running out of space? For example, would you sense there was a serious problem at 11:55 A.M., when the bottle was only 3% filled (1/32) and had 97% of open space (just yearning for development)? The point here is that there isn't much time between the moment that the effects of growth become noticeable and the time when they become overwhelming.

Suppose that at 11:58 A.M. some farsighted bacteria see that they are running out of space and launch a full-scale search for new bottles. Luckily, at 11:59 A.M. they discover three new empty bottles, three times as much space as they had ever known. This quadruples the total resource space ever known to the bacteria, for they now have a total of four bottles, whereas before the discovery they had only one. Further suppose that, thanks to their technological proficiency, they are able to migrate to their new habitats without difficulty. Surely, it seems to most of the bacteria that their problem is solved—and just in time.

CHECK POINT

If the bacteria growth continues at the unchanged rate, what time will it be when the three new bottles are filled to capacity?

Check Your Answer

12:02 P.M.!

We see from Table E.2 that quadrupling the resource extends the life of the resource by only two doubling times. In our example the resource is space—but it could as well be coal, oil, uranium, or any nonrenewable resource.

Continued growth and continued doubling lead to enormous numbers. In two doubling times, a quantity will double twice ($2^2 = 4$; quadruple) in size; in three doubling times, its size will increase eightfold ($2^3 = 8$); in four doubling times, it will increase sixteenfold ($2^4 = 16$); and so on.

This is best illustrated by the story of the court mathematician in India who years ago invented the game of chess for his king. The king was so pleased with the game that he offered to repay the mathematician, whose request seemed modest enough. The mathematician requested a single grain of wheat on the first square of the chessboard, two grains on the second square, four on the third square, and so on, doubling the number of grains on each succeeding square until all squares had been used. At this rate there would be 2^{63} grains of wheat on the 64th square. The king soon saw that he could not fill this "modest" request, which amounted to more wheat than had been harvested in the entire history of Planet Earth!

FIGURE E.3

A single grain of wheat placed on the first square of the chessboard is doubled on the second square, this number is doubled on the third, and so on, presumably for all 64 squares. Note that each square contains one more grain than all the preceding squares combined. Does enough wheat exist in the world to fill all 64 squares in this manner?

It is interesting and important to note that the number of grains on any square is one grain more than the total of all grains on the preceding squares. This is true anywhere on the board. Note from Table E.3 that when eight grains are placed on the fourth square, the eight is one more than the total of seven grains that were already on the board. Or the 32 grains placed on the sixth square is one more than the total of 31 grains that were already on the board. We see that in one doubling time we use more than all that had been used in all the preceding growth!

So if we speak of doubling energy consumption in the next however many years, bear in mind that this means in these years we will consume more energy than has

TABLE E.3
Filling the Squares on the Chessboard

Square Number	Grains on Square	Total Grains Thus Far
1	1	1
2	2	3
3	4	7
4	8	15
5	16	31
6	32	63
7	64	127
⋮	⋮	⋮
64	2^{63}	$2^{64}-1$

heretofore been consumed during the entire preceding period of steady growth. And if power generation continues to use predominantly fossil fuels, then except for some improvements in efficiency, we would burn up in the next doubling time a greater amount of coal, oil, and natural gas than has already been consumed by previous power generation, and except for improvements in pollution control, we can expect to discharge even more toxic wastes into the environment than the millions upon millions of tons already discharged over all the previous years of industrial civilization. We would also expect more human-made calories of heat to be absorbed by Earth's ecosystem than have been absorbed in the entire past! At the previous 7% annual growth rate in energy production, all this would occur in one doubling time of a single decade. If over the coming years the annual growth rate remains at half this value, 3.5 percent, then all this would take place in a doubling time of two decades. Clearly this cannot continue!

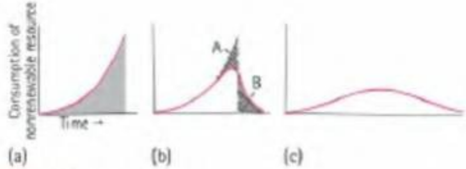
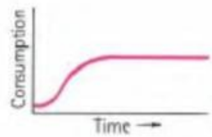


FIGURE E.4
(a) If the exponential rate of consumption for a nonrenewable resource continues until it is depleted, consumption falls abruptly to zero. The shaded area under this curve represents the total supply of the resource. (b) In practice, the rate of consumption levels off and then falls less abruptly to zero. Note that the crosshatched area A is equal to the crosshatched area B. Why? (c) At lower consumption rates, the same resource lasts a longer time.

The consumption of a nonrenewable resource cannot grow exponentially for an indefinite period, because the resource is finite and its supply finally expires. The most drastic way this could happen is shown in Figure E.4(a), where the rate of consumption, such as barrels of oil per year, is plotted against time, say in years. In such a graph the area under the curve represents the supply of the resource. We see that when the supply is exhausted, the consumption ceases altogether. This sudden change is rarely the case, for the rate of extracting the supply falls as it becomes more scarce. This is shown in Figure E.4(b). Note that the area under the curve is equal to the area under the curve in (a). Why? Because the total supply is the same in both cases. The principal difference is the time taken to finally extinguish the supply. History shows that the rate of production of a nonrenewable resource rises and falls in a nearly symmetric manner, as shown in (c). The time during which production rates rise is approximately equal to the time during which these rates fall to zero or near zero.

Production rates for all nonrenewable resources decrease sooner or later. Only production rates for renewable resources, such as agriculture or forest products, can be maintained at steady levels for long periods of time (Figure E.5), provided such production does not depend on waning nonrenewable resources such as petroleum. Much of today's agriculture is so petroleum-dependent that it can be said that modern agriculture is simply the process whereby land is used to convert petroleum into food. The implications of petroleum scarcity go far beyond rationing of gasoline for cars or fuel oil for home heating.

FIGURE E.5
A curve showing the rate of consumption of a renewable resource such as agricultural or forest products, where a steady rate of production and consumption can be maintained for a long period, provided this production is not dependent upon the use of a nonrenewable resource that is waning in supply.



The consequences of unchecked exponential growth are staggering. It is important to ask: Is growth really good? In answering this question, bear in mind that human growth is an early phase of life that continues normally through adolescence. Physical growth stops when physical maturity is reached. What do we say of growth that continues in the period of physical maturity? We say that such growth is obesity—or worse, cancer.

QUESTIONS TO PONDER

1. According to a French riddle, a lily pond starts with a single leaf. Each day the number of leaves doubles, until the pond is completely covered by leaves on the 30th day. On what day was the pond half covered? One-quarter covered?
2. In an economy that has a steady inflation rate of 7% per year, in how many years does a dollar lose half its value?
3. At a steady inflation rate of 7%, what will be the price every 10 years for the next 50 years for a theater ticket that now costs \$20? For a coat that now costs \$200? For a car that now costs \$20,000? For a home that now costs \$200,000?
4. If the sewage treatment plant of a city is just adequate for the city's current population, how many sewage treatment plants will be necessary 42 years later if the city grows steadily at 5% annually?
5. If world population doubles in 40 years and world food production also doubles in 40 years, how many people then will be starving each year compared to now?
6. Suppose you get a prospective employer to agree to hire your services for wages of a single penny for the first day, 2 pennies for the second day, and double each day thereafter providing the employer keeps to the agreement for a month. What will be your total wages for the month?
7. In the preceding exercise, how will your wages for only the 30th day compare to your total wages for the previous 29 days?
8. If fusion power were harnessed today, the abundant energy resulting would probably sustain and even further encourage our present appetite for continued growth and in a relatively few doubling times produce an appreciable fraction of the solar power input to Earth. Make an argument that the current delay in harnessing fusion is a blessing for the human race.

MULTIPLE-CHOICE PRACTICE EXAM ANSWERS

PART ONE

1. A **2.** C **3.** D **4.** C **5.** B **6.** C **7.** A **8.** B **9.** A **10.** B **11.** B **12.** A **13.** B **14.** C **15.** B **16.** A **17.** D **18.** B **19.** D **20.** A **21.** A **22.** C **23.** A **24.** B **25.** B **26.** B **27.** A **28.** A **29.** B **30.** A

PART TWO

1. D **2.** B **3.** B **4.** A **5.** A **6.** C **7.** A **8.** C **9.** A **10.** D **11.** B **12.** D **13.** A **14.** A **15.** C **16.** B **17.** D **18.** D **19.** A **20.** B

PART THREE

1. C **2.** C **3.** B **4.** C **5.** A **6.** A **7.** A **8.** C **9.** C **10.** C **11.** A **12.** A **13.** B **14.** C **15.** A **16.** C **17.** C **18.** B **19.** C **20.** C **21.** B **22.** B **23.** B **24.** A **25.** C **26.** D **27.** D **28.** A **29.** A **30.** B

PART FOURE

1. B **2.** B **3.** A **4.** D **5.** B **6.** B **7.** A **8.** D **9.** D **10.** C **11.** B **12.** D **13.** D **14.** C **15.** C **16.** C **17.** A **18.** D **19.** B **20.** A **21.** D **22.** A **23.** D **24.** B **25.** B **26.** B **27.** D **28.** B **29.** B **30.** B

PART FIVE

1. C **2.** A **3.** B **4.** B **5.** C **6.** B **7.** D **8.** C **9.** C **10.** A **11.** D **12.** D **13.** B **14.** B **15.** B **16.** B **17.** A **18.** D **19.** A **20.** A **21.** D **22.** A **23.** C **24.** A **25.** B **26.** D **27.** A **28.** A **29.** C **30.** D

PART SIX

1. B **2.** A **3.** B **4.** D **5.** B **6.** C **7.** A **8.** B **9.** D **10.** C **11.** A **12.** C **13.** A **14.** C **15.** D **16.** B **17.** A **18.** A **19.** A **20.** B **21.** C **22.** A **23.** B **24.** A **25.** D **26.** D **27.** C **28.** D **29.** B **30.** B

PART SEVEN

1. A **2.** B **3.** A **4.** C **5.** B **6.** D **7.** C **8.** C **9.** B **10.** B **11.** A **12.** A **13.** C **14.** B **15.** A **16.** B **17.** A **18.** C **19.** D **20.** C **21.** D **22.** A **23.** A **24.** A **25.** A **26.** B **27.** A **28.** A **29.** C **30.** D

PART EIGHT

1. B **2.** D **3.** B **4.** B **5.** B **6.** B **7.** D **8.** A **9.** A **10.** A **11.** C **12.** C **13.** A **14.** C **15.** D **16.** B **17.** D **18.** B

ANSWERS TO ODD-NUMBERED RANKINGS, EXERCISES, AND PROBLEMS

CHAPTER ONE EXERCISES

1. The penalty for fraud is professional excommunication. **3.** Aristotle's hypothesis was partially correct. Plant material comes partly from the soil, but mainly from the air and water. An experiment would be to weigh a pot of soil with a small seedling, then weigh the potted plant later after it has grown. The fact that the grown plant will weigh more is evidence that the plant is composed of more material than the soil offers. Keep a record of the weight of water used to water the plant, and cover the soil with plastic wrap to minimize evaporation losses. Then the weight of the grown plant can be compared with the weight of water it absorbs. How can the weight of air taken in by the plant be estimated? **5.** The examples are endless. Knowledge of electricity, for example, has proven to be extremely useful. The number of people who have been harmed by electricity who understood it is far fewer than the number of people who are harmed by it who don't understand it. A fear of electricity is much more harmful than useful to one's general health and attitude. **7.** What is likely being misunderstood is the distinction between theory and hypothesis. In common usage, "theory" may mean a guess or hypothesis, something that is tentative or speculative. But in science a theory is a synthesis of a large body of validated information (e.g., cell theory or quantum theory). The value of a theory is its usefulness (not its "truth"). **9.** The shadow would be longer because on the smaller planet the angle of the pole would be greater relative to the sunlight. The ratio of the shadow to pole height would be greater than 1:8, as in the previous answer.

CHAPTER TWO RANKING

1. C, B, A **3a.** B, A, C, D **3b.** B, A, C, D

CHAPTER TWO EXERCISES

1. The tendency of a rolling ball is to continue rolling in the absence of a force. The fact that it slows down is likely due to the force of friction. **3.** He discredited Aristotle's idea that the rate at which bodies fall is proportional to their weight. **5.** Galileo proposed the concept of inertia before Newton was born. **7.** Nothing keeps the probe moving. In the absence of a propelling or deflecting force, it would continue moving in a straight line. **9.** You should disagree with your friend. In the absence of external forces, a body at rest tends to remain at rest; if moving, it tends to remain moving. Inertia is a *property* of matter to behave this way, not some kind of force. **11.** The tendency of the ball is to remain at rest. From a point of view outside the wagon, the ball stays in place as the back of the wagon moves toward it. (Because of friction, the ball may roll along the cart surface—without friction the surface would slide beneath the ball.) **13.** Your body tends to remain at rest, in accord with Newton's first law. The back of the seat pushes you forward. Without support at the back of your head, your head is not pushed forward with your body, likely injuring your neck. Hence, headrests are recommended. **15.** The law of inertia applies in both cases. When the bus slows, you tend to keep moving at the previous speed and lurch forward. When the bus picks up speed, you tend to keep moving at the previous (lower) speed and you lurch backward. **17.** If there were no friction acting on the cart, it would continue in motion when you stop pushing. But friction does act, and the cart slows. This doesn't violate the law of inertia because an external force indeed acts. **19.** If there were no force acting on the ball, it would continue in motion without slowing. But air drag does act, along with slight friction with the lane, and the ball slows. This doesn't violate the law of inertia because external forces indeed act. **21.** In mechanical equilibrium, the vector sum of all forces, the net forces, necessarily equals zero: $\Sigma F = 0$. **23.** If only a single nonzero force acts on an object, its motion will change and will not be in mechanical equilibrium. There would have to be other forces to result in a zero net force for equilibrium. **25.** If the puck moves in a straight line with unchanging speed, the forces of friction are negligible. Then the net force is practically zero, and the puck can be considered to be in dynamic equilibrium. **27.** The scale will read half her weight. In this way, the net force (upward pull of left rope + upward pull of right rope rope − weight = 0. **29.** The upper limit he can lift is a load equal to his weight. Beyond that he leaves the ground! **31.** The force that prevents downward acceleration is the support (normal) force—the table pushing up on the book. **33.** Normal force is greatest when the table surface is horizontal, and progressively decreases as the angle of tilt increases. As the angle of tilt approaches 90°, the normal force approaches zero. When the table surface is vertical, it no longer presses on the book, which then freely falls. **35.** If the upward force were the only force acting, the book indeed would rise. But another force, that due to gravity, results in the net force being zero. **37.** Without water, the support force is **W**. With water, the support force is **W** + **w**. **39.** The friction force is 600 N for constant speed. Only then will $\Sigma F = 0$. **41.** The net force on the rope is zero. The force exerted by the rope on each person is 300 N (in opposite directions). **43.** We aren't swept off because we are traveling just as fast as the Earth, just as in a fast-moving vehicle you move along with the vehicle. Also, there is no atmosphere through which the Earth moves, which would do more than blow our hats off! **45.** A body in motion tends to remain in motion, so you move with the moving Earth whether or not your feet are in contact with it. When you jump, your horizontal motion matches that of the Earth, traveling with it. Hence the wall does not slam into you. **47.** This is similar to Exercise 46. If the ball is shot while the train is moving at constant velocity (constant speed in a straight line), its horizontal motion before, during, and after being fired is the same as that of the train; so the ball falls back into the chimney as it would have if the train were at rest. If the train changes speed, the ball will miss because the ball's horizontal speed will match the train speed as the ball is fired.

but not when the ball lands. Similarly, on a circular track the ball will also miss the chimney because the ball will move along a tangent to the track while the train turns away from this tangent. So the ball returns to the chimney in the first case, and misses in the second and third cases because of the *change* in motion.

CHAPTER TWO PROBLEMS

1. Since each scale reads 350 N, Lucy's total weight is **700 N.** **3.** From the equilibrium rule, $\Sigma F = 0$, the upward forces are 800 N, and the downward forces are 500 N + the weight of the staging. So the staging must weigh **300 N.**

CHAPTER THREE RANKING

1. D, C, A, B **3a.** B, A=C **3b.** A, B, C **3c.** C, B, A

CHAPTER THREE EXERCISES

1. The impact speed will be the relative speed, 2 km/h (100 km/h − 98 km/h = 2 km/h). **3.** Your fine for speeding is based on your instantaneous speed; the speed registered on a speedometer or a radar gun. **5.** Constant velocity means no acceleration, so the acceleration of light is zero. **7.** The car approaches you at twice the speed limit. **9.** Acceleration occurs when the speedometer reading changes. No change, no acceleration. **11a.** Yes, because of the change of direction. **11b.** Yes, because of velocity changes. **13.** You cannot say which car underwent the greater acceleration unless you know the times involved. **15.** A vertically thrown ball has zero speed at the top of its trajectory, but acceleration there is g. **17a.** Yes. For example, an object sliding or rolling horizontally on a frictionless plane. **17b.** Yes. For example, a vertically thrown ball at the top of its trajectory. **19.** Only on the middle hill does speed along the path decrease with time, for the hill becomes less steep as motion progresses. When the hill levels off, acceleration will be zero. On the left hill, acceleration is constant. On the right hill, acceleration increases as the hill becomes steeper. In all three cases, speed increases. **21.** The acceleration is zero, for no change in velocity occurs. Whenever the change in velocity is zero, the acceleration is zero. If the velocity is "steady," "constant," or "uniform," the change in velocity is zero. Remember the definition of acceleration! **23.** At 0° the acceleration is zero. At 90° the acceleration is that of free fall, g. So the range of accelerations is 0 to g, or 0 to 10 m/s². **25.** Speed readings would increase by 10 m/s each second. **27.** The acceleration of free fall at the end of the fifth, tenth, or any number of seconds will be g. Its *velocity* has different values at different times, but since it is free from the effects of air resistance, its *acceleration* remains a constant g. **29.** Whether up or down, the rate of change of speed with respect to time is 10 m/s², so each second while going up the speed decreases by 10 m/s. Coming down, the speed increases 10 m/s each second. So with no air drag, the time ascending equals the time descending. **31.** When air drag affects motion, the ball thrown upward returns to its starting level with less speed than its initial speed, and also less speed than the ball tossed downward. So the downward thrown ball hits the ground below with a greater speed. **33.** Its acceleration would actually be less if the air resistance it encounters at high speed retards its motion. (We will treat this concept in detail in Chapter 4.) **35.** The acceleration due to gravity remains a constant g at all points along its path as long as no other forces like air drag act on the projectile. **37.** If it were not for the slowing effect of the air, raindrops would strike the ground with the speed of high-speed bullets! **39.** Air drag decreases speed. So a tossed ball will return with less speed than it possessed initially. **41.** (a) Average speed is greater for the ball on track B. (b) The instantaneous speed at the ends of the tracks is the same because the speed gained on the down-ramp for B is equal to the speed lost on the up-ramp side. (Many people get the wrong answer for Exercise 40 because they assume that since the balls end up with the same speed that they roll for the same time. Not so.) **43.** On the Moon the acceleration due to gravity is considerably less, so hang time would be considerably more (six times more for the same speed!). **45.** Open exercise.

CHAPTER THREE PROBLEMS

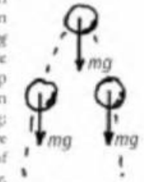
1. Since it starts going up at 30 m/s and loses 10 m/s each second, its time going up is 3 seconds. Its time returning is also 3 seconds, so it's in the air for a total of 6 seconds. Distance up (or down) is $1/2gt^2 = 5 \times 3^2 =$ **45 m.** Or from $d = vt$, where average velocity is $(30 + 0)/2 = 15$ m/s, and time is 3 seconds, we also get $d = 15 \text{ m/s} \times 3 \text{ s} = 45$ m. **3.** Using $g = 10 \text{ m/s}^2$, we see that $v = gt = (10 \text{ m/s}^2)(10 \text{ s}) = 100$ m/s; $v_{av} = \frac{(v_{beginning} + v_{final})}{2} = \frac{(0 + 100)}{2} =$ **50 m/s**, downward. We can get "how far" from either $d = v_{av}t = (50 \text{ m/s})(10 \text{ s}) =$ **500 m**, or equivalently, $d = 1/2gt^2 = 5(10)^2 = 500$ m. (Physics is nice . . . we get the same distance using either formula!) **5.** From $d = 1/2gt^2 = 5t^2$, $t = \sqrt{d/5} = \sqrt{(0.6)/5} =$ 0.35 s. Double for a hang time of **0.7 s.**

CHAPTER FOUR RANKING

1. (a) D, A=B=C (b) A=C, B=D **3.** (a) A=B=C (b) C, A, B

CHAPTER FOUR EXERCISES

1. Yes, as illustrated by a ball thrown vertically into the air. Its velocity is initially up, and finally down, all the while accelerating at a constant g. **3.** No. An object can move in a curve only when a force acts. With no force its path would be a straight line. **5.** No, inertia involves mass, not weight. **7.** The force of friction on the crate must be $-F$. Then the net force on it is zero, which accounts for the state of rest. **9.** Shake the boxes. The box that offers the greater resistance to acceleration is the more massive box, the one containing the sand. **11.** A massive cleaver is more effective in chopping vegetables because its greater mass contributes to greater tendency to keep moving as the cleaver severs the food. **13.** Neither the mass nor the weight of a junked car changes when it is crushed. What does change is its volume, not to be confused with mass and weight. **15.** A dieting person loses mass. Interestingly, a person can lose weight by simply being farther from the center of the Earth, at the top of a mountain, for example. **17.** One kg of mass weighs 2.2 pounds at the Earth's surface. If you weigh 100 pounds, for example, your mass is 100 lb/2.2 kg/lb = 45 kg. Your weight in newtons, using the relationship weight = mg, is then 45 kg × 10 N/kg = 450 N. **19.** Friction is the force that keeps the crate picking up the same amount of speed as the truck. With no friction, the accelerating truck would leave the crate behind. **21.** Acceleration (slowing the car) is opposite to velocity (direction car moves). **23.** Acceleration is the ratio force/mass (Newton's second law), which in free fall is just weight/mass = $mg/m = g$. Since weight is proportional to mass, the ratio weight/mass is the same whatever the weight of a body. **25.** The forces acting horizontally are the driving force provided by friction between the tires and the road, and resistive forces are mainly air drag. These forces cancel and the car is in dynamic equilibrium with a net force of zero. **27.** The *net* force on the wagon, your pull plus friction, is zero. So $\Sigma F = 0$. **29.** The velocity of the ascending coin decreases while its acceleration remains constant (in the absence of air resistance). **31.** The force vector mg is the same at all locations. Acceleration g is therefore the same at all locations also. **33.** At the top of your jump your acceleration is g. Let the equation for acceleration via Newton's second law guide your thinking: $a = F/m = mg/m = g$. If you said zero, you're implying the force of gravity ceases to act at the top of your jump—not so! **35.** When you stop suddenly, your velocity changes rapidly, which means a large acceleration of stopping. By Newton's second law, this means the force that acts on you is also large. Experiencing a large force is what hurts you. **37.** When driving at constant velocity, the zero net force on the car results from the driving force that your engine supplies against the friction drag force. You continue to apply a driving force to offset the drag force that otherwise would slow the car. **39.** High-speed grains of sand grazing the Earth's atmosphere burn up because of friction against the air. **41.** Both forces have the same magnitude. This is easier to understand if you visualize the parachutist at rest in a strong updraft—static equilibrium. Whether equilibrium is static or dynamic, the net force is zero. **43.** The net force is mg, 10 N (or more precisely, 9.8 N). **45.** Agree with your friend. Although acceleration decreases, the ball is nevertheless gaining speed. It will do so until it reaches terminal speed. Only then will it not continue gaining speed. **47.** In each case the paper reaches terminal speed, which means air drag equals the weight of the paper. So air resistance will be the same on each! Of course the wadded paper falls faster for air resistance to equal the weight of the paper. **49.** When anything falls at constant velocity, air drag and gravitational force are equal in magnitude. Raindrops are merely one example. **51.** When a parachutist opens her chute she slows down. That means she accelerates upward. **53.** Just before a falling body attains terminal velocity, there is still a downward acceleration because gravitational force is still greater than air resistance. When the air resistance builds up to equal the gravitational force, terminal velocity is reached. Then air resistance is equal and opposite to gravitational force.



55. The sphere will be in equilibrium when it reaches terminal speed—which occurs when the gravitational force on it is balanced by an equal and opposite force of fluid drag. **57.** The heavier tennis ball will strike the ground first for the same reason the heavier parachutist in Figure 4.15 strikes the ground first. Note that although the air resistance on the heavier ball is smaller relative to the ball's weight, it is actually greater than the air resistance that acts on the other ball. Why? Because the heavier ball falls faster, and air resistance is greater at greater speed. **59.** The ball rises in less time than it falls. By exaggerating the circumstance and considering the feather example in the preceding answer, the time for the feather to flutter from its maximum altitude is clearly longer than the time it took to attain that altitude. The same is true for the not-so-obvious case of the ball.

CHAPTER FOUR PROBLEMS

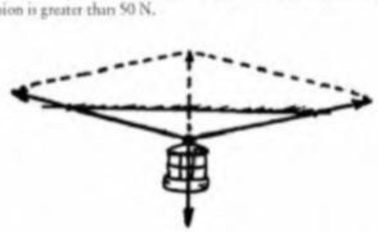
1. 1 N × 1 lb/4.45 N = 0.22 lb. **3.** $a = F/m$ = 200 N/40 kg = **5 m/s²**. **5.** For the jet: $a = F/m$ = 2(30,000 N)/30,000 kg = **2 m/s²**. •**7.** (a) Force on the bus is Ma. New acceleration = same force/new mass = $Ma/(M + M/6) = 6Ma/(6M + M) = 6Ma/7M$ = **(6/7)a.** **7.** (b) New acceleration = $(6/7)a$ = (6/7)1.2 m/s² = **1.0 m/s²**.

CHAPTER FIVE RANKING

1. B, A, C **3.** B, A, C

CHAPTER FIVE EXERCISES

1. The answer is given in the equation $a = F/m$. As fuel is burned, the mass of the rocket becomes less. As m decreases as F remains the same, a increases! There is less mass to be accelerated as fuel is consumed. **3.** No, for each hand pushes equally on the other in accord with Newton's third law—you cannot push harder on one hand than the other. **5.** (a) Two force pairs act; Earth's pull on apple (action), and apple's pull on Earth (reaction). Hand pushes apple upward (action), and apple pushes hand downward (reaction). (b) With no air drag, one force pair acts; Earth's pull on apple, and apple's pull on Earth. **7.** (a) Action; bat hits ball. Reaction; ball hits bat. (b) While in flight there are two interactions, one with the Earth's gravity and the other with the air. Action: Earth pulls down on ball (weight). Reaction: ball pulls up on Earth. And, action: air pushes ball, and reaction: ball pushes air. **9.** When the ball exerts a force on the floor, the floor exerts an equal and opposite force on the ball—hence bouncing. The force of the floor on the ball provides the bounce. **11.** Yes, it's true. The Earth can't pull you downward without you simultaneously pulling Earth upward. The acceleration of Earth is negligibly small, and not noticed, due to its enormous mass. **13.** The scale will read 100 N, the same it would read if one of the ends were tied to a wall instead of tied to the 100-N hanging weight. Although the net force on the system is zero, the tension in the rope within the system is 100 N, as shown on the scale reading. **15.** When the barbell is accelerated upward, the force exerted by the athlete is greater than the weight of the barbell (the barbell, simultaneously, pushes with greater force against the athlete). When acceleration is downward, the force supplied by the athlete is less. **17.** When you pull up on the handlebars, the handlebars simultaneously pull down on you. This downward force is transmitted to the pedals. **19.** When the climber pulls the rope downward, the rope simultaneously pulls the climber upward—the direction desired by the climber. **21.** When you push the car, you exert a force on the car. When the car simultaneously pushes back on you, that force is on you—not the car. You don't cancel a force on the car with a force on you. For cancellation, the forces have to be equal and opposite and act on the same object. **23.** As in the preceding exercise, the force on each cart will be the same. But since the masses are different, the accelerations will differ. The twice-as-massive cart will undergo only half the acceleration of the less-massive cart. **25.** Both will move. Ken's pull on the rope is transmitted to Joanne, causing her to accelerate toward him. By Newton's third law, the rope pulls back on Ken, causing him to accelerate toward Joanne. **27.** The tension in the rope is 250 N. Since they aren't accelerating, each must experience a 250-N force of friction via the ground. This is provided by pushing against the ground with 250 N. **29.** The forces on each are the same in magnitude, and their masses are the same, so their accelerations will be the same. They will slide equal distances of 6 meters to meet at the midpoint. **31.** Vector quantities are velocity and acceleration. All others are scalars. **33.** A pair of vectors can cancel only if they are equal in magnitude and opposite in direction. But three unequal vectors can combine to equal zero—the vectors comprising the tensions in the ropes that support Nellie in Figure 5.26, for example. **35.** No, no, no. A vector quantity and scalar quantity can never be added. **37.** Tension will be greater for a small sag. That's because large vectors in each side of the rope supporting the bird are needed for a resultant that is equal and opposite to the bird's weight. **39.** By the parallelogram rule, the tension is greater than 50 N.



41. To climb upward means pulling the rope downward, which moves the balloon downward as the person climbs. **43.** (a) The other vector is upward as shown.

(b) It is called the normal force. **45.** (a) As shown.

(b) Upward tension force is greater resulting in an upward net force. **47.** The acceleration of the stone at the top of its path, or anywhere the net force on the stone is mg, is g. **49.** (a) As shown below.

(b) Note the resultant of the two normal forces is equal and opposite to the stone's weight.

CHAPTER FIVE PROBLEMS

1. a. $a = \Delta v/\Delta t$ = (25 m/s)/(0.05 s) = **500 m/s²**. b. $F = ma$ = (0.003 kg)(500 m/s²) = **1.5 N**, which is about 1/3 pound. c. By Newton's third law, the same amount, **1.5 N.** **3.** They hit your face with the resultant of the horizontal and vertical components: $R = \sqrt{[(3.0\text{ m/s})^2 + (4.0\text{ m/s})^2]}$ = **5 m/s.** **5.** Ground velocity $V = \sqrt{[(100\text{ km/h})^2 + (100\text{ km/h})^2]}$ = **141 km/h, 45° northeast** (45° from the direction of the wind). The velocity relative to the ground makes the diagonal of a 45°-45°-90° triangle. •**7.** (a) From the 3rd law $F_{\text{on 2m puck}} = F_{\text{on m puck}} \Rightarrow 2m(a_{2m}) = m(a_m) \Rightarrow 2m\dfrac{\Delta v_{2m}}{\Delta t} = m\dfrac{\Delta v_m}{\Delta t}$

Since the force acts for exactly the same Δt for each mass $\Rightarrow \Delta v_{2m} = \frac{1}{2}\Delta v_m$. Since both masses start out at rest $\Rightarrow v_{2m} = \frac{1}{2}v_m$. (b) $v_{2m} = \frac{1}{2}v_m = \frac{1}{2}(0.4\,\frac{\text{m}}{\text{s}}) = \mathbf{0.2\,\frac{m}{s}}$.

CHAPTER SIX RANKING

1. (a) B, D, C, A (b) B, D, C, A **3.** (a) A, B, C (b) A, B, C (c) C, B, A (d) A, B, C

CHAPTER SIX EXERCISES

1. The momentum of a supertanker is enormous, which means enormous impulses are needed for changing motion—which are produced by applying modest forces over long periods of time. Due to the force of water resistance, over time it coasts 25 kilometers to sufficiently reduce the momentum. **3.** Air bags lengthen the time of impact thereby reducing the force of impact. **5.** Stretching ropes extend the time during which momentum decreases, thereby decreasing the jolting force of the rope. Note that bringing a person to a stop more gently does *not* reduce the impulse. It only reduces the force. **7.** Bent knees will allow more time for momentum to decrease, therefore reducing the force of landing. **9.** An extended hand allows more time for reducing the momentum of the ball to zero, resulting in a smaller force of impact on your hand. **11.** The blades impart a downward impulse to the air and produce a downward change in the momentum of the air. The air at the same time exerts an upward impulse on the blades, providing lift. (Newton's third law applies to impulses as well as forces.) **13.** Its momentum is the same (its weight might change, but not its mass). **15.** The large momentum of the spurting water is met by a recoil that makes the hose difficult to hold, just as a shotgun is difficult to hold when it fires birdshot. **17.** Impulse is force × time. The forces are equal and opposite, by Newton's third law, and the times are the same, so the impulses are equal and opposite. **19.** The momentum of the falling apple is transferred to the Earth. Interestingly, when the apple is released, the Earth and the apple move toward each other with equal and oppositely directed momenta. Because of the Earth's enormous mass, its motion is imperceptible. When the apple and Earth hit each other, their momenta are brought to a halt—zero, the same value as before. **21.** The lighter gloves have less padding, and less ability to extend the time of impact, and therefore result in greater forces of impact for a given punch. **23.** Without this slack, a locomotive might simply sit still and spin its wheels. The loose coupling enables a longer time for the entire train to gain momentum, requiring less force of the locomotive wheels against the track. In this way, the overall required impulse is broken into a series of smaller impulses. (This loose coupling can be very important for braking as well.) **25.** In jumping, you impart the same momentum to both you and the canoe. This means you jump from a canoe that is moving away from the dock, reducing your speed relative to the dock, so you don't jump as far as you expected to. **27.** To get to shore, the person may throw keys, coins or an item of clothing. The momentum of what is thrown will be accompanied by the thrower's oppositely directed momentum. In this way, one can recoil toward shore. (One can also inhale facing the shore and exhale facing away from the shore.) **29.** Regarding Exercise 27: If one throws clothing, the force that accelerates the clothes will be paired with an equal and opposite force on the thrower. This force can provide recoil toward shore. Regarding Exercise 28: According to Newton's third law, whatever forces you exert on the ball, first in one direction, then in the other, are balanced by equal forces that the ball exerts on you. Since the forces on the ball give it no final momentum, the forces it exerts on you also give no final momentum. **31.** When two objects interact, the forces they exert on each other are equal and opposite and these forces act simultaneously, so the impulses are equal and opposite. Therefore their changes of momenta are equal and opposite, and the total change of momentum of both objects is zero. **33.** An impulse is responsible for the change in momentum, resulting from a component of gravitational force parallel to the inclined plane. **35.** A system is any object or collection of objects. Whatever momentum such a system has, in the absence of external forces, that momentum remains unchanged—what the conservation of momentum is about. **37.** For the system comprised of ball + Earth, momentum is conserved for the impulses acting are internal impulses. The momentum of the falling apple is equal in magnitude to the momentum of the Earth toward the apple. **39.** Let the system be the car and the Earth together. As the car gains downward momentum during its fall, the Earth gains equal upward momentum. When the car crashes and its momentum is reduced to zero, the Earth stops its upward motion, also reducing its momentum to zero. **41.** Bullets bouncing from the steel plate experience a greater impulse. The plate will be moved more by bouncing bullets than by bullets that stick. **43.** If the air is brought to a halt by the sail, then the impulse against the sail will be equal and opposite to the impulse on the fan. There will be no net impulse and no change in momentum. The boat will remain motionless. Bouncing counts! **45.** Yes, because you push upward on the ball you toss, which means the ball pushes downward on you, which is transmitted to the ground. So normal force increases as the ball is thrown (and goes back to equal *mg* after the ball is released). **47.** In accord with Newton's third law, the forces on each are equal in magnitude, which means the impulses are likewise equal in magnitude, which means both undergo equal changes in momentum. **49.** Cars brought to a rapid halt experience a change in momentum, and a corresponding impulse. But greater momentum change occurs if the cars bounce, with correspondingly greater impulse and therefore greater damage. Less damage results if the cars stick upon impact than if they bounce apart. **51.** The direction of momentum is to the left, for the momentum of the 0.8-kg car is greater. By magnitude, net momentum = (0.5)(1) − (0.8)(1.2) = −0.46. **53.** Yes, you exert an impulse on a ball that you throw. You also exert an impulse on the ball when you catch it. Since you change its momentum by the same amount in both cases, the impulse you exert in both cases is the same. To catch the ball and then throw it back again at the same speed requires twice as much impulse. On a skateboard, you'd recoil and gain momentum when throwing the ball, you'd also gain the same momentum by catching the ball, and you'd gain twice the momentum if you did both—catch and then throw the ball at its initial speed in the opposite direction. **55.** The impulse will be greater if the hand is made to bounce because there is a greater change in the momentum of hand and arm, accompanied by a greater impulse. The force exerted on the bricks is equal and opposite to the force of the bricks on the hand. Fortunately, the hand is resilient and toughened by long practice. **57.** Their masses are the same; half speed for the coupled particles means equal masses for the colliding and the target particles. This is like the freight cars of equal mass shown in Figure 6.14. **59.** The chunks have equal and opposite momenta, with the smaller-mass chunk having greater speed ($mV = Mv$).

CHAPTER SIX PROBLEMS

1. The bowling ball has a momentum of (10 kg)(6 m/s) = 60 kg · m/s, which has the magnitude of the impulse to stop it. That's **60 N · s.** (Note that unit N · s = kg · m/s.) **3.** From $Ft = \Delta mv$, $F = \frac{\Delta mv}{t}$ = [(75 kg)(25 m/s)]/0.1s = **18,750 N.** **5.** Momentum after collision is zero, which means the net momentum before collision must have been zero. So the 1-kg ball must be moving **twice as fast** as the 2-kg ball so that the magnitudes of their momenta are equal. **7.** $\text{Momentum}_{before} = \text{momentum}_{after}$ (5kg)(1m/s) + (1kg)v = 0 5 m/s + v = 0 v = −5 m/s So if the little fish approaches the big fish at 5 m/s, the momentum after will be zero. **9.** Momentum conservation can be applied in both cases. (a) For head-on motion the total momentum is zero, so the wreckage after collision is **motionless.** (b) As shown in Figure 6.18, the total momentum is directed to the northeast—the resultant of two perpendicular vectors, each of magnitude 20,000 kg · m/s. It has magnitude 28,200 kg · m/s. The speed of the wreckage is this momentum divided by the total mass, v = (28,200 kg · m/s)/(2000 kg) = **14.1 m/s.**

CHAPTER SEVEN RANKING

1. (a) B, A, C (b) C, B, A (c) C, B, A **3.** (a) D, B, C, E, A (b) D, B, C, E, A (c) A, E, C, B, D

CHAPTER SEVEN EXERCISES

1. Stopping a lightly loaded truck of the same speed is easier because it has less KE and will therefore require less work to stop. (An answer in terms of impulse and momentum is also acceptable.) **3.** Your friend does twice as much work (4 × 1/2 > 1 × 1). **5.** More force is required to stretch the strong spring, so more work is done in stretching it the same distance as a weaker spring. **7.** Solar energy is merely energy from the Sun. Solar power, like power in general, is the *rate* at which energy is transferred. Solar power is therefore the same from hour to hour, whereas the amount of solar energy depends on the amount of time energy is transferred. **9.** When a rifle with a long barrel is fired, more work is done as the bullet is pushed through the longer distance. A greater KE is the result of the greater work, so of course, the bullet emerges with a greater velocity. (Note that the force acting on the bullet is not constant, but decreases with increasing distance inside the barrel.) **11.** The KE of the tossed ball relative to occupants in the airplane does not depend on the speed of the airplane. The KE of the ball relative to observers on the ground below, however, is a different matter. KE, like velocity, is relative. **13.** The energy goes mostly into frictional heating of the air. **15.** The KE of a pendulum bob is maximum where it moves fastest, at the lowest point; PE is maximum at the uppermost points. When the pendulum bob swings by the point that marks half its maximum height, it has half its maximum KE, and its PE is halfway between its minimum and maximum values. If we define PE = 0 at the bottom of the swing, the place where KE is half its maximum value is also the place where PE is half its maximum value, and KE = PE at this point. (By energy conservation: Total energy = KE + PE.) **17.** Yes to both, relative to Earth, because work was done to lift it in Earth's gravitational field and to impart speed to it. **19.** According to the work-energy theorem, twice the speed corresponds to 4 times the energy, and therefore 4 times the driving distance. At 3 times the speed, driving distance is 9 times as much. **21.** On the hill there is a component of weight along the surface, but on the horizontal there is none. **23.** The fact that the crate pulls back on the rope in action-reaction fashion is irrelevant. The work done on the crate by the rope is the horizontal component of rope force that acts on the crate multiplied by the distance the crate is moved by that force—period. How much of this work produces KE or thermal energy depends on the amount of friction acting. **25.** A Superball will bounce higher than its original height if thrown downward, but if simply dropped, no way. Such would violate the conservation of energy. **27.** Kinetic energy is a maximum as soon as the ball leaves the hand. Potential energy is a maximum when the ball has reached its zenith. **29.** You agree with your second classmate. The coaster could just as well encounter a low summit before or after a higher one, so long as the higher one is enough lower than the initial summit to compensate for energy dissipation by friction. **31.** Yes, a car burns more gasoline when its lights are on. The overall consumption of gasoline does not depend on whether or not the engine is running. Lights and other devices are run off the battery, which "runs down" the battery. The energy used to recharge the battery ultimately comes from the gasoline. **33.** If KEs are the same but masses differ, then the ball with smaller mass has the greater speed. That is, $1/2\ Mv^2 = 1/2\ mV^2$. Likewise with molecules, where lighter ones move faster on the average than more massive ones. (We will see in Chapter 15 that temperature is a measure of average molecular KE—lighter molecules in a gas move faster than same-temperature heavier molecules.) **35.** A machine can multiply force or multiply distance, both of which can be of value. **37.** Einstein's $E = mc^2$. (More on this in Chapters 34 and 35). **39.** The work that the rock does on the ground is equal to its PE before being dropped, mgh = 100 joules. The force of impact, however, depends on the distance that the rock penetrates into the ground. If we do not know this distance we cannot calculate the force. (If we knew the time during which the impulse occurs we could calculate the force from the impulse–momentum relationship—but not knowing the distance or time of the rock's penetration into the ground, we cannot calculate the force.) **41.** When air resistance is a factor, the ball will return with less speed (discussed in Exercise 58 in Chapter 4). It therefore will have less KE. You can see this directly from the fact that the ball loses mechanical energy to the air molecules it encounters, so when it returns to its starting point and to its original PE, it will have less KE. This does not contradict energy conservation, for energy is transformed, not destroyed. **43.** The other 15 horsepower is supplied by electric energy from the batteries (which are ultimately recharged using energy from gasoline). **45.** The question can be restated: Is $(30^2 - 20^2)$ greater or less than $(20^2 - 10^2)$? We see that $(30^2 - 20^2) = (900 - 400) = 500$, which is considerably greater than $(20^2 - 10^2) = (400 - 100) = 300$. So KE changes more for a given Δv at the higher speed. **47.** When the mass is doubled with no change in speed, both momentum and KE are doubled. **49.** Both have the same momentum, but the 1-kg one, the faster one, has the greater KE. **51.** Zero KE means zero speed, so momentum is also zero. **53.** Not at all. For two objects of the same KE, the one of greater mass has greater momentum. (The mathematical relationship is $p^2 = 2m \times \text{KE}$.) **55.** Scissors and shears are levers. The applied force is normally exerted over a short distance for scissors so that the output force is exerted over a relatively long distance (except when you want a large cutting force like cutting a piece of tough rope, and you place the rope close to the "fulcrum" so you can multiply force). With metal-cutting shears, the handles are long so that a relatively small input force is exerted over a long distance to produce a large output force over a short distance. **57.** Energy is transformed into nonuseful forms in an inefficient machine, and is "lost" only in the loose sense of the word. In the strict sense, it can be accounted for and is therefore not lost. **59.** In the popular sense, conserving energy means not wasting energy. In the physics sense energy conservation refers to a law of nature that underlies natural processes. Although energy can be wasted (which really means transforming it from a more useful to a less useful form), it cannot be destroyed. Nor can it be created. Energy is transferred or transformed, without gain or loss. That's what a physicist means in saying energy is conserved. **61.** Your friend is correct, for changing KE requires work, which means more fuel consumption and decreased air quality. **63.** Once used, energy cannot be regenerated, for it dissipates into less useful forms in the environment—inconsistent with the term "renewable energy." Renewable energy refers to energy derived from renewable resources—trees, for example.

CHAPTER SEVEN PROBLEMS

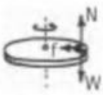
1. Work = $\Delta E = \Delta mgh$ = 300 kg × 10 N/k × 6 m = **18,000 J.** **3.** At three times the speed, it has 9 times (3^2) the KE and will skid 9 times as far—**135 m.** Since the frictional force is about the same in both cases, the distance has to be 9 times as great for 9 times as much work done by the pavement on the car. **5.** From $F \times d = F' \times d/3$, we see $F' = 3F$ = **150 N.** **7.** $(F \times d)_{in} = (F \times d)_{out}$; $F \times 2\text{ m} = 5000\text{ N} \times 0.2\text{ m}$; $F = [(5000\text{ N})(0.2\text{ m})]/2\text{ m} = 500\text{ N}$. **9.** Power = Fd/t = 2J/1s = **2 watts.**

CHAPTER EIGHT RANKING

1. B, C, A **3.** B, A, C **5.** C, A, B

CHAPTER EIGHT EXERCISES

1. Sam's rotational speed ω, RPMs, remains the same, assuming the Ferris wheel is powered and not "free wheeling." Sam's tangential speed, $v = r\omega$ is half because the radial distance r is half. Answers different because tangential speed v is not the same as rotational speed ω. **3.** The tangential speeds are equal, for they have the same speed as the belt. The smaller wheel rotates twice as fast because for the same tangential speed, and r half, ω must be twice. $v_{(big\ wheel)} = r\omega$; $v_{(small\ wheel)} = (r/2 \times 2\omega)$. **5.** For the same twisting speed ω the greater distance r means a much greater speed v. **7.** Yes, rotational inertia is enhanced with long legs. The bird's foot is directly below the bird's CM. **9.** Two conditions are necessary for mechanical equilibrium, $\Sigma F = 0$ and $\Sigma Torque = 0$. **11.** Friction by the road on the tires produces a torque about the car's CM. When the car accelerates forward, the friction force points forward and rotates the car upward. When braking, the direction of friction is rearward, and the torque rotates the car in the opposite direction so the rear end rotates upward (and the nose downward). **13.** The ball to reach the bottom first is the one with the least rotational inertia compared with its mass—that's the softball. **15.** Don't say the same, for the water slides inside the can while the ice is made to roll along with the can. When the water inside slides, it contributes weight rather than rotational inertia to the can. So the can of water will roll faster. (It will even beat a hollow can.) **17.** Advise the youngster to use wheels with the least rotational inertia—lightweight solid ones without spokes (disklike rather than hooplike). **19.** No, for by definition, a torque requires both force and a lever arm. **21.** No, because there is zero lever arm about the CM. Zero lever arm means zero torque. **23.** Friction between the ball and the lane provides a torquar, which spins the ball. **25.** With your legs straight out, your CG is farther away and you exert more torque sitting up. So sit-ups are more difficult with legs straight out. **27.** You bend forward when carrying a heavy load on your back to shift the CG of you and your load above the area bounded by your feet—otherwise you topple backward. **29.** Two buckets are easier because you may stand upright while carrying a bucket in each hand. With two buckets, the CG will be in the center of the support base provided by your feet, so there is no need to lean. (The same can be accomplished by carrying a single bucket on your head.) **31.** The Earth's atmosphere is a nearly spherical shell, which like a basketball, has its center of mass at its center, i.e., at the center of the Earth. **33.** It is dangerous to pull open the upper drawers of a fully-loaded file cabinet that is not secured to the floor because the CG of the cabinet can easily be shifted beyond the support base of the cabinet. When this happens, the torque that is produced causes the cabinet to topple over. **35.** An object is stable when its PE must be raised in order to tip it over, or equivalently, when its PE must be increased before it can topple. By inspection, the first cylinder undergoes the least change in PE compared to its weight in tipping. This is because of its narrow base. The third truncated pyramid requires the most work. **37.** The track will remain in equilibrium as the balls roll outward. This is because the CG of the system remains over the fulcrum. For example, suppose the billiard ball has twice the mass of the golf ball. By conservation of momentum, the twice-as-massive ball will roll outward at half the speed of the lighter ball, and at any time be half as far from the starting point as the lighter ball. So there is no CG change in the system of the two balls. So the torques produced by the weights of the balls multiplied by their relative distances from the fulcrum are equal at all points—because at any time the less massive ball has a correspondingly larger lever arm. **39.** In accord with the equation for centripetal force, twice the speed corresponds to four times the force. **41.** Yes. Letting the equation for centripetal force guide our thinking, increased speed at the same radial distance means greater centripetal force. If this greater centripetal force isn't provided, the car will skid. **43.** On a banked road the normal force, at right angles to the road surface, has a horizontal component that provides the centripetal force. Even on a perfectly slippery surface, this component of the normal force can provide sufficient centripetal force to keep the car on the track. **45.** There is no component of force parallel to the direction of motion, which work requires. **47.** See art on right. **49.** (a) Except for the vertical force of friction, no other vertical force except the weight of the motorcycle + rider exists. Since there is no change of motion in the vertical direction, the force of friction must be equal and opposite to the weight of motorcycle + rider. (b) The horizontal vector indeed represents the normal force. Since it is the only force acting in the radial direction, horizontally, it is also the centripetal force. So it's both. **51.** As you crawl outward, the rotational inertia of the system increases (like the masses held outward in Figure 8.53). In accord with the conservation of angular momentum, crawling toward the outer rim increases the rotational inertia of the spinning system and decreases the angular speed. **53.** Rotational inertia would increase. By angular momentum conservation, the rotation of the Earth would decrease (just as a skater spins slower with arms outstretched), tending to make a longer day. **55.** In accord with the conservation of angular momentum, if mass moves closer to the axis of rotation, rotational speed increases. So the day would be ever so slightly shorter. **57.** Without the small rotor on its tail, the helicopter and the main rotor would rotate in opposite directions. The small rotor provides a torque to offset the rotational motion that the helicopter would otherwise have. **59.** Gravitational force acting on every particle by every other particle causes the cloud to condense. The decreased radius of the cloud is then accompanied by an increased angular speed because of angular momentum conservation. The increased speed results in many stars being thrown out into a dish-like shape.



CHAPTER EIGHT PROBLEMS

1. In accord with $v = r\omega$, the greater the radius (or diameter), the greater the tangential speed. So the wide part rolls faster. It rolls $9/6 = 3/2 =$ **1.5 times faster.** **3.** The mass of the rock is **1 kg.** (This is a reverse of the Check Yourself question and answer in the chapter!) **5.** From $F = mv^2/r$, substituting, $T = mv^2/L$. (a) Rearranging, $m = TL/v^2$. (b) Substituting numerical values, $m = (10\ \text{N})(2\ \text{m})/(2\ \text{m/s})^2 =$ **5kg.** **7.** (a) In the absence of an unbalanced external torque the angular momentum of the system is conserved. So $(\text{Angular momentum})_{\text{initial}} = (\text{Angular momentum})_{\text{final}}$ $\Rightarrow mv_0L = mv_{\text{new}}(0.33L) \Rightarrow v_{\text{new}} = v_0\left(\frac{L}{0.33L}\right) = \frac{v_0}{0.333}$

(b) $v_{\text{new}} = \frac{v_0}{0.33} = \frac{1.0}{0.33}\frac{\text{m}}{\text{s}} = \mathbf{3.0\frac{m}{s}}$.

CHAPTER NINE RANKING

1. B=C, A, D **3.** (a) B, A=C, D (b) D, A=C, B **5.** B, A, C

CHAPTER NINE EXERCISES

1. Nothing to be concerned about on this consumer label. It simply states the universal law of gravitation, which applies to *all* products. It looks like the manufacturer knows some physics and has a sense of humor. **3.** In accord with the law of inertia, the Moon would move in a straight-line path instead of circling both the Sun and Earth. **5.** The force of gravity is the same on each because the masses are the same, as Newton's equation for gravitational force verifies. When dropped, the crumpled paper falls faster only because it encounters less air drag than the sheet. **7.** Your friend's misconception is a popular one. But investigation of the gravitational equation shows that no matter how big the distance, force never gets to zero. If it were zero, any space shuttle would fly off in a straight-line path! **9.** If gravity between the Moon and its rocks vanished, the rocks, like the Moon, would continue in their orbital path around the Earth. The assumption ignores the law of inertia. **11.** Nearer the Moon, because of its smaller mass and lesser pull at equal distances. **13.** In accord with Newton's 3rd law, the weight of the Earth in the gravitational field of Larry is 300 N, the same as the weight of Larry in Earth's gravitational field. **15.** Earth and Moon *do* rotate around a common point, but it's not midway between them (which would require both Earth and Moon to have the same mass). The point around which Earth and Moon rotate (called the *barycenter*) is within the Earth about 4600 km from the Earth's center. **17.** Letting the equation for gravitation guide your thinking, twice the diameter is twice the radius, which corresponds to 1/4 the astronaut's weight at the planet's surface. **19.** Your weight would decrease if the Earth expanded with no change in its mass and would increase if the Earth contracted with no change in its mass. Your mass and the Earth's mass don't change, but the distance between you and the Earth's center does change. Force is proportional to the inverse square of this distance. **23.** A person is weightless when the only force acting is gravity, and there is no support force. Hence the person in free fall is weightless. But more than gravity acts on the person falling at terminal velocity. In addition to gravity, the falling person is "supported" by air drag. **25.** Gravitational force is indeed acting on a person who falls off a cliff, and on a person in a space shuttle. Both are falling under the influence of gravity. **27.** The two forces are the normal force and mg, which are equal when the elevator doesn't accelerate, and unequal when the elevator accelerates. **29.** The jumper is weightless due to the absence of a support force. **31.** You disagree, for the force of gravity on orbiting astronauts is almost as strong as at Earth's surface. They feel weightless because of the absence of a support force. **33.** The gravitational force varies with distance. At noon you are closer to the Sun. At midnight you are an extra Earth diameter farther away. Therefore the gravitational force of the Sun on you is greater at noon. **35.** Just as differences in tugs on your shirt will distort the shirt, differences in tugs on the oceans distort the ocean and produce tides. **37.** No. Tides are caused by differences in gravitational pulls. If there are no differences in pulls, there are no tides. **39.** Lowest tides occur along with highest tides—spring tides. So the spring tide cycle consists of higher-than-average high tides followed by lower-than-average low tides (best for digging clams!). **41.** Because of its relatively small size, different parts of the Mediterranean Sea and other relatively small bodies of water are essentially equidistant from the Moon (or from the Sun). So one part is not pulled with any appreciably different force than any other part. This results in extremely tiny tides. Tides are caused by appreciable differences in pulls. **43.** The Moon does rotate like a top as it circles Earth. It rotates once per revolution, which is why we see only the same face. If it didn't rotate, we'd see the back side every half month. **45.** Earth. Microtides are greater where difference between your head and feet is greatest compared with the distance to the tide-pulling body, the Earth. **47.** In accord with the inverse-square law, twice as far from the Earth's center diminishes the value of g to 1/4 its value at the surface or $2.45\ \text{m/s}^2$. **49.** Your weight would be less down in the mine shaft. One way to explain this is to consider the mass of the Earth above you which pulls upward on you. This effect reduces your weight, just as your weight is reduced if someone pulls upward on you while you're weighing yourself. Or more accurately, we see that you are effectively within a spherical shell in which the gravitational field contribution is zero; and that you are being pulled only by the spherical portion below you. You are lighter the deeper you go, and if the mine shaft were to theoretically continue to the Earth's center, your weight moves closer to zero. **51.** More fuel is required for a rocket that leaves the Earth to go to the Moon than the other way around. This is because a rocket must move against the greater gravitational field of the Earth most of the way. (If launched from the Moon to the Earth, then it would be traveling with the Earth's field most of the way.) **53.** $F \sim m_1m_2/d^2$, where m_1 is the mass of the Sun (which doesn't change when forming a black hole), m_2 is the mass of the orbiting Earth, and d is the distance between the center of mass of Earth and the Sun. None of these terms change, so the force F that holds Earth in orbit does not change. **55.** The misunderstanding here is not distinguishing between a theory and a hypothesis or conjecture. A theory, such as the theory of universal gravitation, is a synthesis of a large body of information that encompasses well-tested and verified hypotheses about nature. Any doubts about the theory have to do with its applications to yet untested situations, not with the theory itself. One of the features of scientific theories is that they undergo refinement with new knowledge. (Einstein's general theory of relativity has taught us that in fact there are limits to the validity of Newton's theory of universal gravitation.)

CHAPTER NINE PROBLEMS

1. From $F = GmM/d^2$, three times d squared is $9\ d^2$, which means the force is **one ninth** of surface weight. **3.** From $F = G2m2M/(2d^2) =$

$4/4\,(GmM/d^2)$, with the same force of gravitation. **5.** $g = \frac{GM}{d^2} = \frac{(6.67 \times 10^{-11})(6.0 \times 10^{24})}{[(6380 + 200) \times 10^3]^2} = 9.24$ N/kg or 9.24 m/s^2; 9.24/9.8 = 0.94 or **94%.**

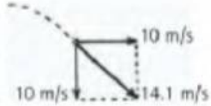
CHAPTER TEN RANKING

1. (a) B, C, A, D (b) B, D, A, C (c) A=B=C=D (10 m/s^2) **3.** (a) A, B, C (b) C, B, A

CHAPTER TEN EXERCISES

1. Divers can orient their bodies to change the force of air resistance so that the ratio of *net* force to mass is nearly the same for each. **3.** Yes, it will hit with a higher speed in the same time because the horizontal (not the vertical) component of motion is greater. **5.** The crate will not hit the Porsche, but will crash a distance beyond it determined by the height and speed of the plane. **7.** (a) The paths are parabolas. (b) The paths would be straight lines. **9.** Minimum speed occurs at the top, which is the same as the horizontal component of velocity anywhere along the path. **11.** Kicking the ball at angles greater than 45° sacrifices some distance to gain extra time. A kick greater than 45° doesn't go as far, but stays in the air longer, giving players on the kicker's team a chance to run downfield and be close to the player on the other team who catches the ball. **13.** Both balls have the same range (see Figure 10.9). The ball with the initial projection angle of 30°, however, is in the air for a shorter time and hits the ground first. **15.** Any vertically projected object has zero speed at the top of its trajectory. But if it is fired at an angle, only its vertical component of velocity is zero and the velocity of the projectile at the top is equal to its horizontal component of velocity. This would be 100 m/s when the 141-m/s projectile is fired at 45°. **17.** The hang time will be the same, in accord with the answer to the preceding exercise. Hang time is related to the vertical height attained in a jump, not on horizontal distance moved across a level floor. **19.** From Kepler's third law, $T^2 \sim R^3$, the period is greater when the distance is greater. So the periods of planets farther from the Sun are longer than our year. **21.** Speed does not depend on the mass of the satellite (just as free-fall speed does not). **23.** Gravitation supplies the centripetal force on satellites. **25.** Mars or any body in Earth's orbit would take the same time to orbit. The motion of a satellite, like that of a freely falling object, does not depend on mass. **27.** The Moon has no atmosphere (because escape velocity at the Moon's surface is less than the speeds of any atmospheric gases). A satellite 5 km above the Earth's surface is still in considerable atmosphere, as well as in range of some mountain peaks. Atmospheric drag is the factor that most determines orbiting altitude. **29.** Consider "Newton's cannon" fired from a tall mountain on Jupiter. To match the wider curvature of much larger Jupiter, and to contend with Jupiter's greater gravitational pull, the cannonball would have to be fired significantly faster. (Orbital speed about Jupiter is about 5 times that for Earth.) **31.** Upon slowing, it spirals in toward the Earth and in so doing has a component of gravitational force in its direction of motion which causes it to gain speed. Or put another way, in circular orbit the perpendicular component of force does no work on the satellite and t maintains constant speed. But when it slows and spirals toward Earth there is a component of gravitational force that does work to increase the KE of the satellite. **33.** Hawaii is closer to the equator, and therefore has a greater tangential speed about the polar axis. This speed could be added to the launch speed of a satellite and thereby save fuel. **35.** When descending, a satellite meets the atmosphere at almost orbital speed. When ascending, its speed through the air is considerably less and it attains orbital speed well above air drag. **37.** The component along the direction of motion does work on the satellite to change its speed. The component perpendicular to the direction of motion changes its direction of motion. **39.** When the velocity of a satellite is everywhere perpendicular to the force of gravity, the orbital path is a circle (see Figure 10.20). **41.** No way, for the Earth's center is a focus of the elliptical path (including the special case of a circle), so an Earth satellite orbits the center of the Earth. The plane of a satellite coasting in orbit always intersects the Earth's center. **43.** The inverse-square law of gravity finds gravity a mere 62 miles high very nearly as strong as it is on Earth's surface. Gravity is an inverse-square law phenomenon that has nothing to do with being above the atmosphere. **45.** Period is greater for satellites farther from Earth. **47.** It could be dropped by firing it straight backward at the same speed of the satellite. Then its speed relative to Earth would be zero, and it would fall straight downward. **49.** If the speed of the probe relative to the satellite is the same as the speed of the satellite relative to the Moon, then, like the projected capsule that fell to Earth in the previous question, it will drop vertically to the Moon. If fired at twice the speed, it and the satellite would have the same speed relative to the Moon, but in the opposite direction, and might collide with the satellite after half an orbit. **51.** Communication satellites only appear motionless because their orbital period coincides with the daily rotation of the Earth. **53.** The design is a good one. Rotation would provide a centripetal force on the occupants. Watch for this design in future space habitats. **55.** Since Moon's surface gravity is much less than Earth's, less thrust and less fuel is required to launch it to escape speed from the Moon. **57.** Gravitation may "seem" to cancel, but it doesn't. The airplane is simply in a state of free fall and occupants inside experience no support force. No support force means no sensation of weight. **59.** Acceleration is maximum where gravitational force is maximum, and that's when Earth is closest to the Sun, at the perigee. At the apogee, force and acceleration are minimum.

CHAPTER TEN PROBLEMS



1. (a) One second after being thrown, its horizontal component of velocity is 10 m/s, and its vertical component is also 10 m/s. By the Pythagorean theorem, $V = \sqrt{(10^2 + 10^2)} =$ **14.1 m/s.** (It is moving at a 45° angle.)
(b) In 30 seconds; $d = vt = 280$ m/s $\times$ 30 s = **8400 m.** (c) The engine is **directly below** the airplane. (In a more practical case, air resistance is overcome for the plane by its engines, but not for the falling engine, so the engine's speed is reduced by air drag and it covers less than 8400 horizontal meters, landing behind the plane.) **3.** At the top of its trajectory, the vertical component of velocity is zero, leaving only the horizontal component. The horizontal component at the top or anywhere along the path is the same as the initial horizontal component, **100 m/s** (the side of a square where the diagonal is 141). **5.** Total energy = 5000 MJ + 4500 MJ = 9500 MJ. Subtract 6000 MJ and KE = **3500 MJ.** **7.** Hang time depends only on the vertical component of initial velocity and the corresponding vertical distance attained. From $d = 5t^2$ a vertical 1.25 m drop corresponds to 0.5 s ($t = \sqrt{2d/g} = \sqrt{2(1.25)/10} = 0.5$ s). Double this (time up and time down) for a hang time of 1 s. Hang time is the **same** whatever the horizontal distance traveled.

CHAPTER ELEVEN RANKING

1. (a) A, D, B, C (b) A, D, B, C (c) A, D, B, C **3.** A, B, D, C

CHAPTER ELEVEN EXERCISES

1. One (although perhaps more than one isotope). **3.** The average speed of molecules increases. **5.** The cat leaves a trail of molecules and atoms on the grass. These in turn leave the grass and mix with the air, where they enter the dog's nose, activating its sense of smell. **7.** The atoms that make up a newborn baby or anything else in this world originated in the explosions of ancient stars. The *molecules* that make up the baby, however, were formed from atoms ingested by the mother and transferred to her womb. **9.** Of the substances listed, H_2, He, Na, and U are pure elements. H_2O and NaCl are compounds made of two elements, and three different elements contribute to H_2SO_4. **11.** Brownian motion is the result of more atoms or molecules bumping against one side of a tiny particle than the other. This produces a net force on the particle, which affects its motion. Such Brownian motion is not observed for larger particles because the numbers of bumps on opposite sides is more nearly equal, and the inertia of the larger particle is greater. **13.** Individual carbon atoms have less mass than individual oxygen atoms, so equal masses of each means more carbons than oxygens. **15.** Nine. **17.** The element is copper, atomic number 29. Any atom having 29 protons is by definition copper. **19.** Lead. **21.** To become negative, gain an electron. **23.** Germanium would become arsenic. **25.** Germanium, which is in the same column directly below silicon in the periodic table. **27.** Protons contribute more to an atom's mass, and electrons more to an atom's size. **29.** The hydrogen molecules, having less mass, move faster than the heavier oxygen molecules. **31.** You really are a part of every person around you in the sense that you are composed of atoms not only from every person around you, but from every person who ever lived on Earth! The child's statement in the Part 2 photo opener is indisputable. And the atoms that now compose you will make up the atomic pool that others will draw upon. **33.** They assumed that a water molecule is made of one hydrogen atom and one oxygen atom, HO. **35.** Open-ended.

CHAPTER TWELVE RANKING

1. D, A, B, C

CHAPTER TWELVE EXERCISES

1. Both the same, for 1000 mg = 1 g. **3.** The carbon that comprises much of the mass of a tree originates from CO_2 in the air. **5.** Evidence for crystalline structure includes the symmetric diffraction patterns given off by various materials, micrographs such as the one shown by Professor Hubisz in the chapter-opener photo, the 3-dimensional shape of materials such as quartz, and even brass doorknobs that have been etched by the perspiration of hands. **7.** Iron is denser than cork, but not necessarily heavier. A common cork from a wine bottle, for example, is heavier than an iron thumbtack, but it wouldn't be heavier if the volumes of each were the same. **9.** Density of water decreases when it becomes ice. **11.** Density has not only to do with the mass of the atoms that make up a material, but with the spacing between the atoms as well. The atoms of the metal iridium, for example, are not as massive as uranium atoms, but due to their close spacing they make up the densest of the metals. Uranium atoms are not as closely spaced as iridium atoms. **13.** Water is denser, so a liter of water has more mass than a liter of ice. (Once a liter of water freezes, its volume is greater than 1 liter.) **15.** The top part of the spring supports the entire weight of the spring and stretches more than, say, the middle, which only supports half the weight and stretches half as far. Parts of the spring toward the bottom support very little of the spring's weight and hardly stretch at all. **17.** A twice-as-thick rope has four times the cross-section and is therefore four times as strong. The length of the rope does not contribute to its strength. (Remember the old adage, a chain is only as strong as its weakest link—the strength of the chain has to do with the thickness of the links, not the length of the chain.)

19. Case 1: Tension at the top and compression at the bottom.

19. Case 2: Compression at the top and tension at the bottom.

21. A horizontal I-beam is stronger when the web is vertical because most of the material is where it is needed for the most strength, in the top and bottom flanges. When supporting a load, one flange will be under tension and the other flange under compression. But when the web is horizontal, only the edges of the flanges, much smaller than the flanges themselves, play these important roles. **23.** Like the dams in the preceding exercise, the ends should be concave as on the left. Then the pressure due to the wine inside produces compression on the ends that strengthens rather than weakens the barrel. If the ends are convex as on the right, the pressure due to the wine inside produces tension, which tends to separate the boards that make up the ends. **25.** Scale a beam up to twice its linear dimensions, I-beam or otherwise, and it will be four times as thick. Along its cross-section then, it will be four times as strong. But it will be eight times as heavy. Four times the strength supporting eight times the weight results in a beam only half as strong as the original beam. The same holds true for a bridge that is scaled up by two. The larger bridge will be only half as strong as the smaller one. (Larger bridges have different designs than smaller bridges. How they differ is what architects and engineers get paid for!) Interestingly, how strength depends on size was one of Galileo's "two new sciences," published in 1638. **27.** Since each link in a chain is pulled by its neighboring links, tension in the hanging chain is exactly along the chain—parallel to the chain at every point. If the arch takes the same shape, then compression all along the arch will similarly be exactly along the arch—parallel to the arch at every point. There will be no internal forces tending to bend the arch. This shape is a catenary, and is the shape of modern-day arches such as the one that graces the city of St. Louis. **29.** The candymaker needs less taffy for the larger apples because the surface area is less per kilogram. (This is easily noticed by comparing the peelings of the same number of kilograms of small and large apples.) **31.** The answer to this question uses the same principle as the answer to the previous exercise. The greater surface area of the coal in the form of dust insures an enormously greater proportion of carbon atoms in the coal having exposure to the oxygen in the air. The result is very rapid combustion. **33.** An apartment building has less area per dwelling unit exposed to the weather than a single-family unit of the same volume. The smaller area means less heat loss per unit. (It is interesting to see the nearly cubical shapes of apartment buildings in northern climates—a cube has the least surface area for a solid with rectangular sides.) **35.** The surface area of crushed ice is greater which provides more melting surface to the surroundings. **37.** Rusting is a surface phenomenon. For a given mass, iron rods present more surface area to the air than thicker piles. **39.** The wider, thinner burger has more surface area for the same volume. The greater the surface area, the greater will be the heat transfer from the stove to the meat. **41.** Mittens have less surface than gloves. Anyone who has made mittens and gloves will tell you that much more material is required to make gloves. Hands in gloves will cool faster than hands in mittens. Fingers, toes, and ears have a disproportionately large surface area relative to other parts of the body and are therefore more prone to frostbite. **43.** Small animals radiate more energy per bodyweight, so the flow of blood is correspondingly greater, and the heartbeat faster. **45.** The inner surface of the lungs is not smooth, but is sponge-like. As a result, there is an enormous surface exposed to the air that is breathed. This is nature's way of compensating for the proportional decrease in surface area for large bodies. In this way, an adequate amount of oxygen vital to life is taken in. **47.** Large raindrops fall faster than smaller raindrops for the same reason that heavier parachutists fall faster than lighter parachutists. Both larger things have less surface area and therefore less air resistance relative to their weights. **49.** Scaling plays a significant role in the design of the hummingbird and the eagle. The wings of a hummingbird are smaller than those of the eagle relative to the size of the bird, but are larger relative to the mass of the bird. The hummingbird's swift maneuvers are possible because the small rotational inertia of the short wings permits rapid flapping that would be impossible for wings as large as those of an eagle. If a hummingbird were scaled up to the size of an eagle, its wings would be much shorter than those of an eagle, so it couldn't soar. Its customary rate of flapping would be insufficient to provide lift for its disproportionately greater weight. Such a giant hummingbird couldn't fly, and unless its legs were disproportionately thicker, it would have great difficulty walking. The great difference in the design of hummingbirds and eagles is a natural consequence of the area to volume ratio of scaling. Interesting!

CHAPTER TWELVE PROBLEMS

1. Density $= \frac{\text{mass}}{\text{volume}} = \frac{5\text{ kg}}{V}$. Now the volume of a cylinder is its (round area) × (its height) ($\pi r^2 h$). So density $= \frac{5\text{kg}}{\pi r^2 h} = \frac{5000\text{ g}}{(3.14)(3^2)(10)\text{cm}^3} = \mathbf{17.7\ g/cm^3}$. **3.** 50 N is 5/3 times 30 N, so the spring will stretch 5/3 times as far, **10 cm.** Or from Hooke's law: $F = kx$, $x = F/k = 50\text{ N}/(30\text{ N}/6\text{ cm}) = 10\text{ cm}$. (The spring constant $k = 5$ N/cm.) **5.** (a) **Eight** smaller cubes (see Figure 12.15). (b) Each face of the original cube has an area of 4 cm^2 and there are 6 faces, so the total area is **24 cm^2**. Each of the smaller cubes has an area of 6 cm^2 and there are eight of them, so their total surface area is **48 cm^2**, twice as great. (c) The surface-to-volume ratio for the original cube is (24 cm^2)/(8 cm^3) = **3 cm^{-1}**. For the set of smaller cubes, it is (48 cm^2)/(8 cm^3) = **6 cm^{-1}**, twice as great. (Notice that the surface-to-volume ratio has the unit inverse cm.) **·7.** $\$700 \times 10^9 \times \frac{1\text{ gram}}{\$28.49} = \mathbf{2.46 \times 10^{10}\ gram} \times \frac{1\text{ cm}^3}{19.3\text{ g}} = 1.28 \times 10^9\text{ cm}^3 \times (\frac{1\text{ m}}{100\text{ cm}})^3 = \mathbf{1.28 \times 10^3\ m^3}$. Since this is a cube of volume $V = L^3$, each side $L = \sqrt[3]{V} = \sqrt[3]{1.28 \times 10^3\text{ m}^3} = \mathbf{10.8m.}$ (This turns out to be more than five times the total stored in Fort Knox, and about 16 times the world's annual gold production.)

CHAPTER THIRTEEN RANKING

1. C, A, B **3.** A, B, C

CHAPTER THIRTEEN EXERCISES

1. Water. **3.** Pressure would be appreciably greater by the woman, which would hurt you more. **5.** There is less pressure with a waterbed due to the greater contact area. **7.** Your upper arm is at the same level as your heart, so the blood pressure in your upper arms will be the same as the blood pressure in your heart. **9.** No, in orbit where support is absent there are no pressure differences due to gravity. **11.** Both are the same, for pressure depends on depth. **13.** The water can be no deeper than the spouts, which are at the same height, so both teapots hold the same amount of liquid. **15.** A one-kilogram block of aluminum is larger than a one-kilogram block of lead. The aluminum therefore displaces more water. **17.** The smaller the window area, the smaller the crushing force of water on it. **19.** This dramatically illustrates that water pressure depends on depth, which directly relates to Plug-and-Chug 4. **21.** Water seeking its own level is a consequence of pressure depending on depth. In a bent U-tube full of water, for example, the water in one side of the tube tends to push water up the other side until the pressures at the same depth in each tube are equal. If the water levels were not the same, there would be more pressure at a given level in the fuller tube, which would move the water until the levels were equal. **23.** In deep water, you are buoyed up by the water displaced and as a result, you don't exert as much pressure against the stones on the bottom. When you are up to your neck in water, you hardly feel the bottom at all. **25.** The diet drink is less dense than water, whereas the regular drink is denser than water. (Water with dissolved sugar is denser than pure water.) Also, the weight of the can is less than the buoyant force that would act on it if totally submerged. So it floats, where buoyant force equals the weight of the can. **27.** Mountain ranges are very similar to icebergs: Both float in a denser medium, and extend farther down into that medium than they extend above it. Mountains, like icebergs, are bigger than they appear to be. The concept of floating mountains is *isostacy*: Archimedes' principle for rocks. **29.** The force needed will be the weight of 1 L of water, which is 9.8 N. If the weight of the carton is not negligible, then the force needed would be 9.8 N minus the carton's weight, for then the carton would be "helping" to push itself down. **31.** The buoyant force on the ball beneath the surface is much greater than the force of gravity on the ball, producing a large net upward force and large acceleration. **33.** While floating, BF equals the weight of the submarine. When submerged, BF equals the submarine's weight *plus* the weight of water taken into its ballast tanks. Looked at another way, the submerged submarine displaces a greater weight of water than the same submarine floating. **35.** When a ship is empty its weight is least and it displaces the least water and floats highest. Carrying a load of anything increases its weight and makes it float lower. It will float as low carrying a few tons of Styrofoam as it will carrying the same number of tons of iron ore. So the ship floats lower in the water when loaded with Styrofoam than when empty. If the Styrofoam were outside the ship, below water line, then the ship would float higher as a person would with a life preserver. **37.** The water level will fall. This is because the iron will displace a greater amount of water while being supported than when submerged. A floating object displaces its weight of water, which is more than its own volume, while a submerged object displaces only its volume. (This may be illustrated in the kitchen sink with a dish floating in a dishpan full of water. Silverware in the dish takes the place of the scrap iron. Note the level of water at the side of the dishpan, and then throw the silverware overboard. The floating dish will float higher and the water level at the side of the dishpan will fall. Will the volume of the silverware displace enough water to bring the level to its starting point? No, not as long as it is denser than water.) **39.** Buoyant force will remain unchanged on the sinking rock because it displaces the same volume and weight of water at any depth. **41.** The balloon will sink to the bottom because its density increases with depth. The balloon is compressible, so the increase in water pressure beneath the surface compresses it and reduces its volume, thereby increasing its density. Density further increases as it sinks lower to regions of greater pressure and compression. Think buoyant force: as its volume is reduced by increasing pressure as it descends, the amount of water it displaces becomes less. So buoyant force decreases as it descends. **43.** A body floats higher in denser fluid because it does not have to sink as far to displace a weight of fluid equal to its own weight. A smaller volume of the displaced denser fluid is able to match the weight of the floating body. **45.** Since both preservers are the same size, they will displace the same amount of water when submerged and be buoyed up with equal forces. Effectiveness is another story. The amount of buoyant force exerted on the heavy gravel-filled preserver is much less than its weight. If you wear it, you'll sink. The same amount of buoyant force exerted on the lighter Styrofoam preserver is greater than its weight and it will keep you afloat. The *amount* of the force and the *effectiveness* of the force are two different things. **47.** Ice cubes will float lower in a mixed drink because the mixture of alcohol and water is less dense than water. In a less dense liquid a greater volume of liquid must be displaced to equal the weight of the floating ice. In pure alcohol, the volume of alcohol equal to that of the ice cubes weighs less than the ice cubes, and buoyancy is less than weight and ice cubes will sink. Submerged ice cubes in a cocktail indicate that it is predominantly alcohol. **49.** The total weight on the scale is the same either way, so the scale reading will be the same whether or not the wooden block is outside or floating in the beaker. Likewise for an iron block, where the scale reading shows the total weight of the system. **51.** If the gravitational field of the Earth increased, both water and fish would increase in weight and weight density by the same factor, so the fish would stay at its prior level in water. **53.** Because of surface tension, which tends to minimize the surface of a blob of water, its shape without gravity and other distorting forces will be a *sphere*—the shape with the least surface area for a given volume. **55.** Part of whatever pressure you add to the water is transmitted to the hungry crocodiles, via Pascal's principle. If the water were confined, that is, not open to the atmosphere, the crocs would receive every bit of pressure you exert. But even if you were able to slip into the pool to quietly float without exerting pressure via swimming strokes, your displacement of water raises the water level in the pool. This ever-so-slight rise, and accompanying ever-so-slight increase in pressure at the bottom of the pool, is an ever-so-welcome signal to the hungry crocodiles. **57.** In Figure 13.21, the increased pressure in the reservoir is a result of the applied force distributed over the input piston area. This increase in pressure is transmitted to the output piston. In Figure 13.23, however, the pressure increase is supplied by the mechanical pump, which has nothing to do with the area of fluid interface between the compressed air and the liquid. Many hydraulic devices have a single piston upon which pressure is exerted. **59.** Surface tension accounts for the "floating" of the razor blade. The weight of the blade is less than the restoring forces of the water surface that tends to resist stretching.

CHAPTER THIRTEEN PROBLEMS

1. Force per nail is 120 pounds/600 nails = **0.2 pounds per nail.** Quite tolerable. **3.** Density = m/V = 6 kg/1 liter = 6 kg/liter. (Since there are 1000 liters in 1 cubic meter, density may be expressed in units kg/m^3. Density = 6 kg/1 liter × 1000 liter/m^3 = **6000 kg/m^3**, six times the density of water.) **5.** (a) BF is 10 N − 8 N = **2 N.** (b) The gain in scale reading is 2 N; total weight = **12 N.** (c) Weight of the rock is 10 N, so total weight is **20 N.** **7.** The relative areas are as the squares of the diameters: $6^2/2^2 = 36/4 = 9$. The large piston can lift **9 times** the input force to the smaller piston.

CHAPTER FOURTEEN RANKING

1. A, B, C **3.** C, A, B

CHAPTER FOURTEEN EXERCISES

1. Some of the molecules in the Earth's atmosphere *do* go off into outer space—those like helium with speeds greater than escape speed. But the average speeds of most molecules in the atmosphere are well below escape speed, so the atmosphere is held to Earth by Earth gravity. **3.** The tires heat, giving additional motion to the gas molecules within. **5.** When the diameter is doubled, the area is four times as much. For the same pressure, this would mean four times as much force. **7.** The ridges near the base of the funnel allow air to escape from a container it is inserted into. Without the ridges, air in the container would be compressed and would tend to prevent filling as the level of liquid rises. **9.** The bubble's mass does not change. Its volume increases because its pressure decreases (Boyle's law), and its density decreases (same mass, more volume). **11.** If the item is sealed in an air-tight package at sea level, then the pressure in the package is about 1 atmosphere. Cabin pressure is reduced somewhat for high altitude flying, so the pressure in the package is greater than the surrounding pressure and the package therefore puffs outwards. **13.** Unlike water, air is easily compressed. In fact, its density is proportional to its pressure (at a given temperature). So, near the ground, where the pressure is greater, the air's density is greater and corresponds to more squashed bricks; at high altitude, where the pressure is less, the air's density is less, corresponding to less squashed bricks. **15.** A perfect vacuum pump could pump water no higher than 10.3 m. This is because the atmospheric pressure that pushes the water up the tube weighs as much as 10.3 vertical meters of water of the same cross-sectional area. **17.** The height of the column in a mercury barometer is determined by pressure, not force. Fluid pressures depend on density and depth—pressure at the bottom of a wide column of mercury is no different than at the bottom of a narrow column of mercury of the same depth. The weight of fluid *per area* of contact is the same for each. Likewise with the surrounding air, which explains why wide-tube barometers show the same height as narrow-tubed barometers. **19.** The height would be less. The weight of the column balances the weight of an equal-area column of air. The denser liquid would need less height to have the same weight as the mercury column. **21.** If an elephant steps on you, the pressure that the elephant exerts is over and above the atmospheric pressure that already is exerted on you. It is the *extra* pressure the elephant's foot produces that crushes you. For example, if atmospheric pressure the size of an elephant's foot were somehow removed from a patch of your body, you would be in serious trouble. You would be soothed, however, if an elephant stepped onto this area! **23.** If the air pressure in the inflated balloon were equal to the outside air pressure, the extra weight of the air in the balloon would be canceled by an equal buoyant force and the scale reading would not change. But to keep a rubber balloon inflated, its air pressure inside has to be greater than outside air pressure. Then the extra weight is greater than the buoyant force and the scale will show a greater weight. **25.** One's lungs, like an inflated balloon, are compressed when submerged in water, and the air within is compressed. Air will not of itself flow from a region of low pressure into a region of higher pressure. The diaphragm in one's body reduces lung pressure to permit breathing, but this limit is strained when nearly 1 m below the water surface. It is exceeded at more than 1 m. **27.** Weight is the force with which something presses on a supporting surface. When the buoyancy of air plays a role, the net force against the supporting surface is less, indicating a smaller weight. Buoyant force is more appreciable for larger volumes, like feathers. So the mass of feathers that weigh 1 pound is more than the mass of iron that weighs 1 pound. **29.** Helium is less dense than air, and will weigh less than an equal volume of air. A helium-filled bottle would weigh less than the air bottle (assuming they are filled to the same pressure). However, the helium-filled bottle will weigh more than the empty bottle. **31.** An object rises in air only when buoyant force exceeds its weight. A steel tank of anything weighs more than the air it displaces, so won't rise. A helium-filled balloon weighs less than the air it displaces and rises. **33.** The volume of gas in the balloon increases. **35.** Pressure of the water decreases and the bubbles expand. **37.** The stretched rubber of an inflated balloon provides an inward pressure. So the pressure inside is balanced by the sum of two pressures; the outside air pressure plus the pressure of the stretched balloon. (The fact that air pressure is greater inside an inflated balloon than outside is evident when it is punctured—the air "explodes" outward.) **39.** The balloon which is free to expand will displace more air as it rises than the balloon which is restrained. Hence, the balloon, which is free to expand, will have more buoyant force exerted on it than the balloon that does not expand, and will rise higher. (See also Problem 8.) **41.** According to Bernoulli's principle, the wind at the top of the chimney lowers the pressure there, producing a better "draw" in the fireplace below. **43.** Air speed across the wing surfaces, necessary for flight, is greater when facing the wind. **45.** The rotating habitat is a centrifuge, and denser air is "thrown to" the outer wall. Just as on Earth, the maximum air density is at "ground level," and becomes less with increasing altitude (distance toward the center). Air density in the rotating habitat is least at the zero-*g* region, the hub. **47.** (a) Speed increases (so that the same quantity of gas can move through the pipe in the same time). (b) Pressure decreases (Bernoulli's principle). (c) The spacing between the streamlines decreases, because the same number of streamlines fit in a smaller area. **49.** A tennis ball has about the same size as a baseball, but much less mass. Less mass means less inertia, and more acceleration for the same force. A Ping-Pong ball provides a more obvious curve due to spinning because of its low mass. **51.** An airplane flies upside down by tilting its fuselage so that there is an angle of attack of the wing with oncoming air. (It does the same when flying right side up, but then, because the wings are designed for right-side-up flight, the tilt of the fuselage may not need to be as great.) **53.** In accord with Bernoulli's principle, the sheets of paper will move together because air pressure between them is reduced, and be less than the air pressure on the outside surfaces. **55.** A solid-walled wharf is disadvantageous to ships pulling alongside because water currents are constrained and speed up between the ship and the wharf. This results in a reduced water pressure, and the normal pressure on the other side of the ship then forces the ship against the wharf. The pilings avoid this mishap by allowing the freer passage of water between the wharf and the ship.

CHAPTER FOURTEEN PROBLEMS

1. According to Boyle's law, the pressure will increase to **three times** its original pressure. **3.** To effectively lift $(0.25)(80\text{ kg}) = 20\text{ kg}$, the mass of displaced air would be 20 kg. Density of air is about 1.2 kg/m^3. From density = mass/volume, the volume of 20 kg of air, also the volume of the balloon (neglecting the weight of the hydrogen) would be volume = mass/density = $(20\text{ kg})/(1.2\text{ kg/m}^3) = $ **17 m³**. **5.** From $P = \frac{F}{A}$, $F = PA = (0.04)\left(10^5\frac{\text{N}}{\text{m}^2}\right)(100\text{ m}^2) = 4 \times 10^5\text{ N}$.

CHAPTER FIFTEEN EXERCISES

1. Inanimate things such as chairs and tables have the same temperature as the surrounding air. People and other mammals, however, generate their own heat and have body temperatures that are normally higher than air temperature. **3.** Yes, the same average speed, but not the same instantaneous speed. At any moment molecules with the same average speed can have enormously different instantaneous speeds. **5.** You cannot establish by your own touch whether or not you are running a fever because there would be no temperature difference between your hand and forehead. If your forehead is a couple of degrees higher in temperature than normal, your hand is also a couple of degrees higher. **7.** The hot coffee has a higher temperature, but not a greater internal energy. Although the iceberg has less internal energy per mass, its enormously greater mass gives it a greater total energy than that in the small cup of coffee. (For a smaller volume of ice, the fewer number of more energetic molecules in the hot cup of coffee may constitute a greater total amount of internal energy—but not compared to an iceberg.) **9.** Calorie is largest, which is 1000 calories. **11.** The average speed of molecules in both containers is the same. There is greater internal energy in the full glass (twice the matter at the same temperature). More heat will be required to increase the temperature of the full glass by 1°C, twice as much, in fact. **13.** Gaseous pressure changes with changes in temperature. **15.** Different substances have different thermal properties due to differences in the way energy is stored internally in the substances. When the same amount of heat produces different changes in temperatures in two substances of the same mass, we say they have different specific heat capacities. Each substance has its own characteristic specific heat capacity. Temperature measures the average kinetic energy of random motion, but not other kinds of energy. **17.** The slowly cooling object has the greater specific heat capacity. **19.** A high specific heat capacity. The more ways a molecule can move internally, the more energy it can absorb to excite these internal motions. This greater capacity for absorbing energy makes a higher specific heat capacity. **21.** Alcohol, for less specific heat means less thermal inertia and a greater change in temperature. **23.** The brick will cool off too fast and you'll be cold in the middle of the night. Bring a jug of hot water with its higher specific heat to bed and you'll make it through the night. **25.** The climate of Iceland, like that of Bermuda in the previous exercise, is moderated by the surrounding water. **27.** As the ocean off the coast of San Francisco cools in the winter, the heat it loses (transfers) warms the atmosphere it comes in contact with. This warmed air blows over the California coastline to produce a relatively warm climate. If the winds were easterly instead of westerly, the climate of San Francisco would be chilled by winter winds from dry and cold Nevada. The climate would be reversed also in Washington, D.C. because air warmed by the cooling of the Atlantic Ocean would blow over Washington, D.C. and produce a warmer climate in winter there. **29.** Water is an exception. **31.** When the rivets cool they contract. This tightens the plates being attached. **33.** The tires heat up, which heats the air within. The molecules in the heated air move faster, which increases air pressure in the tires. (See Exercise 14.) **35.** Cool the inner glass and heat the outer glass. If it's done the other way around, the glasses will stick even tighter (if not break). **37.** If they expanded differently, as for different materials, the key and lock wouldn't match. **39.** The photo was likely taken on a warm day. If it were taken on a cold day there would be more space between the segments. **41.** Overflow is the result of liquid gasoline expanding more than the solid tank. **43.** The heated balls would have the same diameter. **45.** The gap in the ring will become wider when the ring is heated. Try this: Draw a couple of lines on a ring where you pretend a gap to be. When you heat the ring, the lines will be farther apart—the same amount as if a real gap were there. Every part of the ring expands proportionally when heated uniformly—thickness, length, gap, and all. **47.** The U shape takes up the slack of expansion or contraction, without changing the positions of the end points. **49.** In the construction of a light bulb, it is important that the metal leads and the glass have the same rate of heat expansion. If the metal leads expand more than glass, the glass may crack. If the metal expands less than glass upon being heated, air will leak in through the resulting gaps. **51.** 4°C. **53.** The atoms and molecules of most substances are more closely packed in solids than in liquids. So most substances are denser in the solid phase than in the liquid phase. Such is the case for iron and aluminum and most all other metals. But water is different. In the solid phase the structure is open-spaced and ice is less dense than water. Hence ice floats in water. **55.** Volume increases. **57.** At 0°C it will contract when warmed a little; at 4°C it will expand, and at 6°C it will expand. **59.** Ponds would be more likely to freeze if water had a lower specific heat capacity. This is because the temperature would decrease more when water gives up energy; water would more readily be cooled to the freezing point.

CHAPTER FIFTEEN PROBLEMS

1. Heat gained by the cooler water = heat lost by the warmer water. Since the masses of water are the same, the final temperature is midway, 30°C. So you'll end up with 100 g of **30°C** water. **3.** $\Delta L = \alpha L_0 \Delta T = (11 \times 10^{-6}/°C)(1300\ m)(15°C) = \mathbf{0.21\ m}$.

CHAPTER SIXTEEN EXERCISES

1. The metal doorknob conducts heat better than wood. **3.** No, the coat is not a source of heat, but merely keeps the thermal energy of the wearer from leaving rapidly. **5.** When the temperatures of the blocks are the same as the temperature of your hand, then no heat transfer occurs. Heat will flow between your hand and something being touched only if there is a temperature difference between them. **7.** Copper and aluminum are better conductors than stainless steel, and therefore more quickly establish a uniform temperature over the bottom of the pan and transfer heat to the cookware's interior. **9.** Air is an excellent insulator. The reason that fiberglass is a good insulator is principally because of the vast amount of air spaces trapped in it. **11.** Heat from the relatively warm ground is conducted by the gravestone to melt the snow in contact with the gravestone. Likewise for trees or any materials that are better conductors of heat than snow, and that extend into the ground. **13.** The snow and ice of the igloo is a better insulator than wood. You would be warmer in the igloo than the wooden shack. **15.** The conductivity of wood is relatively low whatever the temperature—even in the stage of red-hot coals. You can safely walk barefoot across red hot wooden coals if you step quickly (such as removing the wooden-handled pan with bare hands quickly from the hot oven in the previous exercise) because very little heat is conducted to your feet. Because of the poor conductivity of the coals, energy from within the coals does not readily replace the energy that transfers to your feet. This is evident in the diminished redness of the coal after your foot has left it. Stepping on red-hot *iron* coals, however, is a different story. That would be a resounding ouch! **17.** The temperature will be in between because one decreases in temperature and the other increases in temperature. **19.** It is correct to say that the increase in *thermal energy* of one object equals the decrease in *thermal energy* of the other—not temperature. The statement is correct when the hot and warm objects are the same material and same mass. **21.** Disagree, for although the mixture has the same temperature, which is to say, the same KE per molecule, the lighter hydrogen molecules have more speed than heavier nitrogen for the same KE. **23.** Hydrogen molecules will be the faster moving when mixed with oxygen molecules. They will have the same temperature, which means they will have the same average kinetic energy. Recall that $KE = 1/2\ mv^2$. Since the mass of hydrogen is considerably less than oxygen, the speed must correspondingly be greater. **25.** Molecules of gas with greater mass have a smaller average speed. So molecules containing heavier U-238 are slower on the average. This favors the diffusion of the faster gas containing U-235 through a porous membrane (which is how U-235 was separated from U-238 by scientists in the 1940s). **27.** More molecules are in the cooler room. The greater number of slower-moving molecules there produce air pressure at the door equal to the fewer number of faster-moving molecules in the warmer room. **29.** They ride in "thermals," updrafts of air. **31.** If ice cubes were at the bottom they wouldn't be in contact with the warmest part of the tea at the surface, so cooling would be less. Ice cubes are preferable at the surface to decrease the temperature of the warmer part of the tea. **33.** Faster-moving (warm air) molecules migrate upward through the "open window" in the atmosphere, producing upward convection. **35.** When we warm a volume of air, we add energy to it. When we expand a volume of air, we normally take energy out of it (because the expanding air does work on its surroundings). So the conditions are quite different and the results will be different. Expanding a volume of air actually lowers its temperature. **37.** In winter you want warm air near the floor, so the fan should push warmer ceiling air downward. In summer you want cooler air near the floor, so the fan should pull air upward. **39.** Radiation requires no medium for transfer. **41.** Human eyes are insensitive to the infrared radiated by objects at average temperatures. **43.** A good reflector is a poor radiator of heat, and a poor reflector is a good radiator of heat. **45.** Heat radiates into the clear night air and the temperature of the car goes down. Normally, heat is conducted to the car by the relatively warmer ground, but the rubber tires prevent the conduction of heat from the ground. So heat radiated away is not easily replaced and the car cools to temperatures below that of the surroundings. In this way frost can form on a below-freezing car in the above-freezing environment. **47.** When it is desirable to reduce the radiation that comes into a greenhouse, whitewash is applied to the glass to simply reflect much of the incoming radiation. Energy reflected is energy not absorbed. **49.** If the upper atmosphere permitted the escape of more terrestrial radiation than it does presently, more energy would escape and the Earth's climate would be cooler. **51.** Because warm air rises, there's a higher temperature at the ceiling than at the walls. With a greater difference in inside and outside temperatures, thicker insulation is needed to slow the transfer of heat. **53.** Turn your heater off altogether and save fuel. When it is cold outside, your house is constantly losing heat. How much is lost depends on the insulation and the difference in inside and outside temperature (Newton's law of cooling). Keeping ΔT high consumes more fuel. To consume less fuel, keep ΔT low and turn your heater off altogether. Will more fuel be required to reheat the house when you return than would have been required to keep it warm while you were away? Not at all. When you return, you are replacing heat lost by the house at an average temperature below the normal setting, but if you had left the heater on, it would have supplied more heat, enough to make up for heat lost by the house at its normal, higher temperature setting. (Perhaps your instructor will demonstrate this with the analogy of leaking water buckets.) **55.** If the Earth's temperature increases, its rate of radiating will increase. And if much of this extra terrestrial radiation is blocked, and the temperature of the Earth increases more, then its rate of radiating simply increases further. A new and higher equilibrium temperature is established.

CHAPTER SIXTEEN PROBLEMS

1. (a) The amount of heat absorbed by the water is $Q = cm\Delta T = (1.0\ cal/g\ C°)(50.0\ g)(50°C - 22°C) = 1400\ cal$. At 40% efficiency only 0.4 of the energy from the peanut raises the water temperature, so the calorie content of the peanut is $1400/0.4 = \mathbf{3500\ cal}$, or equivalently, **3.5 Calories.** (b) The food value of a peanut is $3500\ cal/0.6\ g = \mathbf{5833\ cal/g}$, or equivalently, **5.8 Calories per gram.** **3.** The coffee decreases 25°C in temperature in eight hours. Newton's law of cooling tells us that its rate of cooling is proportional to the temperature difference. So when the temperature difference is half as great, the rate of cooling will be half as great. Hence, the coffee will lose 12.5 degrees in another eight hours, half as much as in the first eight hours, cooling from 50°C to **37.5°C.** •**5.** Q gained by water = Q lost by nails, so $(cm\Delta T)_{water} = (cm\Delta T)_{nails}$. $(1.0\ g°C)(100g)(T - 20°C) = (0.12\ cal/g°C)(100\ g)(40° - T)$, where $T = \mathbf{22.1°C}$. (b) Although the masses are the same, the specific heats are widely apart, iron being very low and water incredibly high. It takes as much heat as the iron can release to raise water by 2.1°C.

CHAPTER SEVENTEEN EXERCISES

1. Alcohol produces more cooling because of its higher rate of evaporation. **3.** The water evaporates rapidly in the dry air, gaining its energy from your skin, which is cooled. **5.** When you blow over the top of a bowl of hot soup, you increase net evaporation and its cooling effect by removing the warm vapor that tends to condense and reduce net evaporation. **7.** The temperature of the water lowers. **9.** If the perfume doesn't evaporate it will produce no odor. The odor of a substance is evidence for its evaporation. Don't invest in this invention! **11.** A fan does not cool the room, but instead promotes evaporation of perspiration, which cools the body. **13.** The wet cloth cools by evaporation. As evaporation progresses, the temperature of the water in the cloth drops, and cools the bottle to a temperature below that of the bucket of water. **15.** Visibility of the windows is impaired if there is any condensation of water between the panes of glass. Hence the gas between the panes should contain no water vapor. **17.** Aside from the connotation of kissing molecules and parking on a cool night, the warm air generated in the car's interior meets the cold glass and a lowering of molecular speed results in condensation of water on the inside of the windows. **19.** A temperature gradient normally exists in a room, with cooler air near the bottom. Hence frost forms on the colder part of the window, the bottom. **21.** Clouds tend to form over islands because land has a lower specific heat capacity than water, so the land is warmed faster than the surrounding water. This causes updrafts above the warmed land; the rising air laden with H_2O expands and cools, allowing the H_2O molecules to coalesce (Figure 17.7). **23.** You can add heat without changing temperature when the substance is undergoing a change of phase. **25.** When water is boiling, it is being cooled by the boiling process as fast as it is being heated by the stove. Hence its temperature remains the same—100°C. **27.** Decreased pressure lessens the squeezing of molecules, which favors their tendency to separate and form vapor. **29.** The hot water is below the boiling point for the very high pressure there, somewhat like the higher boiling point of water in a pressure cooker. **31.** As in the answer to the previous exercise, high temperature and the resulting internal energy given to the food are responsible for cooking—if the water boils at a low temperature (presumably under reduced pressure), the food isn't hot enough to cook. **33.** Both heat and pressure are involved in boiling. Reduction of pressure only can produce boiling (see Figure 17.13). **35.** The air in the flask is very low in pressure, so that the heat from your hand will produce boiling at this reduced pressure. (Your instructor will want to be sure that the flask is strong enough to resist implosion before handing it to you!) **37.** The lid on the pot traps heat that quickens boiling; the lid also slightly increases pressure on the boiling water that raises its boiling temperature. The hotter water correspondingly cooks food in a shorter time, although the effect is not significant unless the lid is held down as on a pressure cooker. **39.** After a geyser has erupted, it must refill and then undergo the same heating cycle. If the rates of filling and heating don't change, then the time to boil to the eruption stage will be the same. **41.** Yes, ice can be much colder than 0°C, which is the temperature at which ice will melt when it absorbs energy. The temperature of an ice-water mixture in equilibrium is 0°C. Iced tea, for example, is 0°C. **43.** Both freezing point and boiling points are the same for a pure substance. **45.** The water that freezes is pure water. Melt the ice and you'll have pure water. **47.** The wood, because its greater specific heat capacity means it will release more energy in cooling. **49.** Your eyeglasses are colder than the inside air and condensation of the air in the room occurs on your eyeglasses—another example of Figure 17.7. **51.** Sugar doesn't freeze with the water in the punch, so half-frozen punch has the sugar of the original mixture—twice the original concentration. **53.** Condensation occurs on the cold coils, which is why the coils drip water. **55.** The temperature of nearby air decreases due to energy absorbed by the melting ice. **57.** The answer to this is similar to the previous answer, and also the fact that the coating of ice acts as an insulating blanket. Every gram of water that freezes releases 80 calories, much of it to the fruit; the thin layer of ice then acts as an insulating blanket against further loss of heat. **59.** Dogs have no sweat glands (except between the toes for most dogs) and therefore cool by the evaporation of moisture from the mouth and the respiratory track. So dogs literally cool from the inside out when they pant.

CHAPTER SEVENTEEN PROBLEMS

1. (a) 1 kg 0°C ice to 0°C water requires **80 kilocalories.** (b) 1 kg 0°C water to 100°C water requires **100 kilocalories.** (c) 1 kg 100°C water to 100°C steam requires **540 kilocalories.** (d) 1 kg 0°C ice to 100°C steam requires (80 + 100 + 540) = **720 kilocalories** or 720,000 calories. **3.** First, find the number of calories that 10 g of 100°C steam will give in changing to 10 g of 0°C water. 10 g of steam changing to 10 g of boiling water at 100°C releases 5400 calories. 10 g of 100°C water cooling to 0°C releases 1000 calories. So 6400 calories are available for melting ice. $\frac{6400 \text{ cal}}{80 \text{ cal/g}}$ = **80 grams** of ice. **5.** The quantity of heat lost by the iron is $Q = cm\Delta T = (0.11 \text{ cal/g°C})(50 \text{ g})(80°\text{C}) = 440$ cal. The iron will lose a quantity of heat to the ice $Q = mL$. The mass of ice melted will therefore be $m = Q/L = (440 \text{ cal})/(80 \text{ cal/g})$ = **5.5 grams.** (The lower specific of heat of iron shows itself compared with the result of the previous problem.) **7.** PE = Q: $0.5\,mgh = cm\Delta T$ $\quad \Delta T = 0.5\,mgh/cm = 0.5\,gh/c = (0.5)(9.8 \text{ m/s}^2)(100 \text{ m})/450 \text{ J/kg°C}$ = **1.1°C.** Mass cancels out.

CHAPTER EIGHTEEN EXERCISES

1. In the case of the 500-degree oven it makes a lot of difference. 500 kelvins is 227°C, quite a bit different than 500°C. But in the case of the 50,000-degree star, the 273 increments either way makes practically no difference. Give or take 273, the star is still 50,000 K or 50,000°C when rounded off. **3.** Not ordinarily. They undergo the same change in *internal energy*, which translates to the same temperature change when both objects are the same mass and composed of the same material. **5.** Its absolute temperature is 273 K. Double this and you have 546 K. Expressed in Celsius: 546 − 273 = 273°C. **7.** You do work in compressing the air, which increases its internal energy. This is evidenced by an increase in temperature. **9.** The pump gets hot because you are *compressing* the air within. The tire valve feels cool because the escaping air is *expanding*. These are adiabatic processes. **11.** Gas pressure increases in the can when heated, and decreases when cooled. The pressure that a gas exerts depends on the average kinetic energy of its molecules, therefore on its temperature. **13.** It warms because it is adiabatically compressed. **15.** Solar energy. The terms renewable and nonrenewable really refer to time scales for regeneration—tens of years for wood versus millions of years for coal and oil. **17.** This transfer would not violate the 1st law because energy has been transferred without loss or gain. It would violate the 2nd law because internal energy will not freely transfer from a cooler to a warmer object. **19.** The can is crushed by atmospheric pressure when vapor pressure in the can has been significantly reduced. Reduction of vapor pressure in the can is accomplished by condensation of the vapor on the surface of water entering the opening in the can. If that water is boiling, then it supplies vapor at about the same rate as condensation occurs, resulting in no net condensation and no crunching. But even hot water, if its temperature is less than 100°C, will result in net condensation and a crushed can. **21.** In accord with Carnot's equation, efficiency is higher with greater difference in temperature between the heat source (combustion chamber in the engine) and sink (air surrounding the exhaust). **23.** Only when the sink is at absolute zero (0 K) will a heat engine have an ideal efficiency of 100%. **25.** No. In this case the heat sink is also in the room. That's why the condensation coils are in a region *outside* the region to be cooled. Temperature of the room actually increases because the refrigerator motor warms the surrounding air. **27.** You *are* cooled by the fan, which blows air over you to increase the rate of evaporation from your skin, but you are a small part of the overall system, which warms. **29.** It doesn't violate the second law of thermodynamics because an external agent does work on the system. **31.** You do work in compressing the gas, which increases the internal energy. **33.** It does what heat engines do: converts energy of one kind (solar) into mechanical energy (the rocking of the bird). **35.** As the gas streams out of the nozzle, much of the kinetic energy of its molecules is ordered energy of the flowing gas, and less of the kinetic energy is in random motion, so the temperature drops. Expansion of the gas also contributes to its lower temperature. **37.** The universe is moving toward a more disordered state. **39.** More energy would be used to extract the energy than would be available from it. So although extracting ocean energy is possible, it is not practical, and cannot produce net power. **41.** It is fundamental in that it governs the general tendency throughout nature to move from order to disorder, yet it is inexact in the sense that it is based on probability, not certainty. **43.** No, the freezing of water is not an exception to the entropy principle because work has been put into the refrigeration system to prompt this change of state. There is actually a greater net disorder when the environment surrounding the freezer is considered. **45.** Such machines violate at least the second law of thermodynamics, and the first law as well. These laws are so richly supported by so many experiments over so long a time that the Patent Office wisely assumes that there is a flaw in the claimed invention rather than in the laws of thermodynamics. **47.** Your classmate isn't distinguishing between perpetual motion and perpetual motion machines. Your classmate is correct about perpetual motion being the normal state of the universe, but what is not possible is a perpetual motion machine that puts out more energy (including friction loss) than is put in.

CHAPTER EIGHTEEN PROBLEMS

1. Ideal efficiency is (2700 − 270)/2700 = 2430/2700 = 0.90 or **90%.** **3.** If by "twice as cold" she means one-half the absolute temperature, the temperature would be (1/2)(273 + 10) = 141.5 K. To find how many Celsius degrees below 0°C this is, first subtract 141.5 K from 273 K; this is 273 K − 141.5 K = 131.5 K below the freezing point of ice, or −**131.5°C.** (Or simply, 141.5 K − 273 K = −131.5°C.) *Very cold!* **5.** Ideal efficiency = $\frac{T_{hot} - T_{cold}}{T_{hot}}$ = (2700 K − 300 K)/2700 K = **89%.** **7.** Heating each kg of water through 3 degrees takes 3°C × 1kg × 4184 J/kg °C = 12,550 J. The number of joules of heat supplied to the water each second is 1.5×10^8, so the number of kilograms of water heated each second is $(1.5 \times 10^8 \text{ J})/(12{,}550 \text{ J/kg}) =$ **12,000 kg.**

CHAPTER NINETEEN RANKING

1. (a) D, B, A, C (b) D, A, B, C (c) C, B, A, D (d) D, A, B, C **3.** B, A, C

CHAPTER NINETEEN EXERCISES

1. The period of a pendulum does not depend on the mass of the bob, but does depend on the length of the string. **3.** A shorter pendulum swings to and fro with a higher frequency and shorter period. **5.** Assuming the center of gravity of the suitcase doesn't change when loaded with books, the pendulum rate of the empty case and loaded case will be the same. This is because the period of a pendulum is independent of mass. Since the length of the pendulum doesn't change, the frequency and hence the period are unchanged. **7.** The period increases, for period and frequency are reciprocals of each other. **9.** Lower frequency produces waves farther apart, so wavelength increases. Wavelength and frequency are inverse to each other. **11.** Letting $v = f\lambda$ guide thinking, twice the speed means twice the frequency. **13.** The periods are equal. Interestingly, an edge-on view of a body moving in uniform circular motion is seen to vibrate in a straight line. How? Exactly in simple harmonic motion. So the up and down motion of pistons in a car engine are simple harmonic, and have the same period as the circularly rotating shaft that they drive. **15.** Shake the garden hose to-and-fro in a direction perpendicular to the hose to produce a sine-like curve. **17.** (a) Transverse. (b) Longitudinal. (c) Transverse. **19.** Frequency and period are reciprocals of one another; $f = 1/T$, and $T = 1/f$. Double one and the other is half as much. So doubling the frequency of a vibrating object halves the period. **21.** Violet light has the greater frequency. **23.** Only frequency doesn't change from one rope to the other. **25.** The frequency of vibration and the number of waves passing by each second are the same. **27.** For mechanical waves, something that vibrates. For E&M waves, vibrating electric charges. **29.** The energy of a water wave spreads along the increasing circumference of the wave until its magnitude diminishes to a value that cannot be distinguished from thermal motions in the water. The energy of the waves adds to the internal energy of the water. **31.** The speed of light is 300,000 km/s, about a million times faster than sound. Because of this difference in speeds, lightning is seen a million times sooner than it is heard. **33.** The frequency is doubled. **35.** (a) The frequency increases. (b) The wavelength decreases. (c) The speed is unchanged (because the air remains motionless relative to you). **37.** No, the effects of shortened waves and stretched waves would cancel one another. **39.** Police use radar waves that are reflected from moving cars. From the shift in the returned frequencies, the speed of the reflectors (car bodies) is determined. **41.** Oops, careful. The Doppler effect is about changes in *frequency*, not speed. **43.** A boat that makes a bow wave is traveling faster than the waves of water it generates. **45.** The fact that you hear an airplane in a direction that differs from where you see it simply means the airplane is moving, and not necessarily faster than sound (a sonic boom would be evidence of supersonic flight). If the speed of sound and the speed of light were the same, then you'd hear a plane where it appears in the sky. But because the two speeds are so different, the plane you see appears ahead of the plane you hear. **47.** The speed of the sound source rather than the loudness of the sound is crucial to the production of a shock wave. At subsonic speeds, no overlapping of the waves will occur to produce a shock wave. Hence no sonic boom is produced. **49.** Open-ended.

CHAPTER NINETEEN PROBLEMS

1. (a) $f = 1/T = 1/0.10 \text{ s} =$ **10 Hz;** (b) $f = 1/5 =$ **0.2 Hz;** (c) $f = 1/(1/60) \text{ s} =$ **60 Hz.** **3.** The skipper notes that 15 meters of wave pass each 5 seconds, or equivalently, that 3 meters pass each 1 second, so the speed of the wave must be Speed $= \frac{\text{distance}}{\text{time}} = \frac{15 \text{ m}}{5 \text{ s}} =$ **3 m/s.** Or in wave terminology: Speed = frequency × wavelength = (1/5 Hz)(15 m) = **3 m/s.** **5.** $d = vt = (340 \text{ m/s})(1/600 \text{ s}) =$ **0.57 m.** Or use speed = wavelength × frequency to get wavelength = speed/frequency = (340 m/s)/(600 Hz) = 0.57 m. **7.** Speed of plane = 1.41 × speed of sound **(Mach 1.41)**. In the time it takes sound to go from A to C, the plane goes from A to B. Since the triangle A-B-C is a 45-45-90 triangle, the distance AB is $\sqrt{2} = 1.41$ times as long as the distance AC.

CHAPTER TWENTY RANKING

1. B, C, A

CHAPTER TWENTY EXERCISES

1. Light travels about a million times faster than sound, hence the delay between what you see and what you hear. **3.** Between us and other planets is a vacuum. Sound does not travel in a vacuum. **5.** Bees buzz when in flight because they flap their wings at audio frequencies. **7.** The carrier frequency of electromagnetic waves emitted by the radio station is 101.1 MHz. **9.** The wavelength of sound from Source A is half the wavelength of sound from Source B. **11.** Light travels about a million times faster than sound in air, so you see a distant event a million times sooner than you hear it. **13.** When sound passes a particular point in the air, the air is first compressed and then rarefied as the sound passes. So its density is increased and then decreased as the wave passes. **15.** Because snow is a good absorber of sound, it reflects little sound—hence quietness. **17.** The Moon is described as a silent planet because it has no atmosphere to transmit sounds. **19.** If the speed of sound were different for different frequencies, say, faster for higher frequencies, then the farther a listener is from the music source, the more jumbled the sound would be. In that case, higher-frequency notes would reach the ear of the listener first. The fact that this jumbling doesn't occur is evidence that sound of all frequencies travel at the same speed. (Be glad this is so, particularly if you sit far from the stage, or if you like outdoor concerts.) **21.** Sound travels slower in cold air because the air molecules that compose cold air themselves travel slower and therefore take a bit longer before they bump into each other, which results in slower sound. **23.** Refraction is the result of changing wave speeds, where part of a wave travels at a different speed than other parts. This occurs in non-uniform winds and non-uniform temperatures. Interestingly, if winds, temperatures, or other factors could not change the speed of sound, then refraction would not occur. (The fact that refraction does indeed occur is evidence for the changing speeds of sound.) **25.** Sound is more easily heard when the wind traveling toward the listener at elevations above ground level travels faster than wind near the ground. Then the waves are bent downward as is the case of the refraction of sound shown in Figure 20.8. **27.** In accord with the inverse-square law, the intensity decreases to 1/9 when distance is tripled. **29.** First, in outer space there is no air or other material to carry sound. Second, if there were, the faster-moving light would reach you before the sound. **31.** If a single disturbance at some unknown distance sends longitudinal waves at one known speed, and transverse waves at a lesser known speed, and you measure the difference in time of wave arrival, you can calculate the distance. The wider the gap in time, the greater the distance—which could be in any direction. If you use this distance as the radius of a circle on a map, you know the disturbance occurred somewhere on that circle. If you telephone two friends who have made similar measurements of the same event from different locations, you can transfer their circles to your map, and the point where the three circles intersect is the location of the disturbance. **33.** Soldiers break step when crossing a bridge so they will not set the bridge into forced vibration or resonance. **35.** Agree with the speed of sound, but not the frequency. Sound's frequency depends only on the vibration of the source itself, not the medium. **37.** The lower strings resonate with the upper strings. **39.** When you are equally distant from the speakers, their tones interfere constructively. When you step to one side, the distance to one speaker is greater than the distance to the other speaker and the two waves are no longer in phase. They interfere destructively. (If you step far enough to one side, they will interfere constructively again.) **41.** Long waves are most canceled, which makes the resulting sound so tinny. For example, when the speaker cones are, say, 4 centimeters apart, waves more than a meter long are nearly 180° out of phase, whereas 2-centimeter waves will be in phase. The higher frequencies are least canceled by this procedure. This must be tried to be appreciated. **43.** By resonance, when the buildup of vibrations in the glass exceed the breaking point of the glass. **45.** No, for the same word refers to different aspects of music. The beat of music involves rhythm, and the beats of sound involve throbbing due to interference. **47.** The "beat frequency" is 2 per minute, so you and your friend will be in step twice per minute, or every 30 seconds. You can see this also from the fact that your friend's stride length is a little shorter than yours, 24/25 as long to be exact, so when you have taken exactly 24 strides—which is after half a minute—your friend will have taken exactly 25 and you will be back in step. **49.** The possible frequencies are 264 + 4 = 268 Hz, or 264 − 4 = 260 Hz.

CHAPTER TWENTY PROBLEMS

1. Wavelength = speed/frequency $= \frac{340 \text{ m/s}}{340 \text{ Hz}} =$ **1 m.** Similarly for a 34,000 hertz wave: wavelength $= \frac{340 \text{ m/s}}{34\,000 \text{ Hz}} = 0.01 \text{ m} =$ **1 cm.** **3.** The ocean floor is 4590 meters down. The 6-second time delay means that the sound reached the bottom in 3 seconds. Distance = speed × time = 1530 m/s × 3 s = **4590 m.** **5.** The single blow you hear after you see Sally stop hammering originated with the next-to-last blow you saw. The very first blow would have appeared as silent, and succeeding blows synchronous with successive strikes. In one second sound travels 340 meters in air, the distance between you and Sally. **7.** There are 3 possible beat frequencies: 2 Hz, 3 Hz, and 5 Hz. These are of differences in fork frequencies: 261 − 259 = **2 Hz**; 261 − 256 = **5 Hz**; 259 − 256 = **3 Hz.**

CHAPTER TWENTY-ONE RANKING

1. a. C, B, A b. C, B, A c. A, B, C

CHAPTER TWENTY-ONE EXERCISES

1. Agree, for pitch is the subjective form of frequency. **3.** Agree. **5.** The strings warm up and expand during play. Hence they should be tuned while warm so re-tuning is minimized while on stage. **7.** Amplitude. **9.** Pitch depends on frequency. It does not depend on loudness or quality. **11.** Different strings have different mass and different tension. For a single string, a finger can change the length of vibrating part. **13.** The wavelength is the length of two loops, 60 cm. **15.** The greater mass increases the inertia of the string which decreases the frequency at which it will vibrate. **17.** The sounding board of the guitar presents more area of vibration, which produces louder sound. With no sounding board on the work bench, the sound is not as loud. **19.** The fundamental for a string occurs when only two nodes exist: one at each end of the string, so that it vibrates in one segment. By touching the midpoint, a third node is imposed there and the string vibrates in two segments. The wavelength is diminished by one-half, so the frequency increases by two. (Note the speed of the wave along the string doesn't change: speed = frequency × wavelength.) **21.** Agree. **23.** The amplitude in a sound wave corresponds to the overpressure of the compression or equivalently the underpressure of the rarefaction. **25.** The pattern on the right has the greater amplitude and is therefore louder. **27.** Sound intensity is a purely objective and physical attribute of a sound wave and can be measured by various acoustical instruments. Loudness, though closely related, is a physiological sensation, and can vary from person to person or for one person at different times. **29.** An electronic organ produces the sounds of various musical instruments by duplicating and superimposing the sine waves that make up the overall waves produced by these instruments. **31.** Your voice sounds fuller in a shower principally because of the small enclosure that causes your voice to reverberate as it reflects from wall to wall. **33.** The range of human hearing, from about 20 Hz to about 20,000 Hz, is a factor of about 1000. This is ten octaves because ten doublings of frequency gives a factor of approximately 1000 (1024 to be exact). The range of a piano is a little more than seven octaves. **35.** Frequency of second harmonic is twice the fundamental, or 440 Hz. The third is three times the harmonic, or 660 Hz. **37.** Not including endpoints, there are 5 nodes in a wave two wavelengths long, and 7 nodes in a wave three wavelengths long. (Make a drawing and count them!) **39.** Although the speed of sound past a listener on a windy day will change, the wavelength will correspondingly change also, resulting in no change in frequency or pitch. Or look at it this way: suppose a friend is placing bottles on a conveyor belt, say at a "frequency" of one each second. Then you, at the other end of the belt, take off one bottle each second. Now suppose your friend increases the speed of the belt, but still puts on one bottle each second. Can you see that the bottles (farther apart now) will still arrive to you at the rate of one per second? **41.** A Fourier analyzer is a device that sorts out the individual sine waves from a mixture of two or more sine waves, which is just what the human ear does. You hear the pure tones that make up a complex tone. **43.** We each perceive what we have been taught or have learned to perceive. This applies to our appreciation of art, our taste for food, and drink, and to the value we give to that which we smell, and to the textures we touch. Our perception of what is real in terms of religious beliefs, political beliefs, and our notions about where we fit in the scheme of things, is a product of what we have learned (or have not learned). **45.** Open-ended.

CHAPTER TWENTY-ONE PROBLEMS

1. For the highest frequencies, $\lambda = v/f = (340\ \text{m/s})/(20{,}000\ \text{Hz}) = 0.017\ \text{m}$ or 17 mm. For the lowest frequencies, $\lambda = v/f = (340\ \text{m/s})/(20\ \text{Hz}) = 17\ \text{m}$. **3.** Period $= 1/f = 1/264$ second (0.0038 s, or 3.8 ms). **5.** Sound at 40 dB is 10 thousand times more intense (each *additive* increment of 10 dB corresponds to a *factor* 10 in intensity). **7.** One octave above 1000 Hz is **2000 Hz,** and two octaves above 1000 Hz is **4000 Hz.** One octave below 1000 Hz is **500 Hz,** and two octaves below 1000 Hz is **250 Hz.**

CHAPTER TWENTY-TWO RANKING

1. A, C, B

CHAPTER TWENTY-TWO EXERCISES

1. Something is electrically charged when it has an excess or deficiency of electrons, compared with the number of protons in the atomic nuclei of the material. **3.** The objects aren't charged because of their equal number of protons. **5.** When wiped, the DVD becomes charged, which polarizes and attracts dust particles. **7.** The charged wrap nicely polarizes nonconducting plastic rather than metal, resulting in better sticking. **9.** The wires at toll-collecting stations are used to discharge the cars so that paying the toll is not a shocking experience for the driver or the collector. **11.** The leaves, like the rest of the electroscope, acquire charge from the charged object and repel each other because they both have the same sign of charge. The weight of the conducting metal foil is so small that even tiny forces are clearly evident. **13.** The charged body need not touch the ball of an electroscope. If a negative charge is simply brought near, some electrons in the ball are repelled and driven to the gold leaves, leaving the ball positively charged. Or if a positive charge is brought near the ball, some electrons will be attracted and move up to the ball to make it negative and leave the leaves positively charged. This is charge separation due to *induction.* (If by small chance you are attempting an answer to this question without having witnessed this, pity, pity, pity! Better that your time is spent studying the physics of familiar things.) **15.** The penny will be slightly more massive with a negative charge, for it will have more electrons than when neutral. If it were positively charged, it would be slightly lighter because of missing electrons. **17.** By induction: Bring the positively charged object near the object to be charged and the far side of the uncharged object will become positively charged. If you then touch the far side, you will in effect remove this charge because electrons will flow from your body to the positive charge. Remove your finger and the object then has a negative charge. (Interestingly enough, touching any side will produce the same result.) **19.** Electrons are easily dislodged from the outer regions of atoms, but protons are held tightly within the nucleus. **21.** It says that force decreases with the square of increasing distance, or increases as the square of decreasing distance. **23.** By the inverse-square law, the force increases. It will be four times as great when at half the distance, and nine times as great when at one-third the distance. **25.** Doubling the distance reduces the force to 1/4, whatever the sign of charge. This is in accord with Coulomb's law. **27.** Doubling both charges quadruples the force. The magnitude of the force does not depend on the sign of charge. **29.** Where lines are closer, the field is stronger. **31.** At twice the distance the field strength will be 1/4, in accord with the inverse-square law. **33.** Planet Earth is negatively charged. If it were positive, the field would point outward. **35.** The metal spikes penetrating into the ground reduce electrical resistance between the golfer and the ground, providing an effective electrical path from cloud to ground. Not a good idea! **37.** A neutral atom in an electric field is electrically distorted (see Figure 22.11). If the field is strong enough, the distortion results in ionization, where the charges are torn from each other. The ions then provide a conducting path for an electric current. **39.** The paint particles in the mist are polarized and are therefore attracted to the charged chassis. **41.** The forces on the electron and proton will be equal in magnitude, but opposite in direction. **43.** The electron and proton accelerate in opposite directions. **45.** The field is zero because the force on a test charge midway cancels to zero. **47.** By convention only, the direction of an electric field at any point is the direction of the force acting on a positive test charge placed at that point. A positive charge placed in the vicinity of a proton is pushed away from the proton; hence, the direction of the electric field vector is away from the proton. **49.** Charge will be more concentrated on the corners. (See Figure 22.21.) **51.** When released, its 10 joules of potential energy will become 10 joules of kinetic energy as it passes its starting position. **53.** Voltage = (0.5 J)/0.0001 C = 5000 V. **55.** The charges are of equal magnitude because the charge taken from one plate is given to the other. That's why the net charge of a capacitor is always zero. **57.** It is dangerous because the capacitor may still be charged. **59.** No, not inside any statically charged conducting body. Mutually repelling charges on the surface cancel the electric field inside the body to zero—true for solids as well as hollow conductors. (If the electric field were not zero, then conduction electrons would move in response to the field until electrical equilibrium was established—which is a zero electric field.)

CHAPTER TWENTY-TWO PROBLEMS

1. By the inverse-square law, twice as far is 1/4 the force; **5 N.** The solution involves relative distance only, so the magnitude of charges is irrelevant. **3.** From Coulomb's law, $F = k\frac{q_1 q_2}{d^2} = (9 \times 10^9)\frac{(1.0 \times 10^{-6})^2}{(0.03)^2} = \mathbf{10\ N.}$ This is the same as the weight of a 1-kg mass. **5.** $F(\text{grav}) = Gm_1m_2/d^2 = (6.67 \times 10^{-11})\frac{(9.1 \times 10^{-31})(1.67 \times 10^{-27})}{(1.0 \times 10^{-10})^2} = \mathbf{1.0 \times 10^{-47}\ N.}$ $F(\text{elec}) = kq_1q_2/d^2 = (9 \times 10^9)\frac{(1.6 \times 10^{-19})^2}{(1.0 \times 10^{-10})^2} = \mathbf{2.3 \times 10^{-8}\ N.}$ The electrical force between an electron and a proton is more than 1,000,000,000,000,000,000,000,000,000,000,000,000,000 times greater than the gravitational force between them! (Note that this ratio of forces is the same for any separation of the particles.) **7.** Energy is charge × potential: $PE = qV = (2\ C)(100 \times 10^6\ V) = \mathbf{2 \times 10^8\ J.}$ **9.** (a) $\Delta V = \frac{\text{energy}}{\text{charge}} = \frac{12\ J}{0.0001\ C} = $ **120,000 volts.** **9.** (b) ΔV for twice the charge is $\frac{24\ J}{0.0002} = $ same **120 kV.**

CHAPTER TWENTY-THREE RANKING

1. A–B–C **2.** C, B, A **5.** a. C, B, A **5.** b. A–B–C

CHAPTER TWENTY-THREE EXERCISES

1. Make the pipe wider and apply more pressure. Make the conducting wire thicker and apply more voltage (also you could use material with less resistance). **3.** Six amperes (10 − 4 − 6). **5.** As the current in the filament of a light bulb increases, the bulb glows brighter. **7.** Normally a current-carrying wire is not electrically charged because for every electron in the wire there is a proton. **9.** Only circuit 5 is complete and will light the bulb. (Circuits 1 and 2 are "short circuits" and will quickly drain the cell of its energy. In circuit 3 both ends of the lamp filament are connected to the same terminal and are therefore at the same potential. Only one end of the lamp filament is connected to the cell in circuit 4.) **11.** Agree with the friend who says energy, not current, is used up. **13.** Agree, for then the same appropriate voltage will power the circuit. **15.** Before it heats up, the filament is cooler and has less resistance. **17.** CFLs are more efficient because, relative to incandescents, more of the energy they transfer is light and less is heat. **19.** Thick wires have less resistance and will more effectively carry currents without excessive heating. **21.** A resistor doesn't "attract" or "draw" current, just as a pipe in a plumbing circuit doesn't "draw" water; it instead "allows" or "provides for" the passage of current when an electrical pressure is established across it. **23.** Electric shock *occurs* when current is produced in the body, which is *caused* by an impressed voltage. So the initial *cause* is the voltage, but it is the current that does the damage. **25.** Electric power in your home is likely supplied at 60 hertz and 110–120 volts via electrical outlets. This is ac. Battery terminals don't alternate, and current provided by them flows in one direction and is dc. **27.** More branches reduce resistance to motion, in both circuits and in toll booths. **29.** (a) volt, (b) ampere, (c) joule. **31.** The equivalent resistance of resistors in parallel is less than the smaller resistance of the two. So connect a pair of resistors in parallel for less resistance. **33.** Voltage across parallel branches, whatever the resistance, remains the same. **35.** The sign is a joke. High voltage may be dangerous, but high resistance is a property of all nonconductors. **37.** Damage generally occurs by excess heating when too much current is driven through an appliance. For the hairdryers, less damage is done plugging the 220-V one into 110 volts. **39.** Zero. Power companies do not sell electrons; they sell energy. Whatever number of electrons flow into a home, the same number flows out. **41.** Electric energy is propagated through a circuit by electric fields moving at close to the speed of light, not by electron collisions. Sound, on the other hand, travels by molecular or atomic collisions—a much slower process. **43.** Bulbs will glow brighter when connected in parallel, for the voltage of the battery is impressed across each bulb. When two identical bulbs are connected in series, half the voltage of the battery is impressed across each bulb. The battery will run down faster when the bulbs are in parallel. **45.** Most of the electric energy in a lamp filament is transformed to heat. For low currents in the bulb, the heat that is produced may be enough to feel but not enough to make the filament glow red or white hot. **47.** More bulbs in series means more resistance and less current. Bulbs glow dimmer. But when more bulbs are connected to the battery in parallel, the brightness of the bulbs doesn't change, for each bulb is connected directly to the battery. Each bulb has its own current path. **49.** What affects the other branches is the voltage impressed across them, and their own resistance—period. Opening or closing a branch doesn't alter either of these. **51.** Agree, because even for the smallest resistor, current has an alternative path(s), making for an overall smaller resistance. **53.** Connect four 40-ohm resistors in parallel. **55.** All are the same for identical resistors in parallel. If the resistors are not the same, the one of greater resistance will have less current through it and less power dissipation in it. Regardless of the resistances, the voltage across both will be identical. **57.** All three are equivalent parallel circuits. Each branch is individually connected to the battery. **59.** More current flows in the 100-watt bulb. We see this from the relationship "power = current × voltage." More current for the same voltage means less resistance. So a 100-watt bulb has less resistance than a 60-watt bulb. Less resistance for the same length of the same material means a thicker filament. The filaments of high wattage bulbs are thicker than those of lower-wattage bulbs. (It is important to note that both watts and volts are printed on a light bulb. A bulb that is labeled 100 W, 120 V, is 100 W *only* if there are 120 volts across it. If there are only 110 volts across it, and the resistance remains unchanged, then the power output would be only 84 watts!)

CHAPTER TWENTY-THREE PROBLEMS

1. From $I = V/R$, if both voltage and resistance are doubled, current remains unchanged. Likewise if both voltage and resistance are halved. **3.** From current $= \frac{\text{voltage}}{\text{resistance}}$, resistance $= \frac{\text{voltage}}{\text{current}} = \frac{120\text{V}}{20\text{A}} = \mathbf{6\ \Omega.}$ **5.** Two headlights draw 6 amps, so the 60 ampere-hour battery will last for about **10 hours.** **7.** (a) From power = current × voltage, current = power/voltage = 4W/120V = **1/30 A.** (b) From current = voltage/resistance (Ohm's law), resistance = voltage/current = 120 V/(1/30 A) = **3600 Ω.** (c) First, 4 watts = 0.004 kilowatt. Second, there are 8760 hours in a year (24 hours/day × 365 days = 8760 hours). So 8760 hours × 0.004 kilowatt = **35.0 kWh.** (d) At the rate of 15 cents per kWh, the annual cost is 35.0 kWh × \$0.15/kWh = **\$5.25.** **9.** Since current is charge per unit time, charge is current × time: $q = It = (9\ A)(60\ s) = (9\ C/s)(60\ s) = \mathbf{540\ C.}$ (Charges of this magnitude on the move are commonplace, but this quantity of charge accumulated in one place would be incredibly large.)

CHAPTER TWENTY-FOUR EXERCISES

1. Separation is easy with a magnet (try it and be amazed!) **3.** How the charge moves dictates the direction of its magnetic field. (A magnetic field is a vector quantity.) Magnetic fields cancel, more in some materials than others. **5.** Attraction will occur because the magnet induces opposite polarity in a nearby piece of iron. North will induce south, and south will induce north. This is similar to charge induction, where a balloon will stick to a wall whether the balloon is negative or positive. **7.** The poles of the magnet attract each other and will cause the magnet to bend, even enough for the poles to touch if the material is flexible enough. **9.** An electric field surrounds a stationary electric charge. An electric field and a magnetic field surround a moving electric charge. (And a gravitational field also surrounds both). **11.** Apply a small magnet to the door. If it sticks, your friend is wrong because aluminum is not magnetic. If it doesn't stick, your friend might be right (but not necessarily—there are lots of nonmagnetic materials). **13.** Over time, domains are knocked out of alignment. **15.** The needle is not pulled toward the north side of the bowl because the south pole of the magnet is equally attracted southward. The net force on the needle is zero. (The net torque, on the other hand, will be zero only when the needle is aligned with the Earth's magnetic field.) **17.** Vertically downward. **19.** The mechanism of alignment involves two factors: First, each filing is turned into a tiny magnet by the magnetic field of the bar magnet, which induces domain alignment in the filing. Second, a pair of equal torques act on the filing whenever it is not parallel to the magnetic field lines. These torques rotate the filings into alignment with the field lines like little compass needles. **21.** Yes, for the compass aligns with the Earth's magnetic field, which extends from the magnetic pole in the Southern Hemisphere to the magnetic pole in the Northern Hemisphere. **23.** Rotation is not produced when the axis of the loop is aligned with the field. **25.** Yes, it does. Since the magnet exerts a force on the wire, the wire, according to Newton's third law, must exert a force on the magnet. **27.** The needle points perpendicular to the wire (east or west). (See Figure 24.8.) **29.** Less power because of reduced electrical resistance. **31.** The beam must be traveling along or parallel to the magnetic field. **33.** The diameter decreases as the proton is pulled in a tighter circle. **35.** Speed or KE doesn't increase because the force is perpendicular to the velocity, doing no work on the particle. **37.** If the particles enter the field moving in the same direction and are deflected in opposite directions (say one left and one right), the charges must be of opposite sign. **39.** If the field interacts with a stationary bar magnet it is magnetic; if with a stationary charge, it is electric. If an electric current is generated in a rotating loop of wire, the field is magnetic. If a force acts only on a moving charge, the field is magnetic. So any of the classes of experiments that deal with electric charge at rest and electric charge in motion could be used to determine the nature of the field in the room. **41.** The Van Allen radiation belts are filled with swarms of high-energy charged particles that can damage living tissue. Astronauts, therefore, make an effort to keep below these belts. **43.** Singly-charged ions traveling with the same speed through the same magnetic field will experience the same magnetic force. The extent of their deflections will then depend on their accelerations, which in turn depend on their respective masses. The least massive ions will be deflected the most and the most massive ions will be deflected least. (See Figure 34.14, further in the book, for a diagram of a mass spectrograph.) **45.** To determine only by their interactions with each other which of two bars is a magnet, place the end of the bar #1 at the midpoint of bar #2 (like making a "T"). If there is an attraction, then bar #1 is the magnet. If there isn't, then bar #2 is the magnet. **47.** Yes, each will experience a force because each is in the magnetic field generated by the other. Interestingly, currents in the same direction attract, and currents in opposite directions repel. **49.** Each coil is magnetically attracted to its electromagnetic neighbor.

CHAPTER TWENTY-FIVE EXERCISES

1. E&M induction requires change; of the intensity of a magnetic field, or of motion in a magnetic field. **3.** The magnetic domains that become aligned in the iron core contribute to the overall magnetic field of the coil and therefore increase its magnetic induction. **5.** Work must be done to move a current-carrying conductor in a magnetic field. This is true whether or not the current is externally produced or produced as a result of the induction that accompanies the motion of the wire in the field. It's also a matter of energy conservation. There has to be more energy input if there is more energy output. **7.** A cyclist will coast farther if the lamp is disconnected from the generator. The energy that goes into lighting the lamp is taken from the bike's kinetic energy, so the bike slows down. The work saved by not lighting the lamp will be the extra "force × distance" that lets the bike coast farther. **9.** As in the previous answer, eddy currents induced in the metal change the magnetic field, which in turn changes the ac current in the coils and sets off an alarm. **11.** Copper wires were not insulated in Henry's time. A coil of non-insulated wires touching one another would comprise a short circuit. Silk was used to insulate the wires so current would flow along the wires in the coil rather than across the loops touching one another. **13.** In both cases, the direction of the magnetic force is perpendicular to the magnetic field and the motion of charges—but with different results. In the motor effect, the magnetic force pushes the wire upward. In the generator effect, the wire is pushed downward and the magnetic force pushes electrons in a direction along the wire to produce a current. **15.** Agree with your friend. Any coil of wire spinning in a magnetic field that cuts through magnetic field lines is a generator. **17.** In accord with electromagnetic induction, if the magnetic field alternates in the hole of the ring, an alternating voltage will be induced in the ring. Because the ring is metal, its relatively low resistance will result in a correspondingly high alternating current. This current is evident in the heating of the ring. **19.** The changing magnetic field produced when the current starts to flow induces a current in the aluminum ring. This current, in turn, generates a magnetic field that opposes the field produced by the magnet under the table. The aluminum ring becomes, momentarily, a magnet that is repelled by the hidden magnet. It is repelled, just as the aluminum ring levitates in the photo opener with Jean Curtis. **21.** If the light bulb is connected to a wire loop that intercepts changing magnetic field lines from an electromagnet, voltage will be induced which can illuminate the bulb. Change is the key, so to stay lit the electromagnet should be powered with ac. **23.** Induction occurs only for a *change* in the intercepted magnetic field. (a) The galvanometer displays a pulse when the switch in the first circuit is closed, as the current in the coil increases from zero. (b) When the current in the first coil is steady, no current is induced in the secondary and the galvanometer reads zero. (*c*) The galvanometer needle will swing in the opposite direction when the switch is opened and current falls to zero. **25.** A transformer requires alternating voltage because the magnetic field in the primary winding must change if it is to induce voltage in the secondary. No change, no induction. **27.** A transformer is analogous to a mechanical lever in that work is transferred from one part to another. What is multiplied in a mechanical lever is *force*, and in an electrical lever, *voltage*. In both cases, energy and power are conserved, so what is not multiplied is energy, a conservation of energy no-no! **29.** The hum heard when a transformer is operating on a 60 hertz ac line is a 60 hertz forced vibration of the iron slabs in the transformer core as their magnetic polarities alternate. The hum is greater if any other mechanical parts are set into vibrations. **31.** High efficiency requires that the maximum number of magnetic field lines produced in the primary are intercepted by the secondary. The core guides the lines from the primary through the secondary. Otherwise some of the magnetic field generated by the primary would go into heating metal parts of the transformer instead of powering the secondary circuit. **33.** The voltage impressed across the lamp is 120 V and the current through it is 0.1 A. We see that the first transformer steps the voltage down to 12 V and the second one steps it back up to 120 V. The current in the secondary of the second transformer, which is the same as the current in the bulb, is one-tenth of the current in the primary, or 0.1 A. **35.** By symmetry, the voltage and current for both primary and secondary are the same. So 12 V is impressed on the meter, with a current of 1 A ac. **37.** No, no, no, a thousand times no! No device can step up energy. This principle is at the heart of physics. Energy cannot be created or destroyed. **39.** As the magnet falls, it induces current that circles in the conducting pipe and is accompanied by its own magnetic field. The moving magnet is slowed by interaction with this induced field. **41.** Motion of conducting sheets through a magnetic field induces swirling currents (eddy currents) with fields that interact with the magnet and slow motion. Such doesn't occur in nonconducting cardboard. **43.** A voltage difference is induced across the wings of a moving airplane. This produces a momentary current and charge builds up on the wing tips to create a voltage difference that counteracts the induced voltage difference. So charge is pulled equally in both directions and doesn't move. **45.** The source of an electromagnetic wave is an oscillating electric charge. **47.** The incident radio wave causes conduction electrons in the antenna to oscillate. This oscillating charge (an oscillating current) provides the signal that feeds the radio. **49.** Agree with your friend, for light is electromagnetic radiation having a frequency that matches the frequency to which our eyes are sensitive.

CHAPTER TWENTY-FIVE PROBLEMS

1. If power losses can be ignored, in accord with energy conservation, the power provided by the secondary is also **100 W**. **3.** From the transformer relationship, $\frac{\text{primary voltage}}{\text{primary turns}} = \frac{\text{secondary voltage}}{\text{secondary turns}}$; $\frac{120\text{V}}{240 \text{ turns}} = \frac{6\text{V}}{x \text{ turns}}$. Solve for x: $x = (6\text{ V})(240 \text{ turns})/(120\text{ V}) =$ **12 turns**. •**5.** (a) Since power is voltage × current, the current in the lines is: current $= \frac{\text{power}}{\text{voltage}} = \frac{100{,}000\text{ W}}{12{,}000\text{ V}} =$ **8.3 A**. (b) Voltage between ends of each wire = current × resistance of the wire = (8.3 A)(10 Ω) = **83 V**. (*c*) In each line, power = current × voltage = (8.3 A)(83 V) = 689 W. For both wires the power wasted as heat is twice this, **1.38 kW**. Compared with 100 kW, this is a small and tolerable loss. So most power gets to the consumer.

CHAPTER TWENTY-SIX EXERCISES

1. Your friend is correct. Also in a profound tone, your friend could say that sound is the only thing we hear! **3.** The fundamental source of electromagnetic radiation is oscillating electric charges, which emit oscillating electric and magnetic fields. **5.** Ultraviolet has shorter wavelengths than infrared. Correspondingly, ultraviolet also has the higher frequencies. **7.** What waves in a light wave are the electric and magnetic fields. Their oscillation frequency is the frequency of the wave. **9.** We can see the Sun and stars. **11.** Speed is *c*, the speed of light. **13.** Agree. **15.** Agree. **17.** The faster wave has the longer wavelength—light, in accord with the rule $\lambda = v/f$. **19.** Radio waves are electromagnetic waves and travel at the speed of light. (Don't confuse sound waves with radio waves!) **21.** Radio waves and light are both electromagnetic, transverse, move at the speed of light, and are created and absorbed by oscillating charge. They differ in their frequency and wavelength and in the type of oscillating charge that creates and absorbs them. **23.** The average speed of light will be less where it interacts with absorbing and re-emitting particles of matter, such as in the atmosphere. The greater the number of interactions along the light's path, the less the average speed. **25.** Walking across a room and pausing to greet others is analogous to the transmission-of-light model in that there is a pause with each interaction. However, the same person that begins the walk ends the walk, whereas in light transmission there is a "death-birth" sequence of events as light is absorbed and "new light" is emitted in its place. The light to first strike the glass is not the same light that finally emerges. (Another analogy is a relay race, where the runner that begins the race is not the runner that crosses the finish line.) **27.** The greater number of interactions per distance tends to slow the light and result is a smaller average speed. **29.** Clouds are transparent to ultraviolet light, which is why clouds offer no protection from sunburn. Glass, however, is opaque to ultraviolet light, and will therefore shield you from sunburn. **31.** Any shadow cast by a faraway object such as a high-flying plane is filled in mainly by light tapering in from the Sun, which is not a point source. This tapering is responsible for the umbra and penumbra of solar eclipses (Figure 26.14). If the plane is low to the ground, however, the tapering of light around the airplane may be insufficient to fill in the shadow, part of which can be seen. This idea is shown in Figure 26.11. **33.** Yes. Evidence is a lunar eclipse, when the Moon passes in the Earth's shadow. **35.** No eclipse occurred because no shadow was cast on any other body. **37.** Rods, not cones, will respond to weak light, so you want to focus low-intensity light on a part of the retina that is composed of rods. That would be off to the side of the fovea. If you're looking at a weak star, look a bit off to the side of where you expect to see it. Then its image will fall on a part of your eye where rods may pick it up. **39.** We see no color at the periphery of our vision simply because there are no cones located on the outermost regions of the retina. **41.** The blind spot is located on the side of the fovea away from your nose. **43.** Energy is spread out and diluted, but not "lost." We distinguish between something being diluted and something being annihilated. In accord with the inverse-square law, light intensity gets weaker with distance, but the total amount of light over a spherical surface is the same at all distances from the source. **45.** Some airliners bounce electromagnetic waves from the ground below, measuring the round trip time in order to find the distance to the ground, much as a ship bounces sonic waves from the ocean floor to measure water depth. Far above the ground an altimeter is fine for determining the airplane's height above sea level, but close to the ground the pilot wants to know the airplane's distance from local ground. **47.** No, for the brightest star may simply be the closest star. **49.** You see your hand in the past! How much? To find out, simply divide the distance between your hands and your eyes by the speed of light. (At 30 cm, this is about a billionth of a second.)

CHAPTER TWENTY-SIX PROBLEMS

1. Speed $= \frac{\text{distance}}{\text{time}} = \frac{300{,}000{,}000\ \text{km}}{1300\ \text{s}} = \mathbf{231{,}000\ km/s}$. This value is 77% the modern value. **3.** From $v = \frac{d}{t}$, $t = \frac{d}{v} = \frac{d}{c} = \frac{1.5 \times 10^{11}\ \text{m}}{3 \times 10^{8}\ \text{m/s}} =$ 500 s (which equals 8.3 min). The time to cross the diameter of the Earth's orbit is twice this, or **1000 s**, as estimated fairly closely by Roemer (Problem 1). **5.** As in the previous problem, $t = \frac{d}{v} = \frac{4.2 \times 10^{16}\ \text{m}}{3 \times 10^{8}\ \text{m/s}} = \mathbf{1.4 \times 10^{8}\ s}$. Converting to years by dimensional analysis, $1.4 \times 10^{8}\ \text{s} \times \frac{1\ \text{h}}{3600\ \text{s}} \times \frac{1\ \text{day}}{24\ \text{h}} \times \frac{1\ \text{yr}}{365\ \text{day}} = \mathbf{4.4\ yr}$. **7.** (a) Frequency = speed/wavelength = $(3 \times 10^{8}\ \text{m/s})/(0.03\ \text{m}) = 1.0 \times 10^{10}\ \text{Hz} = 10\ \text{GHz}$. **7.** (b) Distance = speed × time, so time = distance/speed = $(10{,}000\ \text{m})/(3 \times 10^{8}\ \text{m/s}) = \mathbf{3.3 \times 10^{-5}\ s}$. (Note the importance of consistent SI units to get the right numerical answers.)

CHAPTER TWENTY-SEVEN EXERCISES

1. Red has the longest wavelength; violet has the shortest wavelength. **3.** Red paint is red because it reflects the red component of white light, while absorbing the other components. **5.** Either a white or green garment will reflect incident green light and be cooler. The complementary color, magenta, will absorb green light and be the best garment color to wear when the absorption of energy is desired. **7.** The interior coating absorbs rather than reflects light, and therefore appears black. A black interior in an optical instrument will absorb any stray light rather than reflecting it and passing it around the interior of the instrument to interfere with the optical image. **9.** Tennis balls are yellow green to be more visible, where they match the color to which we are most sensitive. **11.** Red cloth appears red in sunlight, and red by the illumination of the red light from a neon tube. But because the red cloth absorbs cyan light, it appears black when illuminated by cyan light. **13.** The color that will emerge from a lamp coated to absorb yellow is blue, the complementary color. (White − yellow = blue.) **15.** The overlapping blue and yellow beams will produce white light. When the two panes of glass are overlapped and placed in front of a single flashlight, however, little or no light will be transmitted. **17.** Red and green produce yellow; red and blue produce magenta; red, blue, and green produce white. **19.** Agree, for the "light mathematics" is correct. **21.** The orange-yellow is complementary to blue, which combine to black. Cars would be difficult to see under such light. **23.** Purple is seen. See Figure 27.12. **25.** Deep in water red is no longer present in light, so blood looks black. But there is plenty of red in a camera flash, so the blood looks red when so illuminated. **27.** Green + blue = cyan = white − *red*. **29.** The reflected color is white minus red, or cyan. **31.** We cannot see stars in the daytime because their dim light is overwhelmed by the brighter skylight, which is sunlight scattered by the atmosphere. **33.** The daytime sky is black, as it is on the nighttime sky there. **35.** The color of the Sun is yellow-white at all times on the Moon. **37.** Such glasses eliminate the distraction provided by the more strongly scattered blue and violet light yet let the pilot see in a frequency range where the eye is sensitive. (Glasses that transmit predominantly red would also get rid of the scattered blue and violet light but would provide light to which the eye is not very sensitive.) **39.** Agree. **41.** The statement is true. A more positive tone would omit the word "just," for the sunset is not *just* the leftover colors, but *is* those colors that weren't scattered in other directions. **43.** Through the volcanic emissions, the Moon appears cyan, the complementary color of red. **45.** The foam is composed of tiny bits of liquid that scatter light as a cloud does. **47.** If the atmosphere were several times thicker, the sunlight reaching the Earth would be predominantly low frequencies because most of the blue light would be scattered away. Snow would likely appear orange at noon, and a deep red when the Sun is not directly overhead. **49.** Sunset follows the activities of humans and other life that put dust and other particles in the air. So the composition of the sky is more varied at sunset.

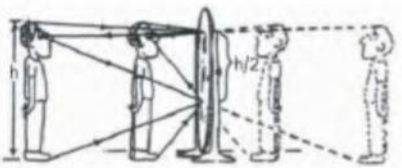
CHAPTER TWENTY-EIGHT RANKING

1. A=B=C (all same) **3.** B, C, A

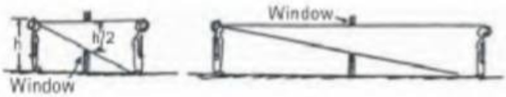
CHAPTER TWENTY-EIGHT EXERCISES

1. Peter's left foot is firmly planted on the table, behind the mirror between his legs. **3.** Fred and McKenzie are between two parallel mirrors. The reflection from one mirror is incident on the other, and so on. Ideally there would be an infinite number of images, but light is lost with each reflection. **5.** Only light from card number 2 reaches her eye.

7. Such lettering is seen in proper form in the rearview mirrors of cars ahead. **9.** When you wave your right hand, image of the waving hand is still on your right, just as your head is still up and your feet still down. Neither left and right nor up and down are inverted by the mirror, but *front and back* are, as the author's sister Marjorie illustrates in Figure 28.8. (Consider three axes at right angles to each other, the standard coordinate system; horizontal x, vertical y, and perpendicular-to-the-mirror z. The only axis to be inverted is z, where the image is $(-z)$.) **11.** When the source of glare is somewhat above the horizon, a vertical window will reflect it to people in front of the window. By tipping the window inward at the bottom, glare is reflected downward rather than into the eyes of passersby. (Note the similarity of this exercise and the previous one.) **13.** Rough pages provide diffuse reflection, which can be viewed from any angle. If the page were smooth it could only be viewed well at certain angles. **15.** The minimum length of a vertical mirror must be half your height in order for you to see a full-length view of yourself. The part of the mirror above and below your line of sight to your image isn't needed, as the sketch shows.



17. The wiped area will be half as tall as your face. **19.** The smallest window will be half the height of the person or her twin. Note that this does not depend on distance, providing both subjects are the same distance from the wall. This illustrates Exercises 12–15 above.



21. Farsighted. **23.** Agree, as inspection of Figure 28.24 shows. Note: wavefronts are closer together in water as compared with in air above. **25.** Red light travels faster through glass and will exit first. **27.** The speeds in both glass and soybean oil are the same (same index of refraction), so there is no refraction between the glass and oil. **29.** Throw the spear below the apparent position of the fish because refraction makes the fish appear closer to the surface than it really is. But in zapping a fish with a laser, make no corrections and simply aim directly at the fish. This is because the light from the fish you see has been refracted in getting to you, and the laser light will refract along the same path in getting to the fish. A slight correction may be necessary, depending on the colors of the laser beam and the fish—see the next exercise. **31.** A fish sees the sky (as well as some reflection from the bottom) when it looks upward at 45°, for the critical angle is 48° for water. If it looks at and beyond 48° it sees only a reflection of the bottom. **33.** In sending a laser beam to a space station, make no corrections and simply aim at the station you see. This is like zapping the fish in Exercise 29. The path of refraction is the same in either direction. **35.** The "nonwettable" leg of the water strider depresses and curves the surface of the water, which effectively produces a lens that directs light away from its path to form the extended shadow region. (Close observation shows a bright ring around the darker region. Interestingly, the overall brightness of the shadow and the bright ring average the same brightness—"conservation of light.") **37.** The fact that two observers standing apart from one another do not see the same rainbow can be understood by exaggerating the circumstance: Suppose the two observers are several kilometers apart. Obviously they are looking at different drops in the sky. Although they may both see a rainbow, they are looking at different rainbows. Likewise if they are closer together. Only if their eyes are at the very same location will they see exactly the same rainbow. **39.** Moon halos and rainbows are similar in that both are produced by light refracting from water. Ice crystals can disperse moonlight into two halos, much as water droplets

disperse light into two rainbows. For both, the outer bow is much fainter than the inner one. Halos and rainbows are different in that a halo and Moon are seen in the same part of the sky, with the Moon in the middle of the halo—whereas a rainbow is seen in the part of the sky opposite to the Sun (your shadow, if it can be seen, is in the middle of the rainbow). Another difference is that for rainbows reflection as well as refraction is important, whereas for halos only refraction is important. Yet another difference is that whereas a rainbow involves liquid water droplets, a halo involves frozen water crystals. **41.** The average intensity of sunlight at the bottom is the same whether the water is moving or is still. Light that misses one part of the bottom of the pool reaches another part. Every dark region is balanced by a bright region—"conservation of light." **43.** Normal sight depends on the amount of refraction that occurs for light traveling from air to the eye. The speed change ensures normal vision. But if the speed change is from water to eye, then light will be refracted less and an unclear image will result. A swimmer uses goggles to make sure that the light travels from air to eye, even if underwater. **45.** The diamond sparkles less because there are smaller angles of refraction between the water and the diamond. Light is already slowed when it meets the diamond so the amount of further slowing, and refraction, is reduced. **47.** The image will be a bit dimmer with original colors, but otherwise unaffected. **49.** If light had the same average speed in glass lenses that it has in air, no refraction of light would occur in lenses, and no magnification would occur. Magnification depends on refraction, which in turn depends on speed changes. **51.** Sharpness. **53.** The image produced by a pinhole is sharp, but very dim—a serious liability for a spy camera. A spy camera needs all the light it can get, particularly for dimly lit areas, which is why a large aperture is advantageous. **55.** For very distant objects, effectively at "infinity," light comes to focus at the focal plane of the lens. So the photosensitive surface is one focal length in back of the lens for very distant shots. For shorter distances, it is farther from the lens. **57.** Yes, the images are indeed upside down! The brain re-inverts them. **59.** Moon maps are upside-down views of the Moon to coincide with the upside-down image that Moon watchers see in a refractive telescope.

CHAPTER TWENTY-EIGHT PROBLEMS

1. 4 m/s. You and your image are both walking at 2 m/s. **3.** The butterfly's image is 20 cm in back of the mirror, so the distance from the image to your eye is 70 cm. **5.** The amount of light transmitted through two sheets of glass is about 85%. To see this, consider an incident intensity of 100 units. Then 92 units are transmitted through the first pane. 92% of this amount is transmitted through the second pane (0.92 of 92 = 84.6).

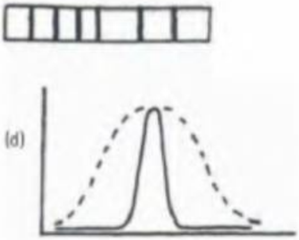
CHAPTER TWENTY-NINE EXERCISES

1. Earth intercepts such a tiny fraction of the expanding spherical wave from the Sun that it can be approximated as a plane wave (just as a small portion of the spherical surface of the Earth can be approximated as flat). The spherical waves from a nearby lamp have noticeable curvature. (See Figures 29.3 and 29.4.) **3.** The wavelengths of AM radio waves are hundreds of meters, much larger than the size of buildings, so they are easily diffracted around buildings. FM wavelengths are a few meters, borderline for diffraction around buildings. Light, with wavelengths a tiny fraction of a centimeter, show no appreciable diffraction around buildings. **5.** By a half wavelength, or an odd number of half-wavelengths. **7.** Blue light will produce narrower-spaced fringes. **9.** Longer wavelength red light. **11.** The spot will be bright due to constructive interference. **13.** Constructive interference. **15.** You'll photograph what you see through the lens—a spectrum of colors on either side of the streetlights. We'll see in the following chapter that the colors diffracted correlate with the illuminating gas in the streetlights. **17.** Young's interference experiment produces a clearer fringe pattern with slits than with pinholes because the pattern is of parallel straight-line-shaped fringes rather than the fringes of overlapping circles. Circles overlap in relatively smaller segments than the broader overlap of parallel straight lines. Also, the slits allow more light to get through; the pattern with pinholes is dimmer. **19.** Diffraction is the principle by which peacocks and hummingbirds display their colors. The ridges in the surface layers of the feathers act as diffraction gratings. **21.** The optical paths of light from upper and lower reflecting surfaces change with different viewing positions. Thus, a change in color can be seen by tilting the shell at different angles. **23.** A necessary condition for interference is that the out-of-phase parts of the wave coincide. If the film is thick, the part of the wave that reflects from one surface will be displaced from the part that reflects from the other surface. No interaction, no cancellation, no interference colors. For thin films, the two parts of the wave coincide as they recombine. **25.** Each colored ring represents a particular thickness of oil film, just as the lines on a surveyor's contour map represent equal elevations. **27.** Ultraviolet, due to its shorter wavelengths. **29.** The problem is serious, for depending on the orientation of the polarization axes of the display and the glasses, no display may be seen. **31.** If the sheet is aligned with the polarization of the light, all the light gets through. If it is aligned perpendicular to the polarization of the light, none gets through. At any other angle, some of the light gets through because the polarized light can be "resolved" (like a vector) into components parallel and perpendicular to the alignment of the sheet. **33.** You can determine the polarization axis for a single sheet of Polaroid by viewing the glare from a flat surface, as in Figure 29.34. The glare is most intense when the polarization axis is parallel to the flat surface. **35.** The axis of the filter should be vertical, not allowing the passage of the glare, which is parallel to the plane of the floor—horizontal. **37.** You can determine that the sky is partially polarized by rotating a single sheet of Polaroid in front of your eye while viewing the sky. You'll notice the sky darken when the axis of the Polaroid is perpendicular to the polarization axis of the skylight. **39.** Making holograms requires coherent light, exactly what a laser provides. Hence practical holography followed the advent of the laser. (Interestingly enough, the first holograms were made before the advent of the laser, and were crude by today's standards. They were made with monochromatic light from a sodium vapor lamp, through a tiny pinhole to provide a close approximation of coherent light, and required very long exposures.)

CHAPTER THIRTY EXERCISES

1. In accord with $E = hf$, a gamma ray photon has greater energy because it has a higher frequency. **3.** Higher-frequency, higher-energy blue light corresponds to a greater change of energy in the atom. **5.** Doubling the wavelength of light halves its frequency. Light of half frequency has half the energy per photon. Think in terms of the equation $c = f\lambda$. Since the speed of light c is constant, λ is inversely proportional to f. **7.** Spectral lines are images of the slit in a spectroscope. If the slit were crescent shaped, the "lines" would also be crescent shaped. **9.** Neon light is not monochromatic, so diffracted light from a neon tube produces a band of colors, most of which are various shades of red. Light from a helium-neon laser is of one color—monochromatic—showing only one of the spectral lines of neon. **11.** By comparing the absorption spectra of various nonsolar sources through Earth's atmosphere, the lines due to Earth's atmosphere can be established. Then when viewing solar spectra, extra lines and extra line intensities can be attributed to the atmosphere of the Sun. **13.** The moving star will show a Doppler shift. Since the star is receding, it will be a red shift (to lower frequency and longer wavelength). **15.** In accord with $E \sim f$, the higher frequency ultraviolet photon has more energy than a photon in the visible part of the spectrum, which in turn has more energy than a photon in the infrared part of the spectrum. **17.** Atoms excited in high-pressure gas interfere with one another in a way similar to the way closely-packed atoms in a solid do, resulting in overlapping waves and smearing of light. **19.** The many spectral lines from the element hydrogen are the result of the many energy states the single electron can occupy when excited. **21.** The "missing" energy may appear as light of other colors or as invisible infrared light. If the atoms are closely packed, as in a solid, some of the "missing" energy may appear as heat. In that case, the illuminated substance warms. **23.** Fluorescence is the process in which high-frequency (high energy) ultraviolet radiation converts to low-frequency (lower energy) visible radiation with some energy left over, perhaps appearing as heat. If your friend is suggesting that low-energy infrared radiation can be converted to higher-energy visible light, that is clearly a violation of the conservation of energy—a no-no! Now if your friend is suggesting that infrared radiation can cause the fluorescence of still lower-frequency infrared radiation, which is not seen as light, then your friend's reasoning is well founded. **25.** Fabrics and other fluorescent materials produce bright colors in sunlight because they both reflect visible light and transform some of the Sun's ultraviolet light into visible light. They literally glow when exposed to the combined visible and ultraviolet light of the Sun. **27.** Just as a time delay occurs with the opening and closing of a spring door, a similar time delay occurs between excitation and de-excitation in a phosphorescent material. **29.** A CFL puts out little heat and much light. For the same wattage, the CFL would put out far less heat than an incandescent bulb. The chickens would be well lit, but cold. **31.** Red + green = yellow. **33.** The acronym says it: *m*icrowave *a*mplification by *s*timulated *e*mission of *r*adiation. **35.** Its energy is very concentrated in comparison with that of a lamp. **37.** If it weren't relatively long-lived, there wouldn't be enough accumulation of atoms in this excited state to produce the "population inversion" that is necessary for laser action. **39.** Your friend's assertion violates the law of energy conservation. A laser or any device cannot put out more energy than is put into it. Power, on the other hand, is another story, as is treated in the following exercise. **41.** f bar is the peak frequency of incandescent radiation—that is, the frequency at which the radiation is most intense. T is the temperature of the emitter. **43.** Both radiate energy, but since temperatures are different, the hotter Sun emits higher frequencies of light than does Earth, and of much greater intensity. **45.** The metal is glowing at all temperatures, whether we can see the glow or not. As its temperature is increased, the glow reaches the visible part of the spectrum and is visible to human eyes—red. So the heated metal passes from infrared (which we can't see) to visible red. It is red hot. **47.** Star's relative temperatures—lowish for reddish; middish for whitish; and hottish for bluish. **49.** A star with peak frequency in the ultraviolet emits enough light in the higher-frequency part of the visible spectrum to appear "violet-hot." As in the previous exercise, if it were cooler, all frequencies of the visible spectrum would be present and the star would appear white.

51. (c)



53. The sum of the two frequencies is equal to the frequency of light emitted in the transition from quantum level 4 to the ground state, quantum level 1. **55.** Only three, one from 4 to ground, one from 3 to ground, and one from 2 to ground. The transition from 4 to 3 would involve the same difference in energy and be indistinguishable from the transition from 3 to 2, or from 2 to ground. Likewise, the transition from 4 to 2 would have the same change in energy as a transition from 3 to ground.

CHAPTER THIRTY PROBLEMS

1. (a) The B-to-A transition has twice the energy and twice the frequency of the C-to-B transition. Therefore, it will have half the wavelength, or 300 nm. Reasoning: Since $c = f\lambda$, $\lambda = c/f$. Wavelength is inversely proportional to frequency. Twice the frequency means half the wavelength. (b) The C-to-A transition has three times the energy and three times the frequency of the C-to-B transition. Therefore it will have one-third the wavelength, or 200 nm.

CHAPTER THIRTY-ONE EXERCISES

1. Saying that something is quantized is saying it is composed of elementary units. Electric charge, for example, is composed of multiples of the charge of the electron, so we say charge is quantized. A gram of pure gold is quantized in that it is made of a whole number of gold atoms. In this chapter we learn that light—radiant energy—is also quantized. **3.** $E \sim f$ is a proportion. When E is divided by f we have the constant h. With h the proportion becomes the exact equation $E = hf$. So we see h is the proportionality constant for the energy and frequency of a photon of light. **5.** Higher-frequency ultraviolet light has more energy per photon. **7.** Higher-frequency green light has more energy per photon. **9.** Finding materials that would respond photoelectrically to red light was difficult because photons of red light have less energy for image production than photons of green or blue light. **11.** The energy of red light is too low per photon to trigger the chemical reaction in the photographic crystals. Very bright light simply means more photons that are unable to trigger a reaction. Blue light, on the other hand, has sufficient energy per photon to trigger a reaction. Very dim blue light triggers fewer reactions only because there are fewer photons involved. It is safer to have bright red light than dim blue light. **13.** The kinetic energy of ejected electrons depends on the frequency of the illuminating light. With sufficiently high frequency, the number of electrons ejected in the photoelectric effect is determined by the number of photons incident upon the metal. So whether or not ejection occurs depends on frequency, and how many electrons are ejected depends on the brightness of the sufficiently high-frequency light. **15.** Ultraviolet photons are more energetic. **17.** Particle nature. **19.** *Electric eye:* A beam of light is directed to a photosensitive surface that completes the path of an electric circuit. When the beam is interrupted, the circuit is broken. The entire photoelectric circuit may be used as a switch for another circuit. *Light meter:* The variation of photoelectric current with variations in light intensity activates a galvanometer, or its equivalent, that is calibrated to show light intensity. *Sound track:* An optical sound track on motion picture film is a strip of emulsion of variable density that transmits light of variable intensity onto a photosensitive surface, which in turn produces an electric current of the desired variations. This current is amplified and then activates the loudspeaker. **21.** There will be colors toward the red end of the spectrum where the meter will show no reading, since no electrons are ejected. As the color is changed toward the blue and violet, a point will be reached where the meter starts to give a reading. If a color for which the meter reads zero is made more intense, the meter will continue to read zero. If a color for which the meter shows a reading is made more intense, the current recorded by the meter will increase as more electrons are ejected. **23.** Young's explanation of the double-slit experiment is based on the wave model of light: Einstein's explanation of the photoelectric effect uses a model in which light is composed of particles. The effectiveness of one model or another doesn't invalidate the other model, particularly in this instance where the models are used to describe completely different phenomena. Models are not to be judged as being "true" or "false" but as being useful or not useful. The particle model of light is useful in making sense of the details of the photoelectric effect, whereas the wave model of light is not useful in understanding these details. On the other hand, the wave model of light is useful for understanding the details of interference, whereas the particle model is not. The effectiveness of one model over another means simply that: One model is more effective than another. This effectiveness doesn't mean that one model is correct and the other invalid. As we gather more data and gain new insights, we refine our models. The fact that two quite different models are needed to describe light lead to what is called the "wave-particle duality," a central part of quantum physics. **25.** Diffraction, polarization, and interference are evidence of the wave nature of light; the photoelectric effect is evidence of the particle nature of light. **27.** No. Complementarity isn't a compromise, but suggests that what you see depends on your point of view. What you see when you look at a box, for example, depends on whether you see it from one side, the top, and so on. All measurements of energy and matter show quanta in some experiments and waves in others. For light, we see particle behavior in emission and absorption, and wave behavior in propagation between emission and absorption. **29.** By absorbing energy from the impact of a particle or photon. **31.** Uranium possesses more momentum. Hydrogen has the longer wavelength, which is inversely-proportional to momentum. **33.** The more massive proton has more momentum, while the electron with its smaller momentum has the longer wavelength. **35.** As velocity increases, momentum increases, so by de Broglie's formula, wavelength decreases. **37.** The principal advantage of an electron microscope over an optical microscope is its ability to see things that are too small for viewing with an optical microscope. This is because an object cannot be discerned if it is smaller than the wavelength of the illuminating beam. An electron beam has a wavelength that is typically a thousand times shorter than the wavelength of visible light, which means it can discern particles a thousand times smaller than those barely seen with an optical microscope. **39.** Planck's constant would be zero. **41.** In the best spirit of science, from our observations we develop a theory that gives meaning to those observations. However, it is often the case that belief in a theory precedes observations and influences our perception of those observations and the meaning we give them. We should be aware of this "human factor." Sometimes it is very beneficial and sometimes it is not. **43.** If somebody looks at an electron on the tip of your nose with an electron beam or a light beam, then its motion as well as that of surrounding electrons will be altered. We take the view here that passively looking at light after it has reflected from an object does not alter the electrons in the object. We distinguish between passive observation and probing. The uncertainty principle applies to probing, not to passive observation. (This view, however, is not held by some physicists who assert any measure, passive or probing, alters that being measured at the quantum level. These physicists argue that passive observation provides knowledge, and that without this knowledge, the electron might be doing something else or might be doing a mixture, a superposition, of other things.) **45.** Heisenberg's uncertainty principle applies *only* to quantum phenomena. However, it serves as a popular metaphor for the macro domain. Just as the way we measure affects what's being measured, the way we phrase a question often influences the answer we get. So to various extents we alter that which we wish to measure in a public opinion survey. Although there are countless examples of altering circumstances by measuring them, the uncertainty principle has meaning only in the sub-microscopic world. **47.** The uncertainty principle refers only to the quantum realm, and not the macro world. Air escaping from a tire is a macro-world event. **49.** Unless the term is meant to leap into a completely different realm, then no, because a quantum leap is the *smallest* transition something can undergo.

CHAPTER THIRTY-ONE PROBLEMS

1. Frequency is speed/wavelength: $f = (3 \times 10^{8}\ \mathrm{m/s})/(2.5 \times 10^{-2}\ \mathrm{m}) = 1.2 \times 10^{10}\ \mathrm{Hz}$. Photon energy is Planck's constant × frequency: $E = hf = (6.6 \times 10^{-34}\ \mathrm{J{\cdot}s})(1.2 \times 10^{10}\ \mathrm{Hz}) = \mathbf{7.9 \times 10^{-24}\ J}$. **3.** The ball's momentum is $mv = (0.1\ \mathrm{kg})(0.001\ \mathrm{m/s}) = 1.0 \times 10^{-4}\ \mathrm{kg\,m/s}$, so its de Broglie wavelength is $h/p = (6.6 \times 10^{-34}\ \mathrm{J{\cdot}s})/(1.0 \times 10^{-4}\ \mathrm{kg\,m/s}) = \mathbf{6.6 \times 10^{-30}\ m}$, which is incredibly small relative even to the tiny wavelength of the electron. There is no hope of rolling a ball slowly enough to make its wavelength appreciable.

CHAPTER THIRTY-TWO EXERCISES

1. Photons from the ultraviolet lamp have greater frequency, energy, and momentum. Only wavelength is greater for photons emitted by the TV transmitter. **3.** A small fraction of the alpha particles were deflected (scattered) through a large angle, indicating such a strong electric field within the atom that the positive charge must be concentrated in a small central core—a core that is massive as well as small because the rebounding alpha particles showed no appreciable loss of KE. **5.** Rutherford's experiments showed that the positive charge must be concentrated in a small core, the atomic nucleus. **7.** It would emit a continuous spectrum. Its energy would change gradually and continuously as it spiraled inward and it would radiate at its rotational frequency, which would be continuously increasing. **9.** The same amount of energy is needed to return the electron, as it gave to the photon when dropping to the ground state. **11.** Electrons can be boosted to many energy levels, and therefore make many combinations of transitions to ground level and levels in between. The vast variety of transitions produce the vast numbers of spectral lines in a spectroscope. Even hydrogen, with a single electron, has many lines. **13.** The particle nature of the electron best explains the photoelectric effect, while the wave nature best explains the discreteness of energy levels. **15.** Helium's electrons are in one filled shell. The filled shell means that bonding with other elements is rare. Lithium has two shells, the first filled and the second with only one of eight electrons in it, making it very reactive with other elements. **17.** Yes. In atoms, electrons move on the order of 2 million m/s, and their wave nature is quite pronounced. **19.** Both use Bohr's concept of energy levels in an atom. An orbital is represented by the easier-to-visualize orbit. **21.** The amplitude of a matter wave is called its wave function, represented by the symbol ψ. Where ψ is large, the particle (or other material) is more likely to be found. Where ψ is small, the particle is less likely to be found. (The actual probability is proportional to ψ^2.) **23.** What waves is the probability amplitude. **25.** Electrons have a definite mass and a definite charge, and can sometimes be detected at specific points—so we say they have particle properties; electrons also produce diffraction and interference effects, so we say they have wave properties. There is a contradiction only if we insist the electron may have only particle OR only wave properties. Investigators find that electrons display both particle and wave properties. **27.** Both are consistent. The correspondence principle requires agreement of quantum and classical results when the "graininess" of the quantum world is not important, but permits disagreement when the graininess is dominant. **29.** Bohr's correspondence principle says that quantum mechanics must overlap and agree with classical mechanics in the domain where classical mechanics has been shown to be valid. **31.** The philosopher was speaking of classical physics, the physics of the macroscopic world, where to a high degree of accuracy the same physical conditions produce the same results. Feynman was speaking of the quantum domain where, for small numbers of particles and events, the same conditions are not expected to produce the same results. **33.** The speed of light is large compared with the ordinary speeds with which we deal in everyday life. Planck's constant is small in that it gives wavelengths of ordinary matter far too small to detect and energies of individual photons too small to detect singly with our eyes.

CHAPTER THIRTY-THREE RANKING

1. C, B, A. **3.** a. B, C, A. **3.** b. C, A, B.

CHAPTER THIRTY-THREE EXERCISES

1. Kelvin was not aware of radioactive decay, a source of energy to keep Earth warm for billions of years. **3.** Gamma radiation is in the form of electromagnetic waves, while alpha and beta radiations consist of particles. **5.** It is impossible for a hydrogen atom to eject an alpha particle, for an alpha particle is composed of four nucleons—two protons and two neutrons. It is equally impossible for a 1-kg melon to disintegrate into four 1-kg melons. **7.** The alpha particle has twice the charge, but almost 8000 times the inertia (since each of the four nucleons has nearly 2000 times the mass of an electron). Even though the alpha particle is slower than the electron, it has more momentum due to its great mass, and hence deflects less than an electron in a given magnetic field. **9.** Alpha radiation decreases the atomic number of the emitting element by 2 and the atomic mass number by 4. Beta radiation increases the atomic number of an element by 1 and does not affect the atomic mass number. Gamma radiation does not affect the atomic number or the atomic mass number. So alpha radiation results in the greatest change in both atomic number and mass number. **11.** Gamma predominates inside the enclosed elevator because the structure of the elevator shields against alpha and beta particles better than against gamma-ray photons. **13.** An alpha particle undergoes an acceleration due to mutual electric repulsion as soon as it is out of the nucleus and away from the attracting nuclear force. This is because it has the same sign of charge as the nucleus. Like charges repel. **15.** Because it has twice as much charge as a beta particle, an alpha particle interacts more strongly with atomic electrons and loses energy more rapidly by ionizing the atoms. (The slower speed of the alpha particle also contributes to its ability to ionize atoms more effectively.) **17.** Within the atomic nucleus, it is the strong nuclear force that holds the nucleons together, and the electric force that mutually repels protons and pushes them apart. **19.** Yes, indeed! **21.** Chemical properties have to do with electron structure, which is determined by the number of protons in the nucleus, not the number of neutrons. **23.** In accord with the inverse-square law, at 2 m, double the distance, the count rate will be 1/4 of 360 or 90 counts/minute; at 3 m, the count rate will be 1/9 of 360, or 40 counts/minute. **25.** Number of nucleons and electric charge. **27.** The mass of the element is 157 + 100 = 257. Its atomic number is 100, the transuranic element named fermium, after Enrico Fermi. **29.** After the polonium nucleus emits a beta particle, the atomic number increases by 1 to become 85, and the atomic mass is unchanged at 218. **31.** Both have 92 protons, but U-238 has more neutrons than U-235. **33.** An element can decay to an element of greater atomic number by emitting electrons (beta rays). When this happens, a neutron in the nucleus becomes a proton and the atomic number increases by one. **35.** When a phosphorus nucleus (atomic number 15) emits a positron (a positively-charged electron) the charge of the atomic nucleus decreases by 1, converting it to the nucleus of the element silicon (atomic number 14). **37.** If nuclei were composed of equal numbers of protons and electrons, nuclei would have no net charge. They wouldn't hold electrons in orbit. The fact that atoms do have a positive nucleus and orbiting electrons contradicts your friend's assertion. **39.** The elements below uranium in atomic number with short half-lives exist as the product of the radioactive decay of uranium or another very long-lived element, thorium. For the billions of years that the uranium and thorium last, the lighter elements will be steadily replenished. **41.** Your friend will encounter more radioactivity from the granite outcroppings than he or she will in the same time near a nuclear power plant. Plus, at high altitude your friend will be treated to increased cosmic radiation. But the radiations encountered in the vicinity of the plant, on the granite outcropping, or at high altitude are not appreciably different than the radiation one encounters in the "safest" of situations. Advise your friend to enjoy life anyway! **43.** Although there is significantly more radioactivity in a nuclear power plant than in a coal-fired power plant, almost none of it escapes from the nuclear plant, whereas most of what radioactivity there is in a coal-fired plant does escape, through the stacks. As a result, a typical coal plant injects more radioactivity into the environment than does a typical nuclear plant. **45.** The irradiated food does not become radioactive as a result of being zapped with gamma rays. This is because the gamma rays lack the energy to initiate the nuclear reactions in atoms in the food that could make them radioactive. **47.** Dinosaur bones are simply much too old for carbon dating. **49.** Stone tablets cannot be dated by the carbon dating technique. Nonliving stone does not ingest carbon and transform that carbon by radioactive decay. Carbon dating works for organic materials.

CHAPTER THIRTY-THREE PROBLEMS

1. At the end of the second year **1/4** of the original sample will be left; at the end of the third year, **1/8** will be left; and at the end of the fourth year, **1/16** will be left. **3.** **1/16** will remain after 4 half-lives, so $4 \times 30 = 120$ years. **5.** The intensity is down by a factor of 16.7 (from 100% to 6%). How many factors of two is this? About 4, since $2^4 = 16$. So the age of the artifact is about 4×5730 years or about 23,000 years.

CHAPTER THIRTY-FOUR RANKING

1. A, B, C, D.

CHAPTER THIRTY-FOUR EXERCISES

1. Fission. **3.** Electric repulsion between protons reaches across the whole nucleus, affecting all protons, whereas the attractive nuclear force reaches only from one nucleon to nearer neighbors. So the greater the number of protons in a nucleus, the greater the likelihood that mutual electrical repulsion will overcome the attractive nuclear forces and lead to fission. **5.** A neutron makes a better "bullet" for penetrating atomic nuclei because it has no electric charge and is therefore not electrically repelled by an atomic nucleus. **7.** No. The flattened shape has more surface area, and therefore more neutron leakage, making it subcritical. **9.** The process of assembling small pieces of fission fuel into a single big piece increases average traveling distance, decreases surface area, reduces neutron leakage, and increases the probability of a chain reaction and an explosion. **11.** Only trace amounts of plutonium can occur naturally in U-238 concentrations. When U-238 captures a stray neutron it becomes U-239 and after beta emission becomes Np-239, which further transforms by beta emission to Pu-239. Because of its relatively short half-life (24,360 years) it doesn't last long. Any plutonium initially in Earth's crust has long since decayed. **13.** The resulting nucleus is $_{92}U^{233}$. The mass number is increased by 1 and the atomic number by 2. U-233, like U-235, is fissionable with slow neutrons. (Notice the similarity to the production of $_{94}Pu^{239}$ from $_{92}U^{238}$.) **15.** When a neutron bounces from a carbon nucleus, the nucleus rebounds, taking some energy away from the neutron and slowing it down so it will be more effective in stimulating fission events. A lead nucleus is so massive that it scarcely rebounds at all. The neutron bounces with practically no loss of energy and practically no change of speed (like a marble from a bowling ball). **17.** If the difference in mass for changes in the atomic nucleus increased tenfold (from 0.1% to 1.0%), the energy release from such reactions would increase tenfold as well. **19.** Both chemical burning and nuclear fusion require a minimum ignition temperature to start and in both the reaction is spread by heat from one region to neighboring regions. There is no critical mass. Any amount of thermonuclear fuel or of combustible fuel can be stored. **21.** Each fragment would contain 46 protons (half of 92) and 72 neutrons (half of 144), making it the nucleus of Pd-118, an isotope of palladium, element number 46. **23.** Splitting light nuclei (which happens in particle accelerators) costs energy. As the curve in Figure 34.16 shows, the total mass of the products is greater than the total mass of the initial nucleus. **25.** If uranium were split into three parts, the segments would be nuclei of smaller atomic numbers, more toward iron on the graph of Figure 34.16. The resulting mass per nucleon would be less, and there would be more mass converted to energy in such a fissioning. **27.** The fusion of 2 hydrogen nuclei with an oxygen nucleus would produce a nucleus of neon, atomic number 10. **29.** If the mass per nucleon varied in accord with the shape of the curve of Figure 34.15 instead of the curve of Figure 34.16, then the fissioning of all elements would liberate energy and all fusion processes would absorb rather than liberate energy. This is because all fission reactions (decreasing atomic number) would result in nuclei with less mass per nucleon, and all fusion reactions (increasing atomic number) would result in the opposite; nuclei of more mass per nucleon. **31.** The initial uranium has more mass than the fission products. **33.** Although more energy is released in the fissioning of a single uranium nucleus than in the fusing of a pair of deuterium nuclei, the much greater number of lighter deuterium atoms in a gram of matter than the heavier uranium atoms in a gram of matter, results in more energy liberated per gram for the fusion of deuterium. **35.** A hydrogen bomb produces a lot of fission energy as well as fusion energy. Some of the fission is in the fission bomb "trigger" used to ignite the thermonuclear reaction and some is in fissionable material that surrounds the thermonuclear fuel. Neutrons produced in fusion cause more fission in this blanket. Fallout results mainly from the fission. **37.** Energy from the Sun is our chief source of energy, which itself is the energy of fusion. Harnessing that energy on Earth has proven to be a formidable challenge. **39.** Such speculation could fill volumes. The energy and material abundance that is the possible outcome of a fusion age will likely prompt several fundamental changes. Obvious changes would occur in the fields of commerce. Also, global warming by humans would be greatly reduced. Regional wars based on oil scarcity would be reduced. More development would likely reach underdeveloped parts of the world. A fusion age would likely see changes that would touch every facet of human life. **41.** You don't get something for nothing. There is great misunderstanding about hydrogen. To release it from water or other chemicals costs more energy than you get back when you burn it. Hydrogen represents stored energy, like a battery. It's made in one place and used in another. It burns without pollution, a big advantage, but it should be regarded as a storage and transport medium for energy, not as a fuel. **43.** The KE of the fission products is converted into heat energy for boiling water to turn a turbine. **45.** In 1 billion years U-235 would be in short supply and fission power would likely be a thing of history.

CHAPTER THIRTY-FOUR PROBLEMS

1. The energy released by the explosion in kilocalories is (20 kilotons) $(4.2 \times 10^{12}$ J/kiloton)/(4184 J/kilocalorie) $= 2.0 \times 10^{10}$ kilocalories. This is enough energy to heat 2.0×10^{10} kg of water by 1°C. Dividing by 50, we conclude that this energy could heat 4.0×10^{8} kilograms of water by 50°C. This is nearly half a million tons. **3.** The neutron and the alpha particle fly apart with equal and opposite momenta. But since the neutron has one-fourth the mass of the alpha particle, it has four times the speed. Then consider the kinetic-energy equation, $KE = (1/2)mv^2$. For the neutron, $KE = (1/2)m(4v)^2 = 8\,mv^2$, and for the alpha particle, $KE = (1/2)(4m)v^2 = 2mv^2$. The KEs are in the ratio of 8/2, or 80/20. So we see that the neutron gets 80% of the energy, and the alpha particle 20%. (Alternative method: The formulas for momentum and KE can be combined to give $KE = p^2/2m$. This equation tells us that for particles with the same momentum, KE is inversely proportional to mass.)

CHAPTER THIRTY-FIVE RANKING

1. C, B, A.

CHAPTER THIRTY-FIVE EXERCISES

1. The effects of relativity become pronounced only at speeds near the speed of light or when energies change by amounts comparable to mc^2. In our "nonrelativistic" world, we don't directly perceive such things, whereas we do perceive events governed by classical mechanics. So the mechanics of Newton is consistent with our common sense, based on everyday experience, while the relativity of Einstein is not consistent with common sense. Its effects are outside our everyday experience. **3.** (a) The ball is moving faster relative to the ground when the train is moving (forward). (b) The ball moves at the same speed relative to the freight car whether the train is moving or not. **5.** Michelson and Morley considered their experiment a failure in the sense that it did not confirm the result that was expected, namely that differences in the velocity of light would be encountered and measured. No such differences were found. The experiment was successful in that it widened the doors to new insights in physics. **7.** The *average* speed of light in a transparent medium is less than c, but in the model of light discussed in Chapter 26, the photons that make up the beam travel at c in the void that lies between the atoms of the material. Hence the speed of individual photons is always c. In any event, Einstein's postulate is that the speed of light in *free* space is invariant. **9.** Yes, for example, a distant part of a beam sweeping the sky. What it doesn't allow is energy or particles or the transmission of information to exceed c. **11.** No energy or information is carried perpendicular to the swept beam. **13.** As explained in the answer to Exercise 12, the moving points are not material things. No mass or no information can travel faster than c, and the points so described are neither mass nor information. Hence, their faster motion doesn't contradict special relativity. **15.** It's all a matter of relative velocity. If two frames of reference are in relative motion, events can occur in the order AB in one frame and in the order BA in the other frame. (See the next exercise.) **17.** Experimental evidence in accelerators has again and again shown that as more and more energy is put into a particle, the particle never reaches the speed of light. Its momentum grows without limit, but not its speed. As the speed of light is approached, the momentum of the particle approaches infinity. There is an infinite resistance to any further increase in momentum, and hence speed. So c is the speed limit for material particles. (Kinetic energy likewise approaches infinity as the speed of light is approached.) **19.** When we say that light travels a certain distance in 20,000 years we are talking about distance in our frame of reference. From the frame of reference of a traveling astronaut, this distance may well be far shorter, perhaps even short enough that she could cover it in 20 years of her time (traveling, to be sure, at a speed close to the speed of light). In a distant future, astronauts may travel to destinations many light years away in a matter of months in their frame of reference. **21.** A twin who makes a long trip at relativistic speeds returns younger than his stay-at-home twin sister, but both of them are older than when they separated. If they could watch each other during the trip, there would be no time where either would see a reversal of aging, only a slowing or speeding of aging. A hypothetical reversal would result only for speeds greater than the speed of light. **23.** If you were in a high-speed (or no speed) rocket ship, you would note no changes in your pulse or in your volume. This is because the velocity between the observer, that is, yourself, and the observed is zero. No relativistic effect occurs for the observer and the observed when both are in the same reference frame. **25.** Narrower as well. **27.** Yes, although only high speeds are significant. Changes at low speeds, although there, are imperceptible. **29.** The density of a moving body is measured to increase because of a decrease in volume for the same mass. **31.** For the speed of light equation, v is c. Before relativity, c might have one value in one frame of reference and a different value in another frame. It depended on the motion of the observer. According to relativity, c is a constant, the same for all observers. **33.** The stick must be oriented in a direction perpendicular to its motion, unlike that of a properly-thrown spear. This is because it is traveling at relativistic speed (actually $0.87c$) as evidenced by its increase in momentum. The fact that its length is unaltered means that its long direction is not in the direction of motion. The thickness of the stick, not the length of the stick, will appear shrunken to half size. **35.** As with the stick in the preceding exercise, the momentum of the rocket ship will be twice the classical value if its measured length is half its normal length. **37.** For the moving electron, length contraction reduces the apparent length of the 2-mile long tube. Because its speed is nearly the speed of light, the contraction is great. **39.** The acid bath that dissolved the latched pin will be a little warmer, and a little more massive (in principle). The extra potential energy of the latched pin is transformed into a bit more mass. **41.** To make the electrons hit the screen with a certain speed, they have to be given more momentum and more energy than if they were nonrelativistic particles. The extra energy is supplied by the power utility. The electric bill is more! **43.** The correspondence principle just makes good sense. If a new idea is valid, then it ought to be in harmony with the areas it overlaps. If it doesn't, then either the areas themselves are suspect, or the new idea is suspect. If a new theory is valid, it must account for the verified results of the older theory, whether the theory is or isn't in the field of science. **45.** Both have both the same mass, and hence, the same energy. **47.** Just as time is required for knowledge of distant events to reach our eyes, a lesser yet finite time is required for information on nearby things to reach our eyes. So the answer is yes, there is always a finite interval between an event and our perception of that event. If the back of your hand is 30 cm from your eyes, you are seeing it as it was one-billionth of a second ago. **49.** Kierkegaard's statement, "Life can only be understood backwards; but it must be lived forwards," is consistent with special relativity. No matter how much time might be dilated as a result of high speeds, a space traveler can only effectively slow the passage of time relative to various frames of reference, but can never reverse it—the theory does not provide for traveling backward in time. Time, at whatever rate, flows only forward.

CHAPTER THIRTY-FIVE PROBLEMS

1. Frequency and period are reciprocals of one another (Chapter 19). If the frequency is doubled, the period is halved. For uniform motion, one senses only half as much time between flashes that are doubled in frequency. For accelerated motion, the situation is different. If the source gains speed in approaching, then each successive flash has even less distance to travel and the frequency increases more, and the period decreases more as well with time. **3.** $V = \dfrac{c+c}{1+\dfrac{c^2}{c^2}} = \dfrac{2c}{1+1} = c$ **5.** In the previous problem we see that for $v = 0.99c$, γ is 7.1. The momentum of the bus is more than seven times greater than would be calculated if classical mechanics were valid. The same is true of electrons, or anything traveling at this speed. **7.** Gamma at $v = 0.10c$ is $1/\sqrt{[1-(v^2/c^2)]} = 1/\sqrt{[1-(0.10)^2]} = 1/\sqrt{[1-0.01]} = 1/\sqrt{0.99} = 1.005$. You would measure the passenger's catnap to last 1.005(5 m) = **5.03 min.** **9.** Gamma at $v = 0.5c$ is $1/[\sqrt{1+(v^2/c^2)}] = 1/[\sqrt{1-0.5^2}] = 1/[\sqrt{1-0.25}] = 1/\sqrt{0.75} = 1.15$. Multiplying 1 h of taxi time by γ gives 1.15 h of Earth time. The drivers' new pay will be (10 hours)(1.15) = 11.5 stellars for this trip.

CHAPTER THIRTY-SIX EXERCISES

1. The reference frames of special relativity are of uniform motion—constant velocity. The reference frames of general relativity include accelerated frames. **3.** An astronaut, when in orbit, although in the grip of Earth gravity is weightless because of no support force (as explained back in Chapter 9). Both the astronaut and the space ship are in free fall together. **5.** You would feel as on Earth when the spaceship accelerates at Earth g, or you rotate with a centripetal acceleration of g. **7.** The separation distance of two people walking north from the Earth's equator decreases, and if they continue to the North Pole their separation distance will be zero. At the North Pole, a step in any direction is a step south! **9.** Bending is not taken into account only because it is negligible for short distances. **11.** Agree. The role of the eclipse is simply to better see the bending effect by comparing displacement of stars on the other side of the Sun. **13.** Distortion of the Sun at sunset is due to atmospheric refraction, which doesn't occur on the Moon due to its absence of an atmosphere. Gravitational deflection of light is too slight to be seen grazing the Moon or the Earth. **15.** The change in energy for light is evidenced by a change in frequency. If the energy of light is lowered, as in traveling against a strong gravitational field, its frequency is lowered, and the light is said to be gravitationally red-shifted. If the energy of the light is increased, as when falling in a gravitational field, for example, then the frequency is increased and the light is blue-shifted. **17.** Events on the Moon, as monitored from the Earth, run a bit faster and are slightly blue-shifted. Even though signals escaping the Moon are red-shifted in ascending the Moon's gravitational field, they are blue-shifted even more in descending through Earth's stronger g field, resulting in a net blue shift. **19.** The gravitational field intensity will increase on the surface of a shrinking star because the matter that produces the field is becoming more compact and more localized. This is easiest to see by considering the force on a body of mass m at the surface of the star of mass M via Newton's equation, $F = GmM/d^2$, where the only term that changes is d, which diminishes and therefore results in an increasing F. **21.** At the top of the mountain you age faster (see Figure 36.10). **23.** Time would run slower at the edge. **25.** The photons of light are climbing against the gravitational field and losing energy. Less energy means less frequency. Your friend sees the light red-shifted. The frequency she receives is less than the frequency you sent. **27.** We would need a telescope sensitive to very long wavelength radiation such as radio waves. The light from the astronauts would be red-shifted to very long wavelength, eventually infinitely long wavelength. **29.** There are various ways to "see" black holes. If it is the partner of a visible star, we can see its gravitational effect on the visible star's orbit. We could see its effect on light that passes close enough to be deflected but not close enough to be captured. We can see radiation emitted by matter as it is being sucked into a black hole (before it crosses the horizon to oblivion). In the future, perhaps, we will detect gravitational radiation emitted by black holes as they are being formed. **31.** Mercury follows an elliptical path in its orbit about the Sun, with its perihelion in a stronger part of the Sun's gravitational field than its aphelion. If Mercury followed a circular orbit, then there would be no variation of the Sun's gravitational field in its orbit. **33.** Yes. For example, place the Sun just outside one of the legs in Figure 36.14. **35.** Gravitational waves are extremely long waves. **37.** Einstein's theory of gravitation predicts the same results as Newton's theory of gravitation in weak gravitational fields such as those of the solar system. In weak fields, Einstein's theory *overlaps, corresponds*, and gives the same results as Newton's theory, and therefore obeys the correspondence principle. **39.** Open-ended.

APPENDIX E

1. A dollar loses half its value in one doubling time of the inflationary economy; this is 70/7% = 10 years. **3.** For a 5% growth rate, 42 years is three doubling times (70/5% = 14 years; 42/14 = 3). Three doubling times is an eightfold increase. So in 42 years the city would have to have 8 sewage treatment plants to remain as presently overloaded; more than 8 if overloading is to be reduced while serving 8 times as many people. **5.** Doubling one penny for 30 days yields a total of $10,737,418.23. **7.** It is generally acknowledged that if the human race is to survive, even from an overheating of the world standpoint, while alleviating even part of the misery that afflicts so much of humankind, the present rates of energy consumption and population growth must be reduced. The chances of achieving reduced growth rates are better in a climate of scarce energy than in a climate of abundant energy. We must hope that by the time we have fusion under control, we will have learned to optimize our numbers and to use energy more wisely.

Glossary

A (a) Abbreviation for *ampere.* (b) When a lowercase italic *a*, the symbol for *acceleration.*
aberration Distortion in an image produced by a lens or mirror, caused by limitations inherent to some degree in all optical systems. See *spherical aberration* and *chromatic aberration.*
absolute zero Lowest possible temperature that any substance can have; the temperature at which the atoms of a substance have their minimum kinetic energy. The temperature of absolute zero is -273.15°C, which is -459.7°F and 0 K.
absorption lines Dark lines that appear in an absorption spectrum. The pattern of lines is unique for each element.
absorption spectrum Continuous spectrum, like that generated by white light, interrupted by dark lines or bands that result from the absorption of light of certain frequencies by a substance through which the light passes.
ac Abbreviation for *alternating current.*
acceleration (*a*) Rate at which an object's velocity changes with time; the change in velocity may be in magnitude (speed), or direction, or both.

$$\text{Acceleration} = \frac{\text{change of velocity}}{\text{time interval}}$$

acceleration due to gravity (*g*) Acceleration of a freely falling object. Its value near Earth's surface is about 9.8 m/s each second.
achromatic lenses See *chromatic aberration.*
acoustics Study of the properties of sound, especially its transmission.
action force One of the pair of forces described in Newton's third law. See also *Newton's laws of motion, Law 3.*
additive primary colors Three colors of light—red, blue, and green—that when added in certain proportions will produce any color of the spectrum.
adhesion Molecular attraction between two surfaces making contact.
adiabatic Term applied to expansion or compression of a gas occurring without gain or loss of heat.
adiabatic process Process, often of fast expansion or compression, wherein no heat enters or leaves a system. As a result, a liquid or gas undergoing an expansion will cool, or undergoing a compression will warm.
air resistance Friction, or drag, that acts on something moving through air.
alchemist Practitioner of the early form of chemistry called alchemy, which was associated with magic. The goal of alchemy was to change base metals to gold and to discover a potion that could produce eternal youth.
alloy Solid mixture composed of two or more metals or of a metal and a nonmetal.
alpha particle Nucleus of a helium atom, which consists of two neutrons and two protons, ejected by certain radioactive nuclei.
alpha ray Stream of alpha particles (helium nuclei) ejected by certain radioactive nuclei.
alternating current (ac) Electric current that rapidly reverses in direction. The electric charges vibrate about relatively fixed positions, usually at the rate of 60 Hz.
AM Abbreviation for *amplitude modulation.*
ammeter A device that measures current. See *galvanometer.*
ampere (A) SI unit of electric current. One ampere is a flow of one coulomb of charge per second—6.25×10^{18} electrons (or protons) per second.
amplitude For a wave or vibration, the maximum displacement on either side of the equilibrium (midpoint) position.
amplitude modulation (AM) Type of modulation in which the amplitude of the carrier wave is varied above and below its normal value by an amount proportional to the amplitude of the impressed signal.
amu Abbreviation for *atomic mass unit.*
analog signal Signal based on a continuous variable, as opposed to a digital signal made up of discrete quantities.
aneroid barometer Instrument used to measure atmospheric pressure; based on the movement of the lid of a metal box, rather than on the movement of a liquid.
angle of incidence Angle between an incident ray and the normal to the surface it encounters.
angle of reflection Angle between a reflected ray and the normal to the surface of reflection.
angle of refraction Angle between a refracted ray and the normal to the surface at which it is refracted.
angular momentum Product of a body's rotational inertia and rotational velocity about a particular axis. For an object that is small compared with the radial distance, it is the product of mass, speed, and radial distance of rotation.

$$\text{Angular momentum} = mvr$$

antimatter Matter composed of atoms with negative nuclei and positive electrons.
antinode Any part of a standing wave with maximum displacement and maximum energy.

antiparticle Particle having the same mass as a normal particle, but a charge of the opposite sign. The antiparticle of an electron is a positron.
antiproton Antiparticle of a proton; a negatively charged proton.
apogee Point in an elliptical orbit farthest from the focus around which orbiting takes place. See also *perigee*.
Archimedes' principle Relationship between buoyancy and displaced fluid: An immersed object is buoyed up by a force equal to the weight of the fluid it displaces.
armature Part of an electric motor or generator where an electromotive force is produced. Usually the rotating part.
astigmatism Defect of the eye caused when the cornea is curved more in one direction than in another.
atmospheric pressure Pressure exerted against bodies immersed in the atmosphere resulting from the weight of air pressing down from above. At sea level, atmospheric pressure is about 101 kPa.
atom Smallest particle of an element that has all the element's chemical properties. Consists of protons and neutrons in a nucleus surrounded by electrons.
atomic bonding Linking together of atoms to form larger structures, such as molecules and solids.
atomic mass number Number associated with an atom, equal to the number of nucleons (protons plus neutrons) in the nucleus.
atomic mass unit (amu) Standard unit of atomic mass. It is based on the mass of the common carbon atom, which is arbitrarily given the value of exactly 12. An amu of 1 is one-twelfth the mass of this common carbon atom.
atomic number Number associated with an atom, equal to the number of protons in the nucleus, or, equivalently, to the number of electrons in the electron cloud of a neutral atom.
aurora borealis Glowing of the atmosphere caused by ions from above the atmosphere that dip into the atmosphere; also called northern lights. In the southern hemisphere, they are called aurora australis.
average speed Path distance divided by time interval.

$$\text{Average speed} = \frac{\text{total distance covered}}{\text{time interval}}$$

Avogadro's number 6.02×10^{23} molecules.
Avogadro's principle Equal volumes of all gases at the same temperature and pressure contain the same number of molecules, 6.02×10^{23} in 1 mole (a mass in grams equal to the molecular mass of the substance in atomic mass units).
axis (pl. axes) (a) Straight line about which rotation takes place. (b) Straight lines for reference in a graph, usually the x axis for measuring horizontal displacement and the y axis for measuring vertical displacement.
barometer Device used to measure the pressure of the atmosphere.
beats Sequence of alternating reinforcement and cancellation of two sets of superimposed waves differing in frequency, heard as a throbbing sound.
bel Unit of intensity of sound, named after Alexander Graham Bell. The threshold of hearing is 0 bel (10^{-12} W/m^2). Often measured in decibels (dB, one-tenth of a bel).
Bernoulli's principle Pressure in a fluid along a given streamline decreases as the speed of the fluid increases.
beta particle Electron (or positron) emitted during the radioactive decay of certain nuclei.
beta ray Stream of beta particles (electrons or positrons) emitted by certain radioactive nuclei.
Big Bang Primordial explosion that is thought to have resulted in the creation of our expanding universe.
bimetallic strip Two strips of different metals welded or riveted together. Because the two substances expand at different rates when heated or cooled, the strip bends; used in thermostats.
binary code Code based on the binary number system (which uses a base of 2). In binary code, any number can be expressed as a succession of 1s and 0s. For example, the number 1 is 1, 2 is 10, 3 is 11, 4 is 100, 5 is 101, 17 is 10001, etc. These 1s and 0s can then be interpreted and transmitted electronically as a series of "on" and "off" pulses, the basis for all computers and other digital equipment.
bioluminescence Light emitted from certain living things that have the ability to chemically excite molecules in their bodies; these excited molecules then give off visible light.
biomagnetism Magnetic material located in living organisms that may help them navigate, locate food, and affect other behaviors.
black hole Concentration of mass resulting from gravitational collapse, near which gravity is so intense that not even light can escape.
blind spot Area of the retina where all the nerves carrying visual information exit the eye and go to the brain; this is a region of no vision.
blue shift Increase in the measured frequency of light from an approaching source; called the blue shift because the apparent increase is toward the high-frequency, or blue, end of the color spectrum. Also occurs when an observer approaches a source. See also *Doppler effect*.
boiling Change from liquid to gas occurring beneath the surface of the liquid; rapid vaporization. The liquid loses energy, the gas gains it.
bow wave V-shaped wave produced by an object moving on a liquid surface faster than the wave speed.
Boyle's law The product of pressure and volume is a constant for a given mass of confined gas regardless of changes in either pressure or volume individually, as long as temperature remains unchanged.

$$P_1V_1 = P_2V_2$$

breeder reactor Nuclear fission reactor that not only produces power but produces more nuclear fuel than it consumes by converting a nonfissionable uranium isotope into a fissionable plutonium isotope. See also *nuclear reactor.*
British thermal unit (BTU) Amount of heat required to change the temperature of 1 pound of water by 1 Fahrenheit degree.
Brownian motion Haphazard movement of tiny particles suspended in a gas or liquid resulting from bombardment by the fast-moving molecules of the gas or liquid.
BTU Abbreviation for *British thermal unit.*
buoyancy Apparent loss of weight of an object immersed or submerged in a fluid.
buoyant force Net upward force exerted by a fluid on a submerged or immersed object.
butterfly effect Situation in which a very small change in one place can amplify into a large change somewhere else.
C Abbreviation for *coulomb.*
cal Abbreviation for *calorie.*
calorie (cal) Unit of heat. One calorie is the heat required to raise the temperature of 1 gram of water 1 Celsius degree. One Calorie (with a capital *C*) is equal to 1000 calories and is the unit used in describing the energy available from food; also called a kilocalorie (kcal).

$$1 \text{ cal} = 4.184 \text{ J or } 1 \text{ J} = 0.24 \text{ cal}$$

capacitor Device used to store charge in a circuit.
capillarity Rise of a liquid in a fine, hollow tube or in a narrow space.
carbon dating Process of determining the time that has elapsed since death by measuring the radioactivity of the remaining carbon-14 isotopes.
Carnot efficiency Ideal maximum percentage of input energy that can be converted to work in a heat engine.
carrier wave High-frequency radio wave modified by a lower-frequency wave.
Celsius scale Temperature scale that assigns 0 to the melt-freeze point for water and 100 to the boil-condense point of water at standard pressure (1 atmosphere at sea level).
center of gravity (CG) Point at the center of an object's weight distribution, where the force of gravity can be considered to act.
center of mass Point at the center of an object's mass distribution, where all its mass can be considered to be concentrated. For everyday conditions, it is the same as the center of gravity.
centrifugal force Apparent outward force on a rotating or revolving body.
centripetal force Center-directed force that causes an object to follow a curved or circular path.
CG Abbreviation for *center of gravity.*
chain reaction Self-sustaining reaction that, once started, steadily provides the energy and matter necessary to continue the reaction.
charge See *electric charge.*
charging by contact Transfer of electric charge between objects by rubbing or simple touching.
charging by induction Redistribution of electric charges in and on objects caused by the electrical influence of a charged object close by but not in contact.
chemical formula Description that uses numbers and symbols of elements to describe the proportions of elements in a compound or reaction.
chemical reaction Process of rearrangement of atoms that transforms one molecule into another.
chinook Warm, dry wind that blows down from the eastern side of the Rocky Mountains across the Great Plains.
chromatic aberration Distortion of an image caused when light of different colors (and thus different speeds and refractions) focuses at different points when passing through a lens. Achromatic lenses correct this defect by combining simple lenses made of different kinds of glass.
circuit Any complete path along which electric charge can flow. See also *series circuit* and *parallel circuit.*
circuit breaker Device in an electric circuit that breaks the circuit when the current gets high enough to risk causing a fire.
cloud chamber A device used to detect the paths of particles emitted by radioactive sources.
coherent light Light of a single frequency with all photons exactly in phase and moving in the same direction. Lasers produce coherent light. See also *incoherent light* and *laser.*
compact fluorescent lamp (CFL) A miniature version of a fluorescent lamp, commonly in a spiral shape.
complementarity Principle enunciated by Niels Bohr stating that the wave and particle aspects of both matter and radiation are necessary, complementary parts of the whole. Which part is emphasized depends on what experiment is conducted (i.e., on what questions one puts to nature).
complementary colors Any two colors of light that, when added, produce white light.
component Parts into which a vector can be separated and that act in different directions from the vector. See *resultant.*
compound Chemical substance made of atoms of two or more different elements combined in a fixed proportion.
compression (a) In mechanics, the act of squeezing material and reducing its volume. (b) In sound, the region of increased pressure in a longitudinal wave.
concave mirror Mirror that curves inward like a "cave."
condensation Change of phase of a gas into a liquid; the opposite of evaporation.
conduction (a) In heat, energy transfer from particle to particle within certain materials, or from one material to another when the two are in direct contact. (b) In electricity, the flow of electric charge through a conductor.

conduction electrons Electrons in a metal that move freely and carry electric charge.
conductor (a) Material through which heat can be transferred. (b) Material, usually a metal, through which electric charge can flow. Good conductors of heat are generally good electric charge conductors.
cones See *retina.*
conservation of angular momentum When no external torque acts on an object or a system of objects, no change of angular momentum takes place. Hence, the angular momentum before an event involving only internal torques is equal to the angular momentum after the event.
conservation of charge Principle that net electric charge is neither created nor destroyed but is transferable from one material to another.
conservation of energy Principle that energy cannot be created or destroyed. It may be transformed from one form into another, but the total amount of energy never changes.
conservation of energy for machines Work output of any machine at steady state cannot exceed the work input.
conservation of momentum In the absence of a net external force, the momentum of an object or system of objects is unchanged.

$$mv_{\text{(before event)}} = mv_{\text{(after event)}}$$

conserved Term applied to a physical quantity, such as momentum, energy, or electric charge, that remains unchanged during interactions.
constructive interference Combination of waves so that two or more waves overlap to produce a resulting wave of increased amplitude. See also *interference.*
convection Means of heat transfer by movement of the heated substance itself, such as by currents in a fluid.
converging lens Lens that is thicker in the middle than at the edges and refracts parallel rays of light passing through it to a focus. See also *diverging lens.*
convex mirror Mirror that curves outward. The virtual image formed is smaller and closer to the mirror than the object. See also *concave mirror.*
cornea Transparent covering over the eyeball, which helps focus the incoming light.
correspondence principle If a new theory is valid, it must account for the verified results of the old theory in the region where both theories apply.
cosmic ray One of various high-speed particles that travel throughout the universe and originate in violent events in stars.
cosmology Study of the origin and development of the entire universe.
coulomb (C) SI unit of electrical charge. One coulomb is equal to the total charge of 6.25×10^{18} electrons.
Coulomb's law Relationship among electrical force, charges, and distance: The electrical force between two charges varies directly as the product of the charges (q) and inversely as the square of the distance between them (k is the proportionality constant $9 \times 10^9\ \text{N·m}^2/\text{C}^2$). If the charges are alike in sign, the force is repulsive; if the charges are unlike, the force is attractive.

$$F = k\frac{q_1 q_2}{d^2}$$

crest One of the places in a wave where the wave is highest or the disturbance is greatest in the opposite direction from a trough. See also *trough.*
critical angle Minimum angle of incidence for which a light ray is totally reflected within a medium.
critical mass Minimum mass of fissionable material in a nuclear reactor or nuclear bomb that will sustain a chain reaction. A subcritical mass is one in which the chain reaction dies out. A supercritical mass is one in which the chain reaction builds up explosively.
crystal Regular geometric shape found in a solid in which the component particles are arranged in an orderly, three-dimensional, repeating pattern.
current See *electric current.*
cyclotron Particle accelerator that imparts high energy to charged particles such as protons, deuterons, and helium ions.
dark matter Unseen and unidentified matter that is evident by its gravitational pull on stars in the galaxies.
dB Abbreviation for decibel. See *bel.*
dc Abbreviation for *direct current.*
DDT Abbreviation for the chemical pesticide **d**ichloro **d**iphenyl **t**richloroethane.
de Broglie matter waves All particles have wave properties; in de Broglie's equation, the product of momentum and wavelength equals Planck's constant.
decibel (dB) One-tenth of a *bel.*
de-excitation See *excitation.*
density Mass of a substance per unit volume. Weight density is weight per unit volume. In general, any item per space element (e.g., number of dots per area).

$$\text{Density} = \frac{\text{mass}}{\text{volume}}$$
$$\text{Weight density} = \frac{\text{weight}}{\text{volume}}$$

destructive interference Combination of waves so that crest parts of one wave overlap trough parts of another, resulting in a wave of decreased amplitude. See also *interference.*
deuterium Isotope of hydrogen whose atom has a proton, a neutron, and an electron. The common isotope of hydrogen has only a proton and an electron; therefore, deuterium has more mass.
deuteron Nucleus of a deuterium atom; it has one proton and one neutron.

dichroic crystal Crystal that divides unpolarized light into two internal beams polarized at right angles and strongly absorbs one beam while transmitting the other.

diffraction Bending of light that passes around an obstacle or through a narrow slit, causing the light to spread and to produce light and dark fringes.

diffraction grating Series of closely spaced parallel slits or grooves that are used to separate colors of light by interference.

diffuse reflection Reflection of waves in many directions from a rough surface. See also *polished.*

digital audio Audio reproduction system that uses binary code to record and reproduce sound.

digital signal Signal made up of discrete quantities or signals, as opposed to an analog signal, which is based on a continuous signal.

digital versatile disc (DVD) Formerly called digital video disc, a compact disc that contains video material.

diode Electronic device that restricts current to a single direction in an electric circuit; a device that changes alternating current to direct current.

dipole See *electric dipole.*

direct current (dc) Electric current in which the flow of charge is always in one direction.

dispersion Separation of light into colors arranged according to their frequency—for example, by interaction with a prism or a diffraction grating.

displaced Term applied to the fluid that is moved out of the way when an object is placed in fluid. A submerged object always displaces a volume of fluid equal to its own volume.

diverging lens Lens that is thinner in the middle than at the edges, causing parallel rays of light passing through it to diverge as if from a point. See also *converging lens.*

Doppler effect Change in frequency of a wave of sound or light due to the motion of the source or the receiver. See also *red shift* and *blue shift.*

echo Reflection of sound.

eddy Changing, curling paths in turbulent flow of a fluid.

efficiency In a machine, the ratio of useful energy output to total energy input, or the percentage of the work input that is converted to work output.

$$\text{Efficiency} = \frac{\text{useful energy output}}{\text{total energy input}}$$

elastic collision Collision in which colliding objects rebound without lasting deformation or heat generation.

elastic limit Distance of stretching or compressing beyond which an elastic material will not return to its original state.

elasticity Property of a solid wherein a change in shape is experienced when a deforming force acts on it, with a return to its original shape when the deforming force is removed.

electric charge Fundamental electrical property to which the mutual attractions or repulsions between electrons or protons is attributed.

electric current Flow of electric charge that transports energy from one place to another. Measured in amperes, where 1 ampere is the flow of 6.25×10^{18} electrons (or protons) per second.

electric dipole Molecule in which the distribution of charge is uneven, resulting in slightly opposite charges on opposite sides of the molecule.

electric field Force field that fills the space around every electric charge or group of charges. Measured by force per charge (newtons/coulomb).

electric potential Electric potential energy (in joules) per unit of charge (in coulombs) at a location in an electric field; measured in volts and often called voltage.

$$\text{Voltage} = \frac{\text{electrical energy}}{\text{charge}} = \frac{\text{joules}}{\text{coulomb}}$$

electric potential energy Energy a charge has due to its location in an electric field.

electric power Rate of electrical energy transfer or the rate of doing work, which can be measured by the product of current and voltage.

$$\text{Power} = \text{current} \times \text{voltage}$$

electrical force Force that one charge exerts on another. When the charges are the same sign, they repel; when the charges are opposite, they attract.

electrical resistance Resistance of a material to the flow of electric charge through it; measured in ohms (Ω).

electrically polarized Term applied to an atom or molecule in which the charges are aligned so that one side is slightly more positive or negative than the opposite side.

electricity General term for electrical phenomena, much like gravity has to do with gravitational phenomena, or sociology with social phenomena.

electrode Terminal—for example, of a battery—through which electric current can pass.

electrodynamics Study of moving electric charge, as opposed to electrostatics.

electromagnet Magnet whose magnetic properties are produced by electric current.

electromagnetic induction Phenomenon of inducing a voltage in a conductor by changing the magnetic field near the conductor. If the magnetic field within a closed loop changes in any way, a voltage is induced in the loop. The induction of voltage is actually the result of a more fundamental phenomenon: the induction of an electric field. See also *Faraday's law.*

electromagnetic radiation Transfer of energy by the rapid oscillations of electromagnetic fields, which travel in the form of waves called electromagnetic waves.

electromagnetic spectrum Range of frequencies over which electromagnetic radiation can be propagated. The lowest frequencies are associated with radio waves; microwaves have a higher frequency, and then infrared waves, light, ultraviolet radiation, X-rays, and gamma rays in sequence.
electromagnetic wave Energy-carrying wave emitted by vibrating charges (often electrons) that is composed of oscillating electric and magnetic fields that regenerate one another. Radio waves, microwaves, infrared radiation, visible light, ultraviolet radiation, X-rays, and gamma rays are all composed of electromagnetic waves.
electromotive force (emf) Any voltage that gives rise to an electric current. A battery or a generator is a source of emf.
electron Negative particle in the shell of an atom.
electron volt (eV) Amount of energy equal to that an electron acquires in accelerating through a potential difference of 1 V.
electrostatics Study of electric charges at rest, as opposed to electrodynamics.
element Substance composed of atoms that all have the same atomic number and, therefore, the same chemical properties.
elementary particles Subatomic particles. The basic building blocks of all matter, consisting of two classes of particles, the quarks and the leptons.
ellipse Closed curve of oval shape wherein the sum of the distances from any point on the curve to two internal focal points is a constant.
emf Abbreviation for *electromotive force.*
emission spectrum Distribution of wavelengths in the light from a luminous source.
energy That which can change the condition of matter. Commonly defined as the ability to do work; actually only describable by examples.
engineering Technology directed to the design, construction, and maintenance of works, machinery, roads, railways, bridges, engines, all manner of vehicles from micro-carts to space stations, and to the generation, transmission, and use of electric power. Some main divisions are aerospace, chemical, civil, communication, electrical, electronic, materials, mechanical, mining, and structural.
entropy A measure of the disorder of a system. Whenever energy freely transforms from one form to another, the direction of transformation is toward a state of greater disorder and therefore toward one of greater entropy.
equilibrium In general, a state of balance. For mechanical equilibrium, the state in which no net forces and no net torques act. In liquids, the state in which evaporation equals condensation. More generally, the state in which no net change of energy occurs.
equilibrium rule $\Sigma F = 0$. On an object or system of objects in mechanical equilibrium, the sum of forces equals zero. Also, $\Sigma\tau = 0$; the sum of the torques equal zero.
escape velocity Velocity that a projectile, space probe, etc. must reach to escape the gravitational influence of Earth or the celestial body to which it is attracted.
ether Hypothetical invisible medium that was formerly thought to be required for the propagation of electromagnetic waves and thought to fill space throughout the universe.
eV Abbreviation for *electron volt.*
evaporation Change of phase from liquid to gas that takes place at the surface of a liquid; the opposite of condensation.
excitation Process of boosting one or more electrons in an atom or molecule from a lower to a higher energy level. An atom in an excited state will usually decay (de-excite) rapidly to a lower state by the emission of radiation. The frequency and energy of emitted radiation are related by

$$E = hf$$

excited See *excitation.*
eyepiece Lens of a telescope closest to the eye; which enlarges the real image formed by the first lens.
fact Close agreement by competent observers of a series of observations of the same phenomena.
Fahrenheit scale Temperature scale in common use in the United States. The number 32 is assigned to the melt-freeze point of water, and the number 212 to the boil-condense point of water at standard pressure (1 atmosphere, at sea level).
Faraday's law Induced voltage in a coil is proportional to the product of the number of loops and the rate at which the magnetic field changes within those loops. In general, an electric field is induced in any region of space in which a magnetic field is changing with time. The magnitude of the induced electric field is proportional to the rate at which the magnetic field changes. See also *Maxwell's counterpart to Faraday's law.*

$$\text{Voltage induced} \sim \text{number of loops} \times \frac{\text{magnetic field change}}{\text{change in time}}$$

Fermat's principle of least time Light takes the path that requires the least time when it goes from one place to another.
field See *force field.*
field lines See *magnetic field lines.*
flotation See *principle of flotation.*
fluid Anything that flows; in particular, any liquid or gas.
fluorescence Property of certain substances to absorb radiation of one frequency and to re-emit radiation of a lower frequency.
FM Abbreviation for *frequency modulation.*
focal length Distance between the center of a lens and either focal point; the distance from a mirror to its focal point.
focal plane Plane, perpendicular to the principal axis, that passes through a focal point of a lens or mirror. For a

converging lens or a concave mirror, any incident parallel rays of light converge to a point somewhere on a focal plane. For a diverging lens or a convex mirror, the rays appear to come from a point on a focal plane.

focal point For a converging lens or a concave mirror, the point at which rays of light parallel to the principal axis converge. For a diverging lens or a convex mirror, the point from which such rays appear to come.

focus (pl. foci) (a) For an ellipse, one of the two points for which the sum of the distances to any point on the ellipse is a constant. A satellite orbiting Earth moves in an ellipse that has Earth at one focus. (b) For optics, a focal point.

force Any influence that tends to accelerate an object; a push or pull; measured in newtons. Force is a vector quantity.

force field That which exists in the space surrounding a mass, electric charge, or magnet, so that another mass, electric charge, or magnet introduced into this region will experience a force. Examples of force fields are gravitational fields, electric fields, and magnetic fields.

forced vibration Vibration of an object caused by the vibrations of a nearby object. The sounding board in a musical instrument amplifies the sound through forced vibration.

Fourier analysis Mathematical method that disassembles any periodic waveform into a combination of simple sine waves.

fovea Area of the retina that is in the center of the field of view; region of most distinct vision.

frame of reference Vantage point (usually a set of coordinate axes) with respect to which position and motion may be described.

Fraunhofer lines Dark lines visible in the spectrum of the Sun or a star.

free fall Motion under the influence of gravity only.

free radical Unbonded, electrically neutral, very chemically active atom or molecular fragment.

freezing Change in phase from liquid to solid; the opposite of melting.

frequency For a vibrating body or medium, the number of vibrations per unit time. For a wave, the number of crests that pass a particular point per unit time. Frequency is measured in hertz.

frequency modulation (FM) Type of modulation in which the frequency of the carrier wave is varied above and below its normal frequency by an amount that is proportional to the amplitude of the impressed signal. In this case, the amplitude of the modulated carrier wave remains constant.

friction Force that acts to resist the relative motion (or attempted motion) of objects or materials that are in contact.

fuel cell A device that converts chemical energy to electrical energy, but unlike a battery is continually fed with fuel, usually hydrogen.

fulcrum Pivot point of a lever.

fundamental frequency See *partial tone.*

fuse Device in an electric circuit that breaks the circuit when the current gets high enough to risk causing a fire.

g (a) Abbreviation for *gram.* (b) When a lowercase italic *g*, the symbol for the acceleration due to gravity (at Earth's surface, 9.8 m/s^2). (c) When a lowercase bold **g**, the gravitational field vector (at Earth's surface, 9.8 N/kg). (d) When a uppercase italic *G*, the symbol for the *universal gravitation constant* (6.67×10^{-11} N·m^2/kg^2).

galvanometer Instrument used to detect electric current. With the proper combination of resistors, it can be converted to an ammeter or a voltmeter. An ammeter is calibrated to measure electric current. A voltmeter is calibrated to measure electric potential.

gamma ray High-frequency electromagnetic radiation emitted by atomic nuclei.

gas Phase of matter beyond the liquid phase, wherein molecules fill whatever space is available to them, taking no definite shape.

Geiger counter A device used to measure radioactive decay.

general theory of relativity Einstein's generalization of special relativity, which deals with accelerated motion and features a geometric theory of gravitation.

generator Machine that produces electric current, usually by rotating a coil within a stationary magnetic field.

geodesic Shortest path between points on any surface.

geosynchronous orbit A satellite orbit in which the satellite orbits Earth once each day. When moving westward, the satellite remains at a fixed point (about 36,000 km) above Earth's surface.

global warming See *greenhouse effect.*

gram (g) A metric unit of mass. It is one-thousandth of a kilogram.

gravitation Attraction between objects due to mass. See also *law of universal gravitation* and *universal gravitational constant.*

gravitational field Force field that exists in the space around every mass or group of masses; measured in newtons per kilogram.

gravitational potential energy Energy associated with a gravitational field, which on Earth results from the gravitational interaction of a body and Earth Potential energy (PE) then equals mass (m) times the acceleration due to gravity (g) times height (h) from a reference level such as Earth's surface.

$$PE = mgh$$

gravitational red shift Shift in wavelength toward the red end of the spectrum experienced by light leaving the surface of a massive object, as predicted by the general theory of relativity.

gravitational wave Gravitational disturbance that propagates through spacetime made by a moving mass (undetected at this writing).

graviton Quantum of gravity, similar in concept to the photon as a quantum of light (undetected at this writing).
greenhouse effect Warming effect caused by short-wavelength radiant energy from the Sun that easily enters the atmosphere and is absorbed by Earth, but when radiated at longer wavelengths cannot easily escape Earth's atmosphere.
grounding Allowing charges to move freely along a connection from a conductor to the ground.
group Elements in the same column of the periodic table.
h (a) Abbreviation for hour (though hr. is often used). (b) When an italic *h*, the symbol for *Planck's constant.*
hadron Elementary particle that can participate in strong nuclear force interactions.
half-life Time required for half the atoms of a radioactive isotope of an element to decay. This term is also used to describe decay processes in general.
harmonic See *partial tone.*
heat The energy that flows from one object to another by virtue of a difference in temperature; measured in *calories* or *joules.*
heat capacity See *specific heat capacity.*
heat engine A device that uses heat as input and supplies mechanical work as output, or that uses work as input and moves heat "uphill" from a cooler to a warmer place.
heat of fusion Amount of energy that must be added to a kilogram of a solid (already at its melting point) to melt it.
heat of vaporization Amount of energy that must be added to a kilogram of a liquid (already at its boiling point) to vaporize it.
heat pump A device that transfers heat out of a cool environment and into a warm environment.
heat waves See *infrared waves.*
heavy water Water (H_2O) that contains the heavy hydrogen isotope deuterium. (Can be written D_2O.)
hertz (Hz) SI unit of frequency. One hertz is one vibration per second.
hologram Two-dimensional microscopic interference pattern that shows three-dimensional optical images.
Hooke's law Distance of stretch or squeeze (extension or compression) of an elastic material is directly proportional to the applied force. Where Δx is the change in length and k is the spring constant.

$$F = k\Delta x$$

humidity Measure of the amount of water vapor in the air. Absolute humidity is the mass of water per volume of air. Relative humidity is absolute humidity at that temperature divided by the maximum possible, usually given as a percent.
Huygens' principle Light waves spreading out from a light source can be regarded as a superposition of tiny secondary wavelets.
hypothesis Educated guess; a reasonable explanation of an observation or experimental result that is not fully accepted as factual until tested over and over again by experiment.
Hz Abbreviation for *hertz.*
ideal efficiency Upper limit of efficiency for all heat engines; it depends on the temperature difference between input and exhaust.

$$\text{Ideal efficiency} = \frac{T_{\text{hot}} - T_{\text{cold}}}{T_{\text{hot}}}$$

impulse Product of force and the time interval during which the force acts. Impulse produces change in momentum.

$$\text{Impulse} = Ft = \Delta(mv)$$

incandescence State of glowing while at a high temperature, caused by electrons bouncing around over dimensions larger than the size of an atom, emitting radiant energy in the process. The peak frequency of radiant energy is proportional to the absolute temperature of the heated substance:

$$f \sim T$$

incoherent light Light containing waves with a jumble of frequencies, phases, and possibly directions. See also *coherent light* and *laser.*
index of refraction (n) Ratio of the speed of light in a vacuum to the speed of light in another material.

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

induced (a) Term applied to electric charge that has been redistributed on an object due to the presence of a charged object nearby. (b) Term applied to a voltage, electric field, or magnetic field that is created due to a change in or motion through a magnetic field or electric field.
induction Charging of an object without direct contact. See also *electromagnetic induction.*
inelastic Term applied to a material that does not return to its original shape after it has been stretched or compressed.
inelastic collision Collision in which the colliding objects become distorted and/or generate heat during the collision, and possibly stick together.
inertia Sluggishness or apparent resistance of an object to change its state of motion. Mass is the measure of inertia.
inertial frame of reference Unaccelerated vantage point in which Newton's laws hold exactly.
infrared Electromagnetic waves of frequencies lower than the red of visible light.
infrared waves Electromagnetic waves that have a lower frequency than visible red light.

infrasonic Term applied to sound frequencies below 20 Hz, the normal lower limit of human hearing.
in parallel Term applied to portions of an electric circuit that are connected at two points and provide alternative paths for the current between those two points.
in phase Term applied to two or more waves whose crests (and troughs) arrive at a place at the same time, so that their effects reinforce each other.
in series Term applied to portions of an electric circuit that are connected in a row, so that the current that goes through one must go through all of them.
instantaneous speed Speed at any instant.
insulator (a) Material that is a poor conductor of heat and that delays the transfer of heat. (b) Material that is a poor conductor of electricity.
intensity Power per square meter carried by a sound wave, often measured in decibels.
interaction Mutual action between objects where each object exerts an equal and opposite force on the other.
interference Result of superposing different waves, often of the same wavelength. Constructive interference results from crest-to-crest reinforcement; destructive interference results from crest-to-trough cancellation. The interference of selected wavelengths of light produces colors known as interference colors. See also *constructive interference, destructive interference, interference pattern,* and *standing wave.*
interference pattern Pattern formed by the overlapping of two or more waves that arrive in a region at the same time.
interferometer Device that uses the interference of light waves to measure very small distances with high accuracy. Michelson and Morley used an interferometer in their famous experiments with light.
internal energy The total energy stored in the atoms and molecules within a substance. Changes in internal energy are of principal concern in thermodynamics.
inverse-square law Law relating the intensity of an effect to the inverse square of the distance from the cause. Gravity, electric, magnetic, light, sound, and radiation phenomena follow the inverse-square law.

$$\text{Intensity} \sim \frac{1}{\text{distance}^2}$$

inversely When two values change in opposite directions, so that if one increases and the other decreases by the same factor, they are said to be inversely proportional to each other.
ion Atom (or group of atoms bound together) with a net electric charge, which is due to the loss or gain of electrons. A positive ion has a net positive charge. A negative ion has a net negative charge.
ionization Process of adding or removing electrons to or from the atomic nucleus.
iridescence Phenomenon whereby interference of light waves of mixed frequencies reflected from the top and bottom of thin films produces an assortment of colors.
iris Colored part of the eye that surrounds the black opening through which light passes. The iris regulates the amount of light entering the eye.
isotopes Atoms whose nuclei have the same number of protons but different numbers of neutrons.
J Abbreviation for *joule.*
joule (J) SI unit of work and of all other forms of energy. One joule of work is done when a force of 1 newton is exerted on an object moved 1 meter in the direction of the force.
K (a) Abbreviation for *kelvin.* (b) When a lowercase k, the abbreviation for the prefix *kilo-*. (c) When a lowercase italics *k*, the symbol for the electrical proportionality constant in *Coulomb's law.* It is approximately $9 \times 10^9\ \text{N}\cdot\text{m}^2/\text{C}^2$. (d) When a lowercase italics *k*, the symbol for the spring constant in *Hooke's law.*
kcal Abbreviation for *kilocalorie.*
KE Abbreviation for *kinetic energy.*
kelvin SI unit of temperature. A temperature measured in kelvins (symbol K) indicates the number of units above absolute zero. Divisions on the Kelvin scale and Celsius scale are the same size, so a change in temperature of 1 kelvin equals a change in temperature of 1 Celsius degree.
Kelvin scale Temperature scale, measured in kelvins, K, whose zero (called absolute zero) is the temperature at which it is impossible to extract any more internal energy from a material. 0 K = −273.15°C. There are no negative temperatures on the Kelvin scale.
Kepler's laws *Law 1:* The path of each planet around the Sun is an ellipse with the Sun at one focus.
Law 2: The line from the Sun to any planet sweeps out equal areas of space in equal time intervals.
Law 3: The square of the orbital period of a planet is directly proportional to the cube of the average distance of the planet from the Sun ($T^2 \sim r^3$ for all planets).
kg Abbreviation for *kilogram.*
kilo- Prefix that means thousand, as in kilowatt or kilogram.
kilocalorie (kcal) Unit of heat. One kilocalorie equals 1000 calories, or the amount of heat required to raise the temperature of 1 kilogram of water by 1°C. Equal to one food Calorie.
kilogram (kg) Fundamental SI unit of mass. It is equal to 1000 grams. One kilogram is very nearly the amount of mass in 1 liter of water at 4°C.
kilometer (km) 1000 *meters.*
kilowatt (kW) 1000 *watts.*
kilowatt-hour (kWh) Amount of energy consumed in 1 hour at the rate of 1 kilowatt.
kinetic energy (KE) Energy of motion, equal (nonrelativistically) to mass multiplied by the square of the speed, multiplied by the constant 1/2.

$$\text{KE} = \tfrac{1}{2}mv^2$$

km Abbreviation for *kilometer.*

kPa Abbreviation for *kilopascal.* See *pascal.*
kWh Abbreviation for *kilowatt-hour.*
L Abbreviation for *liter.* (In some textbooks, lowercase l is used.)
laser Optical instrument that produces a beam of coherent light—that is, light with all waves of the same frequency, phase, and direction. The word is an acronym for **l**ight **a**mplification by **s**timulated **e**mission of **r**adiation.
latent heat of fusion The amount of energy required to change a unit mass of a substance from solid to liquid (and vice versa).
latent heat of vaporization The amount of energy required to change a unit mass of a substance from liquid to gas (and vice versa).
law General hypothesis or statement about the relationship of natural quantities that has been tested over and over again and has not been contradicted. Also known as a *principle.*
law of conservation of momentum In the absence of an external force, the momentum of a system remains unchanged. Hence, the momentum before an event involving only internal forces is equal to the momentum after the event:

$$mv_{\text{(before event)}} = mv_{\text{(after event)}}$$

law of inertia See *Newton's laws of motion, Law 1.*
law of reflection The angle of incidence for a wave that strikes a surface is equal to the angle of reflection. This is true for both partially and totally reflected waves. See also *angle of incidence* and *angle of reflection.*
law of universal gravitation For any pair of objects, each particle attracts the other object with a force that is directly proportional to the product of the masses of the objects, and inversely proportional to the square of the distance between them (or their centers of mass if spherical objects), where F is the force, m is the mass, d is distance, and G is the gravitation constant:

$$F \sim \frac{m_1 m_2}{d^2} \text{ or } F = G\frac{m_1 m_2}{d^2}$$

least time See *Fermat's principle of least time.*
length contraction Shrinkage of space, and therefore of matter, in a frame of reference moving at relativistic speeds.
lens Piece of glass or other transparent material that can bring light to a focus.
lepton Class of elementary particles that are not involved with the nuclear force. It includes the electron and its neutrino, the muon and its neutrino, and the tau and its neutrino.
lever Simple machine made of a bar that turns about a fixed point called the fulcrum.
lever arm Perpendicular distance between an axis and the line of action of a force that tends to produce rotation about that axis.
lift In application of Bernoulli's principle, the net upward force produced by the difference between upward and downward pressures. When lift equals weight, horizontal flight is possible.
light Visible part of the electromagnetic spectrum.
light-emitting diode (LED) A diode that emits light.
light-year The distance light travels in a vacuum in one year: 9.46×10^{12} km.
line spectrum Pattern of distinct lines of color, corresponding to particular frequencies of light, that are seen in a spectroscope when a hot gas is viewed. Each element has a unique pattern of lines.
linear momentum Product of the mass and the velocity of an object. Also called momentum. (This definition applies at speeds much less than the speed of light.)
linear motion Straight-line motion, as opposed to circular, angular, or rotational motion.
linear speed Path distance moved per unit of time. Also simply called speed.
liquid Phase of matter between the solid and gaseous phases in which the matter possesses a definite volume but no definite shape: It takes on the shape of its container.
liter (L) Metric unit of volume. A liter is equal to 1000 cm^3.
logarithmic Exponential.
longitudinal wave Wave in which the individual particles of a medium vibrate back and forth in the direction in which the wave travels—for example, sound.
Lorentz contraction See *length contraction.*
loudness Physiological sensation directly related to sound intensity or volume. Relative loudness, or sound level, is measured in decibels.
lunar eclipse Event wherein the full Moon passes into the shadow of Earth.
m Abbreviation for *meter.*
Mach number Ratio of the speed of an object to the speed of sound. For example, an aircraft traveling *at* the speed of sound is rated Mach 1.0; traveling at *twice* the speed of sound, Mach 2.0.
machine Device for increasing (or decreasing) a force or simply changing the direction of a force.
magnet Any object that has magnetic properties, that is, the ability to attract objects made of iron or other magnetic substances. See also *electromagnetism* and *magnetic force.*
magnetic declination Discrepancy between the orientation of a compass pointing toward magnetic north and the true geographic north.
magnetic domain Microscopic cluster of atoms with their magnetic fields aligned.
magnetic field Region of magnetic influence around a magnetic pole or a moving charged particle.
magnetic field lines Lines showing the shape of a magnetic field. A compass placed on such a line will turn so that the needle is aligned with it.

magnetic force (a) Between magnets, it is the attraction of unlike magnetic poles for each other and the repulsion between like magnetic poles. (b) Between a magnetic field and a moving charged particle, it is a deflecting force due to the motion of the particle: The deflecting force is perpendicular to the magnetic field lines and the direction of motion. This force is greatest when the charged particle moves perpendicular to the field lines and is smallest (zero) when it moves parallel to the field lines.
magnetic monopole Hypothetical particle having a single north or a single south magnetic pole, analogous to a positive or negative electric charge.
magnetic pole One of the regions on a magnet that produces magnetic forces.
magnetic pole reversal When the magnetic field of an astronomical body reverses its poles, that is, the location where the north magnetic pole existed becomes the south magnetic pole, and the south magnetic pole becomes the north magnetic pole.
magnetism Phenomena associated with magnetic fields. See also *electromagnetism* and *magnetic force*.
magnetohydrodynamic (MDH) generator Device generating electric power by interaction of a plasma and a magnetic field.
maser Instrument that produces a beam of microwaves. The word is an acronym for **m**icrowave **a**mplification by **s**timulated **e**mission of **r**adiation.
mass Quantity of matter in an object; the measurement of the inertia or sluggishness that an object exhibits in response to any effort made to start it, stop it, or change in any way its state of motion; a form of energy.
mass spectrometer Device that magnetically separates charged ions according to their mass.
mass–energy equivalence Relationship between mass and energy as given by the equation

$$E = mc^2$$

where c is the speed of light.
matter waves See *de Broglie matter waves*.
Maxwell's counterpart to Faraday's law A magnetic field is created in any region of space in which an electric field is changing with time. The magnitude of the induced magnetic field is proportional to the rate at which the electric field changes. The direction of the induced magnetic field is at right angles to the changing electric field.
mechanical advantage Ratio of output force to input force for a machine.
mechanical energy Energy due to the position or the movement of something; potential or kinetic energy (or a combination of both).
mechanical equilibrium State of an object or system of objects for which any impressed forces cancel to zero and no acceleration occurs and when no net torque exists. That is, $\Sigma F = 0$, and $\Sigma\tau = 0$.
mega- Prefix that means million, as in megahertz or megajoule.
melting Change in phase from solid to liquid; the opposite of freezing. Melting is a different process from dissolving, in which an added solid mixes with a liquid and the solid dissociates.
meson Elementary particle with an atomic weight of zero; can participate in the strong interaction.
metastable state State of excitation of an atom that is characterized by a prolonged delay before de-excitation.
meter (m) Standard SI unit of length (3.28 feet).
MeV Abbreviation for million *electron volts*, a unit of energy, or equivalently, a unit of mass.
MHD Abbreviation for *magnetohydrodynamic*.
mi Abbreviation for mile.
microscope Optical instrument that forms enlarged images of very small objects.
microwaves Electromagnetic waves with frequencies greater than radio waves but less than infrared waves.
min Abbreviation for minute.
mirage False image that appears in the distance and is due to the refraction of light in Earth's atmosphere.
mixture Substances mixed together without combining chemically.
MJ Abbreviation for megajoules, million *joules*.
model Representation of an idea created to make the idea more understandable.
modulation Impressing a signal wave system on a higher-frequency carrier wave; amplitude modulation (AM) for amplitude signals and frequency modulation (FM) for frequency signals.
molecule Two or more atoms of the same or different elements bonded to form a larger particle.
momentum Inertia in motion. The product of the mass and the velocity of an object (provided the speed is much less than the speed of light). Has magnitude and direction and therefore is a vector quantity. Also called linear momentum, and abbreviated p.

$$p = mv$$

monochromatic light Light made of only one color and therefore waves of only one wavelength and frequency.
muon Elementary particle in the lepton family.
music Scientifically speaking, sound associated with periodic tones and regularity.
N Abbreviation for *newton*.
nanometer Metric unit of length that is 10^{-9} meter (one-billionth of a meter).
natural frequency Frequency at which an elastic object naturally tends to vibrate if it is disturbed and the disturbing force is removed.
neap tide Tide that occurs when the Moon is halfway between a new Moon and a full Moon, in either direction. The tides due to the Sun and the Moon partly cancel, so that the high tides are lower than average and

the low tides are not as low as average. See also *spring tide.*

net force Combination of all the forces that act on an object.

neutrino Elementary particle in the class of elementary particles called leptons. It is uncharged and almost massless; three kinds—electron, muon, and tau neutrinos, are the most common high-speed particles in the universe; more than a billion pass unhindered through each person every second.

neutron Electrically neutral particle that is one of the two kinds of nucleons that compose an atomic nucleus.

neutron star Star that has undergone a gravitational collapse in which electrons are compressed into protons to form neutrons.

newton (N) SI unit of force. One newton is the force applied to a 1-kilogram mass that will produce an acceleration of 1 meter per second per second.

Newton's law of cooling The rate of cooling of an object—whether by conduction, convection, or radiation—is approximately proportional to the temperature difference between the object and its surroundings.

Newton's laws of motion *Law 1:* Every object continues in a state of rest, or of uniform speed in a straight line, unless acted on by a nonzero net force. Also known as the law of inertia.

Law 2: The acceleration produced by a net force on an object is directly proportional to the magnitude of the net force, is in the same direction as the net force, and is inversely proportional to the mass of the object.

Law 3: Whenever one object exerts a force on a second object, the second object exerts an equal and opposite force on the first.

node Any part of a standing wave that remains stationary; a region of minimal or zero energy.

noise Scientifically speaking, sound associated with irregular vibrations.

normal At right angles to, or perpendicular to. A normal force acts at right angles to the surface on which it acts. In optics, a normal defines the line perpendicular to a surface about which angles of light rays are measured.

normal force Component of support force perpendicular to a supporting surface. For an object resting on a horizontal surface, it is the upward force that balances the weight of the object.

northern lights See *aurora borealis.*

nuclear fission Splitting of an atomic nucleus, particularly that of a heavy element such as uranium-235, into two lighter elements, accompanied by the release of much energy.

nuclear fusion Combining of nuclei of light atoms, such as hydrogen, into heavier nuclei, accompanied by the release of much energy. See also *thermonuclear fusion.*

nuclear reactor Apparatus in which controlled nuclear fission or nuclear fusion reactions take place.

nucleon Principal building block of the nucleus; a neutron or a proton; the collective name for either or both.

nucleus (pl. nuclei) Positively charged center of an atom, which contains protons and neutrons and has almost all the mass of the entire atom but only a tiny fraction of the volume.

objective lens In an optical device using compound lenses, the lens closest to the object observed.

octave In music, the eighth full tone above or below a given tone. The tone an octave above has twice as many vibrations per second as the original tone; the tone an octave below has half as many vibrations per second.

ohm (Ω) SI unit of electrical resistance. One ohm is the resistance of a device that draws a current of 1 ampere when a voltage of 1 volt is impressed across it.

Ohm's law Current in a circuit is directly proportional to the voltage impressed across the circuit and is inversely proportional to the resistance of the circuit.

$$\text{Current} = \frac{\text{voltage}}{\text{resistance}}$$

opaque Term applied to materials that absorb light without re-emission and consequently do not allow light through them.

optical fiber Transparent fiber, usually of glass or plastic, that can transmit light down its length by means of total internal reflection.

oscillation Same as vibration: a repeating to-and-fro motion about an equilibrium position. Both oscillation and vibration refer to periodic motion, that is, motion that repeats.

oscillatory motion To-and-fro vibratory motion, such as that of a pendulum.

out of phase Term applied to two waves for which the crest of one wave arrives coincident with a trough of the second wave. Their effects tend to cancel each other.

overtone Musical term where the first overtone is the second harmonic. See also *partial tone.*

oxidize Chemical process in which an element or molecule loses one or more electrons.

ozone A gas of oxygen molecules composed of three, rather than the usual two, oxygen atoms. O_3 is formed when the molecule of stable oxygen (O_2) is split by UV radiation or electrical discharge. Found naturally in a thin layer in the upper atmosphere.

Pa Abbreviation for the SI unit *pascal.*

parabola Curved path followed by a projectile acting under the influence of gravity only.

parallax Apparent displacement of an object when viewed by an observer from two different positions; often used to calculate the distance of stars.

parallel circuit Electric circuit with two or more devices connected in such a way that the same voltage acts across each one and any single one completes the circuit independently of the others. See also *in parallel.*

partial tone One of the many tones that make up one musical sound. Each partial tone (or partial) has only one frequency. The lowest partial of a musical sound is called the fundamental frequency. Any partial whose frequency is a multiple of the fundamental frequency is called a harmonic. The fundamental frequency is also called the first harmonic. The second harmonic has twice the frequency of the fundamental; the third harmonic, three times the frequency, and so on.
pascal (Pa) SI unit of pressure. One pascal of pressure exerts a normal force of 1 newton per square meter. A kilopascal (kPa) is 1000 pascals.
Pascal's principle Changes in pressure at any point in an enclosed fluid at rest are transmitted undiminished to all points in the fluid and act in all directions.
PE Abbreviation for *potential energy.*
penumbra Partial shadow that appears where some of the light is blocked and other light can fall. See also *umbra.*
percussion In musical instruments, the striking of one object against another.
perigee Point in an elliptical orbit closest to the focus about which orbiting takes place. See also *apogee.*
period In general, the time required to complete a single cycle. (a) For orbital motion, the time required for a complete orbit. (b) For vibrations or waves, the time required for one complete cycle, equal to 1/frequency.
periodic table Chart that lists elements by atomic number and by electron arrangements, so that elements with similar chemical properties are in the same column (group). See Figure 11.9, page 203.
perturbation Deviation of an orbiting object (e.g., a planet) from its path around a center of force (e.g., the Sun) caused by the action of an additional center of force (e.g., another planet).
phase (a) One of the four main forms of matter: solid, liquid, gas, and plasma; often called *state.* (b) The part of a cycle that a wave has advanced at any moment. See also *in phase* and *out of phase.*
phosphor Powdery material, such as that used on the inner surface of a fluorescent light tube, that absorbs ultraviolet photons, then gives off visible light.
phosphorescence Type of light emission that is the same as fluorescence except for a delay between excitation and de-excitation, which provides an afterglow that may last from fractions of a second to hours, or even days, depending on such factors as the type of material and temperature.
photoelectric effect Ejection of electrons from certain metals when exposed to certain frequencies of light.
photon Light manifesting as a particle; as a corpuscle of light.
pigment Fine particles that selectively absorb light of certain frequencies and selectively transmit others.
pitch Term that refers to our subjective impression about the "highness" or "lowness" of a tone, which is related to the frequency of the tone. A high-frequency vibrating source produces a sound of high pitch; a low-frequency vibrating source produces a sound of low pitch.
Planck's constant (*h*) Fundamental constant of quantum theory that determines the scale of the small-scale world.

$$h = 6.6 \times 10^{-34}\ \mathrm{J \cdot s}$$

When multiplied by the frequency of light it equals its energy.

$$E = hf$$

plane mirror Flat-surfaced mirror.
plane-polarized wave A wave confined to a single plane.
plasma Fourth phase of matter, in addition to solid, liquid, and gas. In the plasma phase, existing mainly at high temperatures, matter consists of positively charged ions and free electrons.
polarization Aligning of vibrations in a transverse wave, usually by filtering out waves of other directions. See also *plane-polarized wave* and *dichroic crystal.*
polished Describes a surface that is so smooth that the distances between successive elevations of the surface are less than about one-eighth the wavelength of the light or other incident wave of interest. The result is very little diffuse reflection.
positron Antiparticle of an electron; a positively charged electron.
postulates of special relativity *First:* All laws of nature are the same in all uniformly moving frames of reference. *Second:* The speed of light in free space has the same measured value regardless of the motion of the source or the motion of the observer; that is, the speed of light is invariant.
potential difference Difference in electric potential (voltage) between two points. Free charge flows when there is a difference and will continue until both points reach a common potential.
potential energy (PE) Energy of position, usually related to the relative position of two things, such as a stone and Earth (gravitational PE), or an electron and a nucleus (electric PE).
power Rate at which work is done or energy is transformed, equal to the work done or energy transformed divided by time; measured in watts.

$$\text{Power} = \frac{\text{work}}{\text{time}}$$

precession Wavering of a spinning object, such that its axis of rotation traces out a cone.
pressure Force per surface area where the force is normal (perpendicular) to the surface; measured in pascals. See also *atmospheric pressure.*

$$\text{Pressure} = \frac{\text{force}}{\text{area}}$$

primary colors See *additive primary colors* and *subtractive primary colors.*

principal axis Line joining the centers of curvature of the surfaces of a lens. Line joining the center of curvature and the focus of a mirror.

principle General hypothesis or statement about the relationship of natural quantities that has been tested over and over again and has not been contradicted; also known as a law.

principle of equivalence Observations made in an accelerating frame of reference are indistinguishable from observations made in a gravitational field.

principle of flotation A floating object displaces a weight of fluid equal to its own weight.

prism Triangular solid of a transparent material such as glass that separates incident light by refraction into its component colors. These component colors are often called the spectrum.

projectile Any object that moves through the air or through space, acted on only by gravity (and air resistance, if any).

proton Positively charged particle that is one of the two kinds of nucleons in the nucleus of an atom.

pseudoscience Fake science that pretends to be real science.

pulley Wheel that acts as a lever used to change the direction of a force. A pulley or system of pulleys can also multiply forces.

pupil Opening in the eyeball through which light passes.

quality Characteristic timbre of a musical sound, governed by the number and relative intensities of partial tones.

quantum (pl. quanta) From the Latin word *quantus*, meaning "how much," a quantum is the smallest elemental unit of a quantity, the smallest discrete amount of something. One quantum of electromagnetic energy is called a photon. See also *quantum mechanics* and *quantum theory*.

quantum mechanics Branch of physics concerned with the atomic microworld based on wave functions and probabilities, introduced by Max Planck (1900) and developed by Werner Heisenberg (1925), Erwin Schrödinger (1926), and others.

quantum physics Branch of physics that is the general study of the microworld of photons, atoms, and nuclei.

quantum theory Theory that describes the microworld, where many quantities are granular (in units called quanta), rather than continuous, and where particles of light (photons) and particles of matter (such as electrons) exhibit wave as well as particle properties.

quark One of the two classes of elementary particles (the other is the lepton). Two of the six quarks (up and down) are the fundamental building blocks of nucleons (protons and neutrons).

rad Unit used to measure a dose of radiation; the amount of energy (in centijoules) absorbed from ionizing radiation per kilogram of exposed material.

radiant energy Any energy, including heat, light, and X-rays, that is transmitted by radiation. It occurs in the form of electromagnetic waves.

radiation (a) Energy transmitted by electromagnetic waves. (b) The particles given off by radioactive atoms such as uranium. Do not confuse radiation with radioactivity.

radiation curve of sunlight See *solar radiation curve*.

radio waves Electromagnetic waves of the longest frequency.

radioactive Term applied to an atom having an unstable nucleus that can spontaneously emit a particle and become the nucleus of another element.

radioactivity Process of the atomic nucleus that results in the emission of energetic particles. See *radiation*.

radiotherapy Use of radiation as a treatment to kill cancer cells.

rarefaction Region of reduced pressure in a longitudinal wave.

rate How fast something happens or how much something changes per unit of time; a change in a quantity divided by the time it takes for the change to occur.

ray Thin beam of light. Also, lines drawn to show light paths in optical ray diagrams.

reaction force Force that is equal in strength and opposite in direction to the action force, and one that acts simultaneously on whatever is exerting the action force. See also *Newton's third law*.

real image 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.

red shift Decrease in the measured frequency of light (or other radiation) from a receding source; called the *red shift* because the decrease is toward the low-frequency, or red, end of the color spectrum. See also *Doppler effect*.

reflection Return of light rays from a surface in such a way that the angle at which a given ray is returned is equal to the angle at which it strikes the surface. When the reflecting surface is irregular, the light is returned in irregular directions; this is *diffuse reflection*. In general, the bouncing back of a particle or wave that strikes the boundary between two media.

refraction Bending of an oblique ray of light when it passes from one transparent medium to another. This is caused by a difference in the speed of light in the transparent media. In general, the change in direction of a wave as it crosses the boundary between two media in which the wave travels at different speeds.

regelation Process of melting under pressure and the subsequent refreezing when the pressure is removed.

relationship of impulse and momentum Impulse is equal to the change in the momentum of the object that the impulse acts upon. In symbol notation,

$$Ft = \Delta mv$$

relative Regarded in relation to something else, depending on point of view or frame of reference. Sometimes referred to as "with respect to."

relative humidity Ratio between how much water vapor is in the air and the maximum amount of water vapor that could be in the air at the same temperature.
relativistic Pertaining to the theory of relativity; or approaching the speed of light.
relativity See *special theory of relativity, postulates of the special theory of relativity,* and *general theory of relativity.*
rem Acronym of **r**oentgen **e**quivalent **m**an; it is a unit used to measure the effect of ionizing radiation on human beings.
resistance See *electrical resistance.*
resistor Device in an electric circuit designed to resist the flow of charge.
resolution (a) Method of separating a vector into its component parts. (b) Ability of an optical system to make clear or to separate the components of an object viewed.
resonance Phenomenon that occurs when the frequency of forced vibrations on an object matches the object's natural frequency, producing a dramatic increase in amplitude.
rest energy The "energy of being," given by the equation $E = mc^2$.
resultant Net result of a combination of two or more vectors.
retina Layer of light-sensitive tissue at the back of the eye, composed of tiny light-sensitive antennae called rods and cones. Rods sense light and darkness; cones sense color.
reverberation Persistence of a sound, as in an echo, due to multiple reflections.
revolution Motion of an object turning around an axis that lies outside the object.
Ritz combination principle For an element, the frequencies of some spectral lines are either the sum or the difference of the frequencies of two other lines in that element's spectrum.
rods See *retina.*
rotation Spinning motion that occurs when an object rotates about an axis located within the object (usually an axis through its center of mass).
rotational inertia Reluctance or apparent resistance of an object to change its state of rotation, determined by the distribution of the mass of the object and the location of the axis of rotation or revolution.
rotational speed Number of rotations or revolutions per unit of time; often measured in rotations or revolutions per second or minute.
rotational velocity Rotational speed together with a direction for the axis of rotation or revolution.
RPM Abbreviation for rotations or revolutions per minute.
s Abbreviation for second.
satellite Projectile or smaller celestial body that orbits a larger celestial body.
saturated Term applied to a substance, such as air, that contains the maximum amount of another substance, such as water vapor, at a given temperature and pressure.
scalar quantity Quantity in physics, such as mass, volume, and time, that can be completely specified by its magnitude and has no direction.
scale In music, a succession of notes of frequencies that are in simple ratios to one another.
scaling Study of how size affects the relationship among weight, strength, and surface area.
scatter To absorb sound or light and re-emit it in all directions.
scattering Emission in random directions of light that encounters particles that are small compared to the wavelength of light; more often at short wavelengths (blue) than at long wavelengths (red).
Schrödinger's wave equation Fundamental equation of quantum mechanics, which interprets the wave nature of material particles in terms of probability wave amplitudes. It is as basic to quantum mechanics as Newton's laws of motion are to classical mechanics.
scientific method Orderly method for gaining, organizing, and applying new knowledge.
scintillation counter A device used to measure radiation from radioactive sources.
self-induction Induction of an electric field within a single coil, caused by the interaction of the loops within the same coil. This self-induced voltage is always in a direction opposing the changing voltage that produces it and is commonly called back electromotive force or back emf.
semiconductor Device made of material not only with properties that fall between a conductor and an insulator but with resistance that changes abruptly when other conditions change, such as temperature, voltage, and electric or magnetic field.
series circuit Electric circuit with devices connected in such a way that the electric current through each of them is the same. See also *in series.*
shadow Shaded region that appears where light rays are blocked by an object.
shell model of the atom Model in which the electrons of an atom are pictured as grouped in concentric shells around the nucleus.
shock wave Cone-shaped wave produced by an object moving at supersonic speed through a fluid.
short circuit Disruption in an electric circuit, caused by the flow of charge along a low-resistance path between two points that should not be directly connected, thus deflecting the current from its proper path; an effective "shortening of the circuit."
SI Abbreviation for Système International, an international system of units of metric measure accepted and used by scientists throughout the world. See Appendix A for more details.
simple harmonic motion Vibratory or periodic motion, like that of a pendulum, in which the force acting on the vibrating body is proportional to its displacement from its central equilibrium position and acts toward that position.

simultaneity Occurring at the same time. In special relativity, two events that are simultaneous in one frame of reference need not be simultaneous in a frame moving relative to the first frame.

sine curve Curve whose shape represents the crests and troughs of a wave, as traced out by a pendulum that drops a trail of sand while swinging at right angles to and over a moving conveyor belt.

sine wave The simplest of waves with only one frequency and the shape of a sine curve.

sliding friction Contact force produced by the rubbing together of the surface of a moving object with the material over which it slides.

solar constant 1400 J/m^2 received from the Sun each second at the top of Earth's atmosphere, expressed in terms of power, 1.4 kW/m^2.

solar eclipse Event wherein the Moon blocks light from the Sun and the Moon's shadow falls on part of Earth.

solar power Energy per unit time derived from the Sun. See also *solar constant*.

solar radiation curve Graph of brightness versus frequency (or wavelength) of sunlight.

solid Phase of matter characterized by definite volume and shape.

solidify To become solid, as in freezing or the setting of concrete.

sonic boom Loud sound resulting from the incidence of a shock wave.

sound Longitudinal wave phenomenon that consists of successive compressions and rarefactions of the medium through which the wave travels.

sound barrier The pileup of sound waves in front of an aircraft approaching or reaching the speed of sound, believed in the early days of jet aircraft to create a barrier of sound that a plane would have to break through in order to go faster than the speed of sound. The sound barrier does not exist.

spacetime Four-dimensional continuum in which all events take place and all things exist: Three dimensions are the coordinates of space and the fourth is of time.

special theory of relativity Comprehensive theory of space and time that replaces Newtonian mechanics when velocities are very large; introduced in 1905 by Albert Einstein. See also *postulates of the special theory of relativity*.

specific heat capacity Quantity of heat required to raise the temperature of a unit mass of a substance by 1 degree Celsius (or equivalently, by 1 kelvin); often simply called specific heat.

spectral lines Colored lines that form when light is passed through a slit and then through a prism or diffraction grating, usually in a spectroscope. The pattern of lines is unique for each element.

spectrometer See *spectroscope*.

spectroscope An optical instrument that separates light into its constituent frequencies or wavelengths in the form of spectral lines. A *spectrometer* is an instrument that can also measure the frequencies or wavelengths.

spectrum (pl. spectra) For sunlight and other white light, the spread of colors seen when the light is passed through a prism or diffraction grating. The colors of the spectrum, in order from lowest frequency (longest wavelength) to highest frequency (shortest wavelength), are red, orange, yellow, green, blue, indigo, violet. See also *absorption spectrum, electromagnetic spectrum, emission spectrum,* and *prism*.

speed How fast something moves; the distance an object travels per unit of time; the magnitude of velocity. See also *average speed, linear speed, rotational speed,* and *tangential speed*.

$$\text{Speed} = \frac{\text{distance}}{\text{time}}$$

spherical aberration Distortion of an image caused when the light that passes through the edges of a lens focuses at slightly different points from the point where the light passing through the center of the lens focuses. It also occurs with spherical mirrors.

spring tide High or low tide that occurs when the Sun, Earth, and Moon are all lined up so that the tides due to the Sun and Moon coincide, making the high tides higher than average and the low tides lower than average. See also *neap tide*.

stable equilibrium State of an object balanced so that any small displacement or rotation raises its center of gravity.

standing wave Stationary wave pattern formed in a medium when two sets of identical waves pass through the medium in opposite directions. The wave appears not to be traveling.

static friction Force between two objects at relative rest by virtue of contact that tends to oppose sliding.

streamline Smooth path of a small region of fluid in steady flow.

strong force Force that attracts nucleons to each other within the nucleus; a force that is very strong at close distances but decreases rapidly as the distance increases. Also called strong interaction.

strong interaction See *strong force*.

subcritical mass See *critical mass*.

sublimation Direct conversion of a substance from the solid to the vapor phase without passing through the liquid phase.

subtractive primary colors The three colors of light-absorbing pigments—magenta, yellow, and cyan—that when mixed in certain proportions will reflect any color in the spectrum.

superconductor Material that is a perfect conductor with zero resistance to the flow of electric charge.

supercritical mass See *critical mass*.

superposition principle In a situation where more than one wave occupies the same space at the same time, the displacements add at every point.

supersonic Traveling faster than the speed of sound.
support force Upward force that balances the weight of an object on a surface.
surface tension Tendency of the surface of a liquid to contract in area and thus behave like a stretched elastic membrane.
tachyon Hypothetical particle that can travel faster than light and thus move backward in time.
tangent Line that touches a curve in one place only and is parallel to the curve at that point.
tangential speed Linear speed along a curved path.
tangential velocity Component of velocity tangent to the trajectory of a projectile.
tau The heaviest elementary particle in the class of elementary particles called leptons.
technology Method and means of solving practical problems by implementing the findings of science.
telescope Optical instrument that forms images of very distant objects.
temperature Measure of the average translational kinetic energy per molecule of a substance, measured in degrees Celsius or Fahrenheit or in kelvins.
temperature inversion Condition wherein upward convection of air is stopped, sometimes because an upper region of the atmosphere is warmer than the region below it.
terminal speed Speed attained by an object wherein the resistive forces, often air resistance, counterbalance the driving forces, so motion is without acceleration.
terminal velocity Terminal speed together with the direction of motion (down for falling objects).
terrestrial radiation Radiant energy emitted from Earth.
theory Synthesis of a large body of information that encompasses well-tested and verified hypotheses about aspects of the natural world.
thermal contact State of two or more objects or substances in contact such that heat can flow from one to the other.
thermal equilibrium State wherein substances in thermal contact have reached a common temperature.
thermal pollution Undesirable heat expelled from a heat engine or other source.
thermodynamics Study of heat and its transformation to mechanical energy, characterized by two principal laws:
First Law: A restatement of the law of conservation of energy as it applies to systems involving changes in temperature: Whenever heat is added to a system, it transforms to an equal amount of some other form of energy.
Second Law: Heat cannot be transferred from a colder body to a hotter body without work being done by an outside agent.
thermometer Device used to measure temperature, usually in degrees Celsius, degrees Fahrenheit, or kelvins.
thermonuclear fusion Nuclear fusion brought about by extremely high temperatures; in other words, the welding together of atomic nuclei by high temperature.
thermostat Type of valve or switch that responds to changes in temperature and that is used to control the temperature of something.
time dilation Slowing down of time for an object moving at relativistic speeds.
torque Product of force and lever-arm distance, which tends to produce rotational acceleration.

$$\text{Torque} = \text{lever-arm distance} \times \text{force}$$

total internal reflection The 100% reflection (with no transmission) of light that strikes the boundary between two media at an angle greater than the critical angle.
transformer Device for increasing or decreasing voltage or transferring electric power from one coil of wire to another by means of electromagnetic induction.
transistor See *semiconductor.*
transmutation Conversion of an atomic nucleus of one element into an atomic nucleus of another element through a loss or gain in the number of protons.
transparent Term applied to materials that allow light to pass through them in straight lines.
transuranic element Element higher than uranium in the periodic table.
transverse wave Wave with vibration at right angles to the direction the wave is traveling. Light consists of transverse waves.
tritium Unstable, radioactive isotope of hydrogen whose atom has a proton, two neutrons, and an electron.
trough The lowest part of a wave, in contrast to the highest part, a *crest.*
turbine Paddle wheel driven by steam, water, etc. that is used to do work.
turbogenerator Generator that is powered by a turbine.
ultrasonic Term applied to sound frequencies above 20,000 Hz, the normal upper limit of human hearing.
ultraviolet (UV) Electromagnetic waves of frequencies higher than those of violet light.
umbra Darker part of a shadow where all the light is blocked. See also *penumbra.*
uncertainty principle The principle formulated by Heisenberg, stating that Planck's constant, h, sets a limit on the accuracy of measurement at the atomic level. Accordingly, it is not possible to measure exactly both the position and the momentum of a particle at the same time, nor the energy and the time associated with a particle simultaneously.
universal gravitational constant The proportionality constant G that measures the strength of gravity in the equation for Newton's law of universal gravitation.

$$F = G\frac{m_1 m_2}{d^2}$$

unstable equilibrium State of an object balanced so that any small displacement or rotation lowers its center of gravity.

UV Abbreviation for *ultraviolet.*
V (a) In lowercase italic v, the symbol for *speed* or *velocity.* (b) In uppercase V, the abbreviation for *voltage.*
vacuum Absence of matter; void.
Van Allen radiation belts Two donut-shaped belts of radiation that surround Earth.
vaporization The process of a phase change from liquid to vapor; evaporation.
vector Arrow whose length represents the magnitude of a quantity and whose direction represents the direction of the quantity.
vector quantity Quantity in physics that has both magnitude and direction. Examples are force, velocity, acceleration, torque, and electric and magnetic fields.
velocity Speed of an object and its direction of motion; a vector quantity.
vibration Oscillation; a repeating to-and-fro motion about an equilibrium position—a "wiggle in time."
virtual image Image formed by light rays that do not converge at the location of the image. Mirrors, converging lenses used as magnifying glasses, and diverging lenses all produce virtual images. The image can be seen by an observer but cannot be projected onto a screen.
visible light Part of the electromagnetic spectrum that the human eye can see.
visible spectrum See *electromagnetic spectrum.*
volt (V) SI unit of electric potential. One volt is the electric potential difference across which one coulomb of charge gains or loses 1 joule of energy. 1 V = 1 J/C
voltage Electrical "pressure" or a measure of electrical potential difference.

$$\text{Voltage} = \frac{\text{electric potential energy}}{\text{unit of charge}}$$

voltage source Device, such as a dry cell, battery, or generator, that provides a potential difference.
voltmeter A galvanometer calibrated to read potential differences.
volume Quantity of space an object occupies.
W (a) Abbreviation for *watt.* (b) When an italic W, the abbreviation for *work.*
watt SI unit of power. One watt is expended when 1 joule of work is done in 1 second. 1 W = 1 J/s.
wave A "wiggle in space and time"; a disturbance that repeats regularly in space and time and that is transmitted progressively from one place to the next with no net transport of matter.
wavefront Crest, trough, or any continuous portion of a two-dimensional or three-dimensional wave in which the vibrations are all the same way at the same time.
wave speed Speed with which waves pass a particular point.

$$\text{Wave speed} = \text{frequency} \times \text{wavelength}$$

wave velocity Wave speed stated with the direction of travel.
wavelength Distance between successive crests, troughs, or identical parts of a wave.
weak force Also called weak interaction; the force within a nucleus that is responsible for beta (electron) emission.
weak interaction See *weak force.*
weight The force that an object exerts on a supporting surface (or, if suspended, in a supporting string)—often, but not always, due to the force of gravity.
weight density See *density.*
weightlessness Condition of free fall toward or around Earth in which an object experiences no support force (and exerts no force on a scale).
white light Light, such as sunlight, that is a combination of all the colors. Under white light, white objects appear white and colored objects appear in their individual colors.
work (W) Product of the force on an object and the distance through which the object is moved (when force is constant and motion is in a straight line in the direction of the force); measured in joules.

$$\text{Work} = \text{force} \times \text{distance}$$

work-energy theorem Work done on an object is equal to the kinetic energy gained by the object.

$$\text{Work} = \Delta\text{KE}$$

wormhole Hypothetical enormous distortion of space and time, similar to a black hole, but opening out again in some other part of the universe.
X-ray Electromagnetic radiation, higher in frequency than ultraviolet, emitted by atoms when the innermost orbital electrons undergo excitation.
zero-point energy Extremely small amount of kinetic energy that molecules or atoms have even at absolute zero.

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Some Significant Dates in the History of Physics

ca. 320 BC	**Aristotle** describes motion in terms of natural tendencies.
ca. 250 BC	**Archimedes** discovers the principle of buoyancy.
ca. AD 150	**Ptolemy** refines the Earth-centered system of the world.
1543	**Copernicus** publishes his Sun-centered system of the world.
1575–1596	**Brahe** measures precise positions of the planets in the sky.
1609	**Galileo** first uses a telescope as an astronomical tool.
1609/1619	**Kepler** publishes three laws of planetary motion.
1634	**Galileo** advances understanding of accelerated motion.
1661	**Boyle** relates pressure and volume of gases at constant temperature.
1676	**Roemer** demonstrates that light has finite speed.
1678	**Huygens** develops a wave theory of light.
1687	**Newton** presents the theory of mechanics in his *Principia.*
1738	**Bernoulli** explains the behavior of gases in terms of molecular motions.
1747	**Franklin** suggests the conservation of electrical "fire" (charge).
1780	**Galvani** discovers "animal electricity."
1785	**Coulomb** precisely determines the law of electric force.
1795	**Cavendish** measures the gravitational constant *G*.
1798	**Rumford** argues that heat is a form of motion.
1800	**Volta** invents the battery.
1802	**Young** uses wave theory to account for interference.
1811	**Avogadro** suggests that, at equal temperature and pressure, all gases have equal numbers of molecules per unit volume.
1815–1820	**Young** and others provide evidence for the wave nature of light.
1820	**Oersted** discovers the magnetic effect of an electric current.
1820	**Ampère** establishes the law of force between current-carrying wires.
1821	**Fraunhofer** invents the diffraction grating.
1824	**Carnot** states that heat cannot be transformed wholly to work.
1831	**Faraday** and **Henry** discover electromagnetic induction.
1842–1843	**Mayer** and **Joule** suggest a general law of energy conservation.
1846	**Adams** and **Leverrier** predict the existence of the planet Neptune.
1865	**Maxwell** gives the electromagnetic theory of light.
1869	**Mendeleev** organizes the elements into a periodic table.
1877	**Boltzmann** relates entropy to probability.
1885	**Balmer** finds numerical regularity in the spectrum of hydrogen.
1887	**Michelson** and **Morley** fail to detect the ether.
1888	**Hertz** generates and detects radio waves.
1895	**Roentgen** discovers X-rays.
1896	**Bequerel** discovers radioactivity.
1897	**Thomson** identifies cathode rays as negative corpuscles (electrons).

1900	**Planck** introduces the quantum idea.
1905	**Einstein** introduces the light corpuscle (photon) concept.
1905	**Einstein** advances the special theory of relativity.
1911	**Rutherford** reveals the nuclear atom.
1913	**Bohr** gives a quantum theory of the hydrogen atom.
1915	**Einstein** advances the general theory of relativity.
1923	**Compton's** experiments confirm the existence of the photon.
1924	**de Broglie** advances the wave theory of matter.
1925	**Goudsmit** and **Uhlenbeck** establish the spin of the electron.
1925	**Pauli** states the exclusion principle.
1926	**Schrödinger** develops the wave theory of quantum mechanics.
1927	**Davisson** and **Germer** and **Thomson** verify the wave nature of electrons.
1927	**Heisenberg** proposes the uncertainty principle.
1928	**Dirac** blends relativity and quantum mechanics in a theory of the electron.
1929	**Hubble** discovers the expanding universe.
1932	**Anderson** discovers antimatter in the form of the positron.
1932	**Chadwick** discovers the neutron.
1932	**Heisenberg** gives the neutron–proton explanation of nuclear structure.
1934	**Fermi** proposes a theory of the annihilation and creation of matter.
1938	**Meitner** and **Frisch** interpret results of **Hahn** and **Strassmann** as nuclear fission.
1939	**Bohr** and **Wheeler** give a detailed theory of nuclear fission.
1942	**Fermi** builds and operates the first nuclear reactor.
1945	**Oppenheimer's** Los Alamos team creates a nuclear explosion.
1947	**Bardeen**, **Brattain**, and **Shockley** develop the transistor.
1956	**Reines** and **Cowan** identify the antineutrino.
1957	**Feynman** and **Gell-Mann** explain weak interactions with a "left-handed" neutrino.
1960	**Maiman** invents the laser.
1965	**Penzias** and **Wilson** discover background radiation in the universe left over from the Big Bang.
1967	**Bell** and **Hewish** discover pulsars, which are neutron stars.
1968	**Wheeler** names black holes.
1969	**Gell-Mann** suggests quarks as the building blocks of nucleons.
1977	**Lederman** and his team discover the bottom quark.
1981	**Binning** and **Rohrer** invent the scanning tunneling microscope.
1987	**Bednorz** and **Müller** discover high-temperature superconductivity.
1995	**Cornell** and **Wieman** create a "Bose–Einstein condensate" at 20 billionths of a degree.
2000	**Pogge** and **Martini** provide evidence for supermassive black holes in other galaxies.
2000	Fermilab group identifies the tau neutrino, the last member of the lepton particle group.
2003	Scientists studying radiation in space put the age of the universe at 13.7 billion years.
2005	**Gerald Gabrielse** measures the magnetism of the electron to 1 part in a trillion.
2006	U.S.–Russian team identifies elements number 116 and 118.
2008	CERN laboratory achieves a proton beam in the LHC, the world's largest physics instrument.
2009	The catalog of exoplanets (planets orbiting other stars) grows to more than 350.

Physical Data

Category	Name	Value
Speeds	Speed of light in a vacuum, c	2.9979×10^8 m/s
	Speed of sound (20°C, 1 atm)	343 m/s
Acceleration	Standard acceleration of gravity, g	9.80 m/s^2
Pressure	Standard atmospheric pressure	1.01×10^5 Pa
Distances	Astronomical unit (A.U.), (average Earth–Sun distance)	1.50×10^{11} m
	Average Earth–Moon distance	3.84×10^8 m
	Radius of Sun (average)	6.96×10^8 m
	Radius of Earth (equatorial)	6.37×10^6 m
	Radius of Earth's orbit	1.50×10^{11} m = 1 AU
	Radius of Moon (average)	1.74×10^6 m
	Radius of Moon's orbit	3.84×10^8 m
	Radius of Jupiter (equatorial)	7.14×10^7 m
	Radius of hydrogen atom (approx.)	5×10^{-11} m
Masses	Mass of Sun	1.99×10^{30} kg
	Mass of Earth	5.98×10^{24} kg
	Mass of Moon	7.36×10^{22} kg
	Mass of Jupiter	1.90×10^{27} kg
	Mass of proton, m_p	$1.6726231 \times 10^{-27}$ kg
		938.27231 MeV
	Mass of neutron, m_n	$1.6749286 \times 10^{-27}$ kg
		939.56563 MeV
	Mass of electron, m_e	$9.1093897 \times 10^{-31}$ kg
		0.51099906 MeV
Charge	Charge of electron, e	1.602×10^{-19} C
Other Constants	Gravitational constant, G	6.67259×10^{-11} N·m^2/kg^2
	Planck's constant, h	$6.6260755 \times 10^{-34}$ J·s
		$4.1356692 \times 10^{-15}$ eV·s
	Avogadro's number, N_A	6.0221367×10^{23}/mol
	Black body radiation constant, σ	5.67051×10^{-8} W/m^2·K^4

Standard Abbreviations

A	ampere	g	gram	min	minute
amu	atomic mass unit	h	hour	mph	mile per hour
atm	atmosphere	hp	horsepower	N	newton
Btu	British thermal unit	Hz	hertz	Pa	pascal
C	coulomb	in.	inch	psi	pound per square inch
°C	degree Celsius	J	joule	s	second
cal	calorie	K	kelvin	u	unified atomic mass unit
eV	electron volt	kg	kilogram	V	volt
°F	degree Fahrenheit	lb	pound	W	watt
ft	foot	m	meter	Ω	ohm

Numbers Expressed in Scientific Notation

$1\,000\,000 = 10 \times 10 \times 10 \times 10 \times 10 \times 10$	$= 10^6$	mega
$100\,000 = 10 \times 10 \times 10 \times 10 \times 10$	$= 10^5$	
$10\,000 = 10 \times 10 \times 10 \times 10$	$= 10^4$	
$1000 = 10 \times 10 \times 10$	$= 10^3$	kilo
$100 = 10 \times 10$	$= 10^2$	
$10 = 10$	$= 10^1$	
$1 = 1$	$= 10^0$	
$0.1 = 1/10$	$= 10^{-1}$	
$0.01 = 1/100 = 1/10^2$	$= 10^{-2}$	centi
$0.001 = 1/1000 = 1/10^3$	$= 10^{-3}$	milli
$0.000\,1 = 1/10\,000 = 1/10^4$	$= 10^{-4}$	
$0.0\,000\,1 = 1/100\,000 = 1/10^5$	$= 10^{-5}$	
$0.00\,000\,1 = 1/1\,000\,000 = 1/10^6$	$= 10^{-6}$	micro

Conversion Factors

Length and Volume
1 inch = 2.54 cm (exact)
1 ft = 0.3048 m (exact)
1 m = 39.37 in.
1 mi = 1.6093440 km
1 liter = 10^3 cm^3 = 10^{-3} m^3

Time
1 year = $365\frac{1}{4}$ day = 3.1558×10^7 s
1 d = 86,400 s
1 h = 3600 s

Mass
1 kg = 1000 g
1 kg has a weight of 2.205 lb
1 amu = 1.6605×10^{-27} kg

Pressure
1 Pa = 1 N/m^2
1 atm = 1.01325×10^5 Pa
1 lb/in.^{2} = 6895 Pa

Energy and Power
1 cal = 4.184 J
1 kWh = 3.60×10^6 J
1 eV = 1.602×10^{-19} J
1 u = 931.5 MeV
1 hp = 746 W

Speed
1 m/s = 3.60 km/h = 2.24 mi/h
1 km/h = 0.621 mi/h

Force
1 lb = 4.448 N