CHAPTER 8

Wave Motion

A. WAVES

8.1 WHAT IS A WAVE?

The world is continually criss-crossed by waves of all sorts. Water waves, whether giant rollers in the middle of the ocean or gently formed rain ripples on a still pond, are sources of wonder or pleasure. If the Earth's crust shifts, violent waves in the solid Earth cause tremors thousands of kilome-

FIGURE 8.1 Waves crashing on the shore.

ters away. A musician plucks a guitar string, and sound waves pulse against the ears. Wave disturbances may come in a concentrated bundle, like the shock front from an airplane flying at supersonic speeds. Or the disturbances may come in succession like the train of waves sent out from a steadily vibrating source, such as a bell or a string.

All of these examples are *mechanical* waves, in which bodies or particles physically move back and forth. There are also wave disturbances in electric and magnetic fields. Such waves are responsible for what we experience as X rays, visible light, or radio waves. In all cases involving waves, however, the effects produced depend on the flow of energy, not matter, as the wave moves forward. Waves are cases of energy transfer without matter transfer.

So far in this text, you have considered motion in terms of individual particles or other objects. In this chapter, you will study the cooperative motion of collections of particles in "continuous media," oscillating back and forth as the mechanical waves pass by. You will see how closely related are the ideas of particles and waves used to describe events in nature. Then we shall deal with the properties of light and other electromagnetic waves.

8.2 THE PROPERTIES OF WAVES

To introduce some necessary terms to discuss the fascinating world of waves, suppose that two people are holding opposite ends of a taut rope. Suddenly one person snaps the rope up and down quickly once. That "disturbs" the rope and puts a hump in it which travels along the rope toward the other person. The traveling hump is one kind of a wave, called a *pulse*.

Originally, the rope was motionless. The height above ground of each point on the rope depended only upon its position along the rope and did not change in time. But when one person snaps the rope, a rapid change is created in the height of one end. This disturbance then moves away from its source, down the rope to the other end. The height of each point on the rope now depends also upon time, as each point eventually oscillates up and down and back to the initial position, as the pulse passes.

The disturbance is thus a pattern of *displacement* moving along the rope. The motion of the displacement pattern from one end of the rope toward the other is an example of a *wave*. The hand snapping one end is the *source* of the wave. The rope is the *medium* in which the wave moves.

Consider another example. When a pebble falls into a pool of still liquid, a series of circular crests and troughs spreads over the surface. This moving displacement pattern of the liquid surface is a wave. The pebble is the source; the moving pattern of crests and troughs is the wave; and the liquid surface is the medium. Leaves or other objects floating on the surface of the liquid bob up and down as each wave passes. But they do not experience any net displacement on the average. No *material* has moved from the wave source along with the wave, either on the surface or among the particles of the liquid—only the energy and momentum contained in the disturbance have been transmitted. The same holds for rope waves, sound waves in air, etc.

As any one of these waves moves through a medium, the wave produces a changing displacement of the successive parts of the medium. Thus, we can refer to these waves as *waves of displacement*. If you can see the medium and recognize the displacements, then you can easily see waves. But waves also may exist in media you cannot see, such as air; or they may form as disturbances of a state you cannot detect with your unaided eyes, such as pressure or an electric field.

You can use a loose spring coil (a Slinky) to demonstrate three different kinds of motion in the medium through which a wave passes. First, move

FIGURE 8.2 The transverse disturbance moves in the horizontal plane of the ground, rather than in the vertical plane.

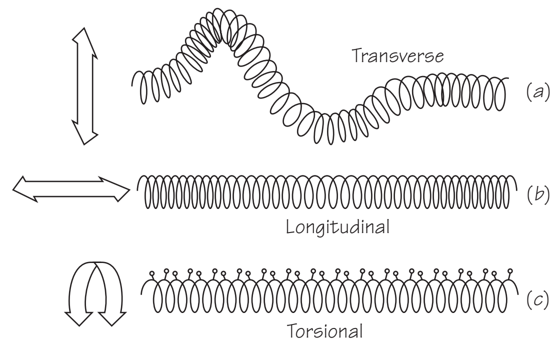


FIGURE 8.3 "Snapshots" of three types of waves on a spring. In (c), the small markers have been put on the top of each coil in the spring.

the end of the spring from side to side, or up and down as in Figure 8.3 (a). A wave of side-to-side or up-and-down displacement will travel along the spring. Now push the end of the spring back and forth, along the direction of the spring itself, as in sketch (b). A wave of back-and-forth displacement will travel along the spring. Finally, twist the end of the spring quickly clockwise and counterclockwise, as in sketch (c). A wave of angular displacement will begin to travel along the spring. (See also the suggested laboratory exploration on waves in the *Student Guide*.)

Waves like those in (a), in which the displacements are perpendicular to the direction the wave travels, are called *transverse* waves. Waves like those in (b), in which the displacements are in the direction the wave travels, are called *longitudinal* waves. Waves like those in (c), in which the displacements are twisting in a plane perpendicular to the direction the wave travels, are called *torsional* waves.

All three types of wave motion can be set up in solids. In fluids, however, transverse and torsional waves die out very quickly and usually cannot be produced at all, except on the surface. Therefore, sound waves in air and water are longitudinal. The molecules of the medium are displaced back and forth along the direction in which the sound energy travels.

It is often useful to make a graph on paper, representing the wave patterns in a medium. This is of course easy to do for transverse waves, but not for longitudinal or torsional waves. But there is a way out. For example, the graph in Figure 8.4 represents the pattern of *compressions* at a given moment as a (longitudinal) sound wave goes through the air. The graph line goes up and down because the graph represents a snapshot of the increase and decrease in density of the air along the path of the wave. It does *not* represent an up-and-down motion of the molecules in the air themselves.

To describe completely transverse waves, such as those in ropes, you must specify the *direction* of displacement. When the displacement pattern of a transverse wave is along one line in a plane perpendicular to the direction

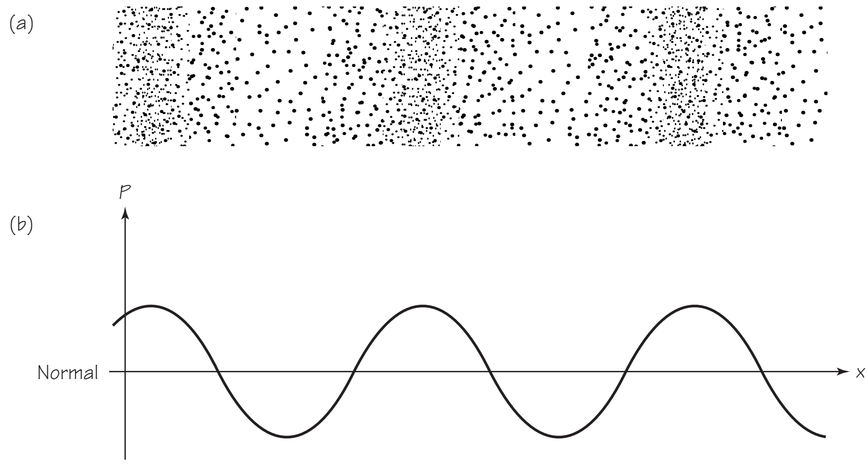


FIGURE 8.4 (a) "Snapshot representation of a sound wave progressing to the right. The dots represent the density of air molecules. (b) Graph of air pressure, P, versus position, x, at the instant of the snapshot.

of motion of the wave, the wave is said to be *polarized*. See the diagrams in Figure 8.5. For waves on ropes and springs, you can observe the polarization directly. In Section 8.18 you will see that for light waves, for example, polarization can have important effects.

All three kinds of waves—longitudinal, transverse, and torsional—have an important characteristic in common. The disturbances move away from their sources through the media and *continue on their own* (although their amplitude may diminish owing to energy loss to friction and other causes). We stress this particular characteristic by saying that these waves *propagate*. This means more than just that they "travel" or "move." An example will clarify the difference between waves that propagate and those that do not. You may have seen one of the great wheat plains of the Middle West,

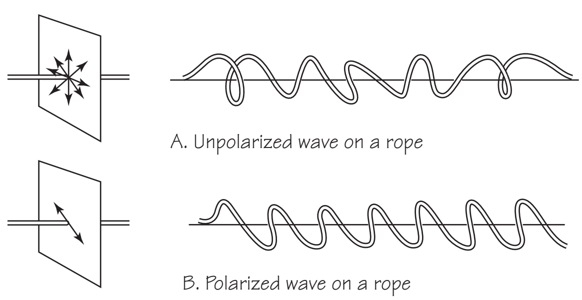


FIGURE 8.5 Polarized/unpolarized waves on rope.

Canada, or Central Europe. Such descriptions usually mention the "beautiful, wind-formed waves that roll for miles across the fields." The medium for such a wave is the wheat, and the disturbance is the swaying motion of the wheat. This disturbance does indeed travel, but it does *not* propagate; that is, the disturbance does not originate at a source and then go on *by itself*. Rather, it must be continually fanned by the wind. When the wind stops, the disturbance does not roll on, but stops, too. The traveling "waves" of swaying wheat are not at all the same as rope and water waves. This chapter will concentrate on waves that originate at sources and propagate themselves through the medium. For the purposes of this chapter, *waves are disturbances which propagate in a medium*.

8.3 WAVE PROPAGATION

Waves and their behavior are perhaps best studied by beginning with large mechanical models and focusing our attention on pulses. Consider, for example, a freight train, with many cars attached to a powerful locomotive, but standing still. If the locomotive starts abruptly, its pull on the next neighboring car sends a displacement wave running down the line of cars.

FIGURE 8.6 A displacement.

The shock of the starting displacement proceeds from the locomotive, clacking through the couplings one by one. In this example, the locomotive is the source of the disturbance, while the freight cars and their couplings are the medium. The "bump" traveling along the line of cars is the wave. The disturbance proceeds all the way from end to end, and with it goes *energy* of displacement and motion. Yet no particles of matter are transferred that far; each car only jerks ahead a bit.

How long does it take for the effect of a disturbance created at one point to reach a distant point? The time interval depends of course on the speed with which the disturbance or wave propagates. This speed, in turn, depends upon the type of wave and the characteristics of the medium. In any case, the effect of a disturbance is never transmitted instantly over any distance. Each part of the medium has inertia, and each portion of the medium is compressible. So time is needed to transfer energy from one part to the next.

The same comments also apply to transverse waves. The series of sketches in the accompanying diagram (Figure 8.7) represents a wave on a rope. Think of the sketches as frames of a motion picture film, taken at equal time intervals. We know that the material of the rope does *not* travel

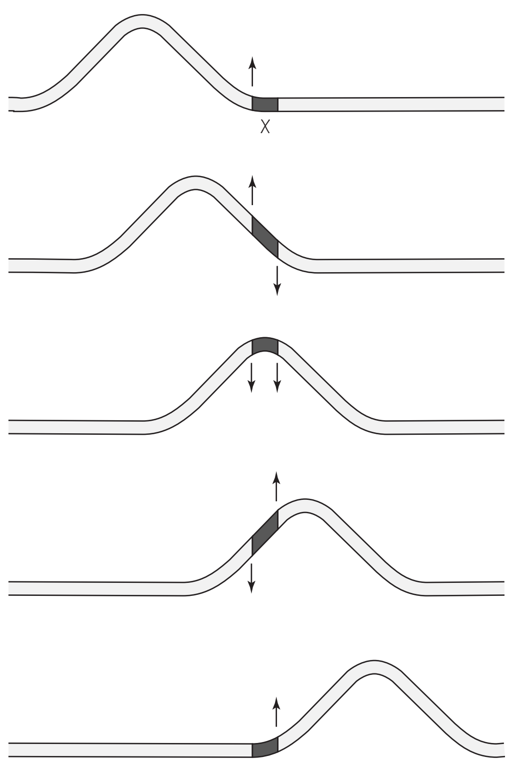


FIGURE 8.7 A rough representation of the forces at the ends of a small section of rope as a transverse pulse moves past.

along with the wave. But each bit of the rope goes through an up-and-down motion as the wave passes. Each bit goes through exactly the same motion as the bit to its left, except a little later.

Consider the small section of rope labeled X in the first diagram. When the pulse traveling on the rope first reaches X, the section of rope just to the left of X exerts an upward force on X. As X is moved upward, a restoring downward force is exerted by the next section. The further upward X moves, the greater the restoring forces become. Eventually, X stops moving upward and starts down again. The section of rope to the left of X now exerts a restoring (downward) force, while the section to the right exerts an upward force. Thus, the trip down is similar, but opposite, to the trip upward. Finally, X returns to the equilibrium position when both forces have vanished.

The time required for X to go up and down, that is, the time required for the pulse to pass by that portion of the rope, depends on two factors. These factors are the *magnitude of the forces* on X and the *mass* of X. To put it more generally: The speed with which a wave propagates depends on the *stiffness* and on the *density* of the medium. The stiffer the medium, the greater will be the force each section exerts on neighboring sections. Thus, the greater will be the propagation speed. On the other hand, the greater the density of the medium, the less it will respond to forces. Thus, the slower will be the propagation. In fact, the speed of propagation depends on the *ratio* of the stiffness factor and the density factor. The exact meaning of stiffness and density factors is different for different kinds of waves and different media. For tight strings, for example, the stiffness factor is the tension T in the string, and the density factor is the mass per unit length, m/l. The propagation speed v is given by

$$v = \sqrt{\frac{T}{m/l}}.$$

8.4 PERIODIC WAVES

Many of the disturbances we have considered so far have been sudden and short-lived, set up by a brief motion like snapping one end of a rope or suddenly displacing one end of a train. In each case, you see a single wave running along the medium with a certain speed. As noted, this kind of wave is called a pulse.

Now consider *periodic waves*, continuous regular rhythmic disturbances in a medium, resulting from *periodic vibrations* of a source. A good example of an object in periodic vibration is a swinging pendulum. Neglecting the effects of air resistance, each swing is virtually identical to every other swing, and the swing repeats over and over again in time. Another example is the up-and-down motion of a weight at the end of a coiled spring. In each case, the maximum displacement from the position of equilibrium is called the *amplitude*, A, as shown in the diagram below for the case of the spring. The time taken to complete one vibration is called the *period*, T, usually given in seconds. The number of vibrations per second is called the *frequency*, f. Note that T and f are reciprocals, in the sense that $T = 1/f$.

What happens when a periodic vibration is applied to the end of a rope? Suppose that the left end of a taut rope is fastened to the oscillating (vibrating) weight on a spring in Figure 8.8. As the weight vibrates up and down, you observe a wave propagating along the rope (see the illustration). The wave takes the form of a series of moving crests and troughs along the length of the rope. The source executes "simple harmonic motion" up and down. Ideally, every point along the length of the rope executes simple harmonic motion in turn. The wave travels to the right as crests and troughs follow one another. Each point or small segment along the rope simply os-

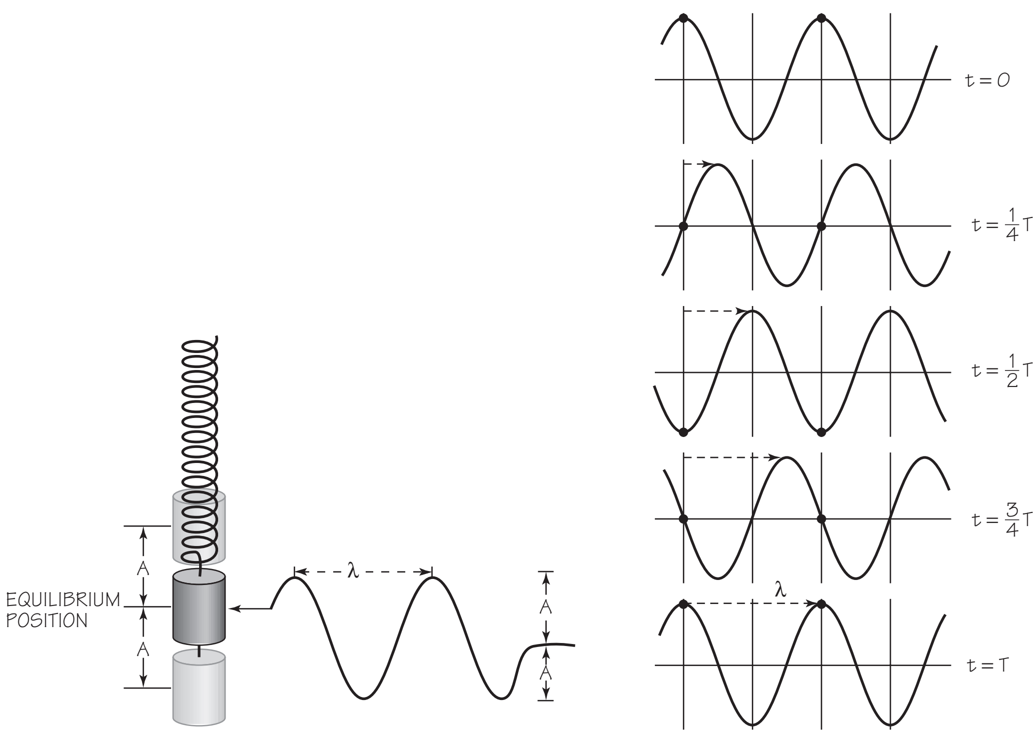


FIGURE 8.8 Spring-mass system attached to a rope, and graph of the periodic motion.

cillates up and down at the same frequency as the source. The amplitude of the wave is represented by A. The distance between any two consecutive crests or any two consecutive troughs is the same all along the length of the rope. This distance, called the *wavelength* of the periodic wave, is conventionally represented by the Greek letter λ (lambda).

If a single pulse or a wave crest moves fairly slowly through the medium, you can easily find its *speed*. In principle, all you need is a clock and a meter stick. By timing the pulse or crest over a measured distance, you can get the speed.

To be sure, it is not always so simple to observe the motion of a pulse or a wave crest. But the speed of a periodic wave can be found indirectly, if one can measure both its frequency and its wavelength. Here is how this works. Using the example of the rope wave, we know that as the wave progresses, each point in the medium oscillates with the frequency and period of the source. The diagram in Figure 8.8 illustrates a periodic wave moving to the right, as it might look in snapshots taken every one-quarter period. Follow the progress of the crest that started out from the extreme left at time $t = 0$. The time it takes this crest to move a distance of one wavelength is equal to the time required for one complete oscillation of the source, or equally of any point on the rope; that is, the crest moves one wavelength λ during one period of oscillation T. The speed v of the crest is therefore given by the equation

$$\begin{aligned} v &= \frac{\text{distance moved}}{\text{corresponding time interval}} \\ &= \frac{\lambda}{T}. \end{aligned}$$

All parts of the wave pattern propagate with the same speed along the rope. Thus, the speed of any one crest is the same as the speed of the wave as a whole. Therefore, the speed v of the wave is also given by

$$\begin{aligned} v &= \frac{\text{wavelength}}{\text{period of oscillation}} \\ &= \frac{\lambda}{T}. \end{aligned}$$

But $T = 1/f$, where f = frequency. Therefore,

$$v = f\lambda$$

or

wave speed = frequency × wavelength.

We can also write this relationship as

$$\lambda = \frac{v}{f}$$

or

$$f = \frac{v}{\lambda}.$$

These expressions show that, for waves of the same speed, the frequency and wavelength are inversely proportional; that is, a wave of twice the frequency would have only half the wavelength, and so on. This inverse relationship of frequency and wavelength will turn out to be very useful in later chapters.

We now go to the last of the definitions that will help to understand how waves behave. The diagram below represents a periodic wave passing through a medium. Sets of points are marked that are moving "in step" as the periodic wave passes. The crest points C and C′ have reached maximum displacement positions in the upward direction. The trough points D and D′ have reached maximum displacement positions in the downward direc-

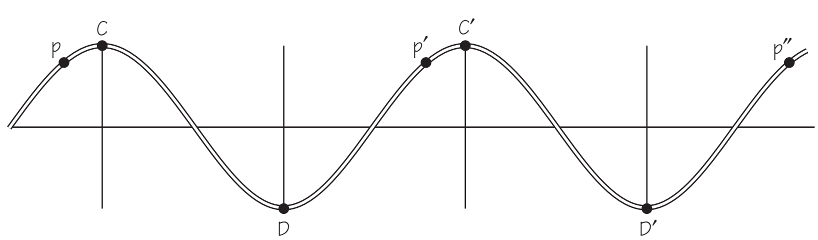


FIGURE 8.9 A "snapshot" of a periodic wave moving to the right. Letters indicate sets of points with the same phase.

tion. The points C and C′ have identical displacements and velocities at any instant of time. Their vibrations are identical and in unison. The same is true for the points D and D′. Indeed there are infinitely many such pairs of points along the medium that are vibrating identically when this wave passes. Note that C and C′ are a distance λ apart, and so are D and D′.

Points that move "in step," such as C and C′, are said to be *in phase* with one another. Points D and D′ also move in phase. Indeed, points separated from one another by distances of λ, 2λ, 3λ, . . . , and $n\lambda$ (n being any whole number) are all in phase with one another. These points can be anywhere along the length of the wave. They need not correspond with only the highest or lowest points. For example, points such as P, P′, P″, are all in phase with one another. Each such point is separated by a distance λ from the next one in phase with it.

On the other hand, we can also see that some pairs of points are exactly *out* of step. For example, point C reaches its maximum upward displacement at the same time that D reaches its maximum downward displacement. At the instant that C begins to go down, D begins to go up (and vice versa). Points such as these are one-half period *out of phase* with respect to one another. C and D′ also are one-half period out of phase. Any two points separated from one another by distances of $\frac{1}{2}\lambda$, $\frac{3}{2}\lambda$, $\frac{5}{2}\lambda$, etc., are one-half period out of phase.

8.5 WHEN WAVES MEET

With the above definitions in hand, we can explore a rich terrain. So far, we have considered single waves. What happens when two waves encounter each other in the same medium? Suppose two waves approach each other on a rope, one traveling to the right and one traveling to the left. The series of sketches in Figure 8.10 shows what would happen if you made this experiment. The waves pass through each other without being modified. After the encounter, each wave looks just as it did before and is traveling onward just as it did before. (How different from two particles meeting head-on!) This phenomenon of waves passing through each other unchanged can be observed with all types of waves. You can easily see that this is true for surface ripples on water. It must be true for sound waves also, since two conversations can take place across a table without distorting each other.

What happens during the time when the two waves overlap? The displacements they provide add together at each point of the medium. The

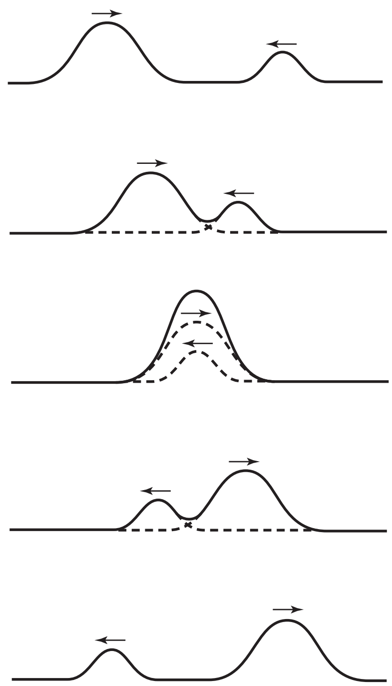


FIGURE 8.10 The superposition of two rope pulses at a point.

displacement of any point in the overlap region is just the *sum* of the displacements that would be caused at that moment by each of the two waves separately, as shown in Figure 8.10. Two waves travel toward each other on a rope. One has a maximum displacement of 0.4 cm upward and the other a maximum displacement of 0.8 cm upward. The total maximum upward displacement of the rope at a point where these two waves pass each other is 1.2 cm.

What a wonderfully simple behavior, and how easy it makes everything! Each wave proceeds along the rope making its own contribution to the rope's displacement no matter what any other wave is doing. This property of waves is called *superposition*. Using it, one can easily determine ahead of time what the rope will look like at any given instant. All one needs to do is to add up the displacements that will be caused by each wave at each point along the rope at that instant. Another illustration of wave superposition is shown in Figure 8.11. Notice that when the displacements are in opposite directions, they tend to cancel each other.

The *superposition principle* applies no matter how many separate waves or disturbances are present in the medium. In the examples just given, only

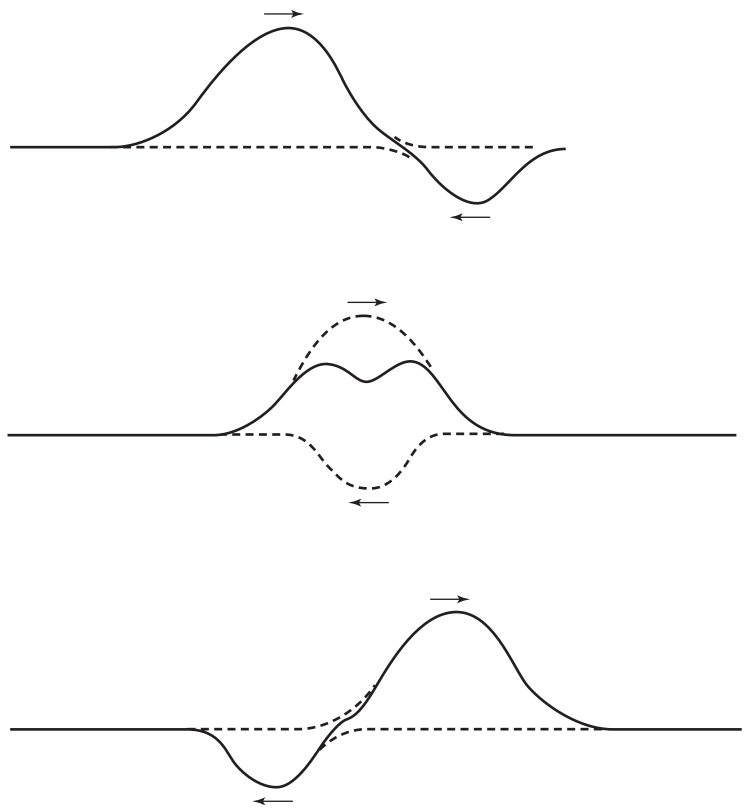


FIGURE 8.11 Superposition of two pulses on a rope.

two waves were present. But you would find by experiment that the superposition principle works equally well for three, ten, or any number of waves. Each makes its own contribution, and the net result is simply the sum of all the individual contributions (see Figure 8.12).

If waves add as just described, then you can think of a complex wave as the sum of a set of simple, sinusoidal waves. In 1807, the French mathematician Augustin Jean Fourier advanced a very useful theorem. Fourier stated that any continuing periodic oscillation, however complex, could be analyzed as the sum of simpler, regular wave motions. This, too, can be demonstrated by experiment. The sounds of musical instruments can be analyzed in this way also. Such analysis makes it possible to "imitate" instruments electronically, by combining and emitting just the right proportions of simple vibrations, which correspond to pure tones.

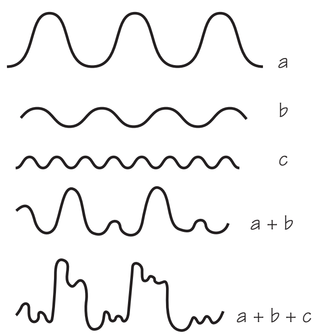


FIGURE 8.12 Sketch of complex waves as addition of two or three waves.

8.6 A TWO-SOURCE INTERFERENCE PATTERN

The figures on page 346 show ripples spreading from a vibrating source touching the water surface in a "ripple tank." The drawing shows a "cut-away" view of the water level pattern at a given instant. The image on the right introduces a phenomenon that will play an important role in later parts of the course. It shows the pattern of ripples on a water surface disturbed by *two* vibrating sources. The two small sources go through the up-and-down motions together, that is, they are in phase. Each source creates its own set of circular, spreading ripples. The image captures the pattern made by the overlapping sets of waves at one instant. This pattern is called an *interference pattern*.

You can interpret what you see here in terms of what you already know about waves. You can predict how the pattern will change with time. First, tilt the page so that you are viewing the interference pattern from a glancing direction. You will see more clearly some nearly straight gray bands. One can explain this feature by the superposition principle.

To start with, suppose that two sources produce identical pulses at the same instant. Each pulse contains one crest and one trough. (See Figure 8.16.) In each pulse the height of the crest above the undisturbed or average level is equal to the depth of the trough below. The sketches show the patterns of the water surface after equal time intervals. As the pulses spread out, the points at which they overlap move too. In the figure, a completely darkened small circle indicates where a crest overlaps another crest. A half-darkened small circle marks each point where a crest overlaps a trough. A blank small circle indicates the meeting of two troughs. According to the superposition principle, the water level should be highest at the completely darkened circles (where the crests overlap). It should be lowest at the blank

WAVES IN A RIPPLE TANK

When something drops in the water, it produces periodic wave trains of crest and troughs, somewhat as shown in the "cut-away" drawing at the left below.

Figure 8.13 is an instantaneous photograph of the shadows of ripples produced by a vibrating point source. The crests and troughs on the water surface show up in the image as bright and dark circular bands. In the photo below right, there were two point sources vibrating in phase. The overlapping waves create an interference pattern.

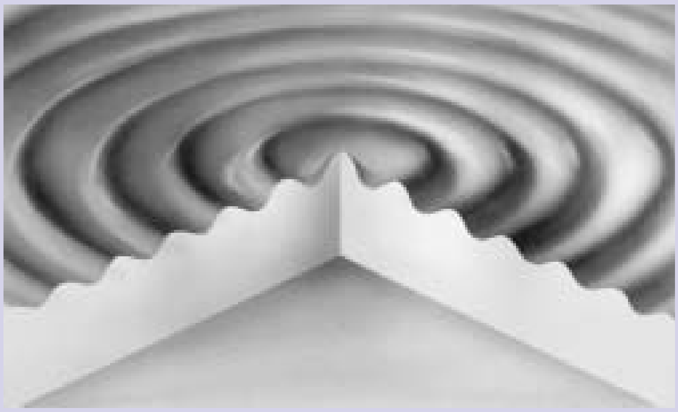


FIGURE 8.13

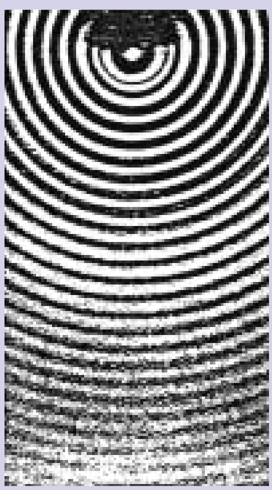


FIGURE 8.14

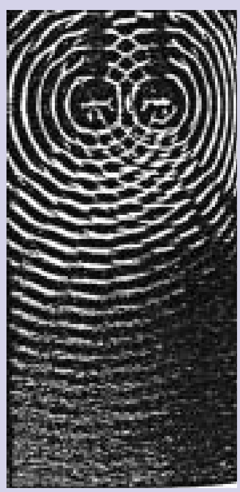


FIGURE 8.15

FIGURE 8.13–8.15 When an object drops in the water, it produces periodic wave trains of crests and troughs, somewhat as shown in the "cut-away" drawing here. Also represented here are two ripple patterns produced by one vibrating point source (left) and two point sources vibrating in phase (right). The overlapping waves create an interference pattern.

circles, and at average height at the half-darkened circles. Each of the sketches in Figure 8.16 represents the spatial pattern of the water level at a given instant.

At the points marked with darkened circles in the figure, the two pulses arrive in phase. At the points indicated by open circles, the pulses also ar-

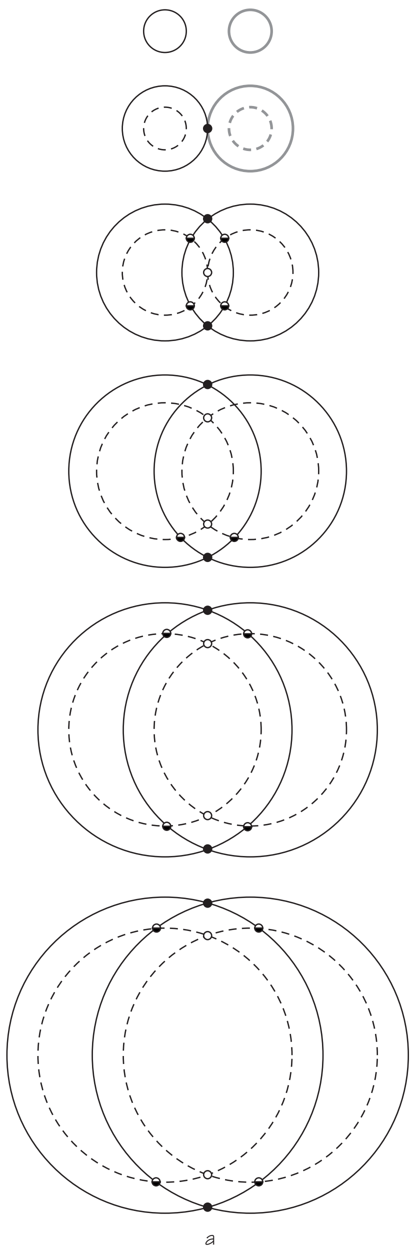


FIGURE 8.16 Pattern produced when two circular pulses, each of a crest and a trough, spread through each other. The very small circles indicate the net displacement at those points (dark circle = double height peak; half-dark circle = average level; blank circle = double depth trough).

rive in phase. In either case, the waves reinforce each other, causing a *greater* amplitude of either the crest or the trough. Thus, the waves are said to *interfere constructively*. In this case, all such points are at the same distance from each source. As the ripples spread, the region of maximum disturbance moves along the central dotted line in (a). At the points marked with half-darkened circles, the two pulses arrive completely out of phase. Here the waves cancel and so are said to interfere *destructively*, leaving the water surface undisturbed.

When two periodic waves of equal amplitude are sent out instead of single pulses, overlap occurs all over the surface, as is also shown in Figure 8.17. All along the central dotted line in Figure 8.17, there is a doubled disturbance amplitude. All along the lines labeled N, the water height remains undisturbed. Depending on the wavelength and the distance between the sources, there can be many such lines of constructive and destructive interference.

Now you can interpret the ripple tank interference pattern shown in the previous drawings (Figures 8.14 and 8.15). The gray bands are areas where waves cancel each other at all times; they are called *nodal lines*. These bands correspond to lines labeled N in the drawing above. Between these bands are other bands where crest and trough follow one another, where the waves reinforce. These are called *antinodal* lines.

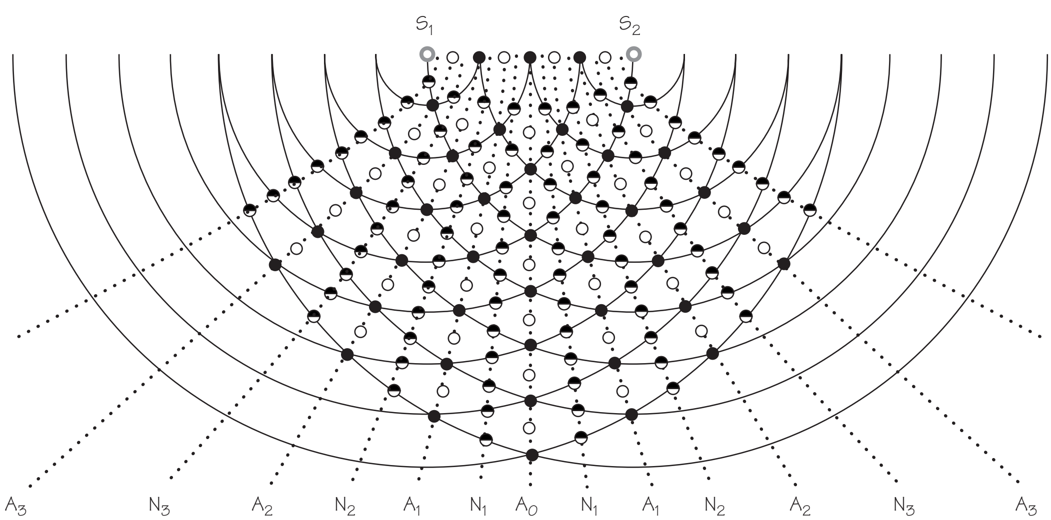


FIGURE 8.17 Analysis of interference pattern. The dark circles indicate where crest is meeting crest, the blank circles where trough is meeting trough, and the half-dark circles where crest is meeting trough. The other lines of maximum constructive interference are labeled A_0, A_1, A_2, etc. Points on these lines move up and down much more than they would because of waves from either source alone. The lines labeled N_1, N_2, etc. represent bands along which there is maximum destructive interference. Points on these lines move up and down much less than they would because of waves from either source alone.

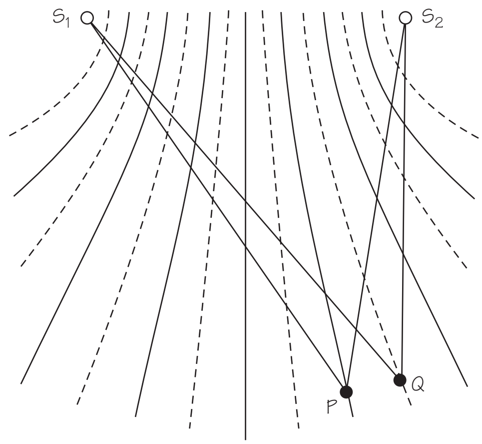


FIGURE 8.18 Detail of interference pattern.

Such an interference pattern is set up by overlapping waves from two sources. For water waves, the interference pattern can be seen directly. But whether visible or not, all waves, including earthquake waves, sound waves, or X rays, can set up interference patterns. For example, suppose two loudspeakers powered by the same receiver are working at the same frequency. By changing your position in front of the loudspeakers, you can find the nodal regions where destructive interference causes only a little sound to be heard. You also can find the antinodal regions where a strong signal comes through.

The beautiful symmetry of these interference patterns is not accidental. Rather, the whole pattern is determined by the wavelength λ and the source separation S_1S_2. From these, you could calculate the angles at which the nodal and antinodal lines spread out to either side of A_0. Conversely, you might know S_1S_2, and might have found these angles by probing around in the two-source interference pattern. If so, you can calculate the wavelength even if you cannot see the crests and troughs of the waves directly. This is very useful, for most waves in nature cannot be directly seen. Their wavelength has to be found by letting waves set up an interference pattern, probing for the nodal and antinodal lines, and calculating λ from the geometry.

The above figure shows part of the pattern of the diagram in Figure 8.17. At any point P on an *antinodal* line, the waves from the two sources arrive *in phase*. This can happen only if P is equally far from S_1 and S_2, or if P is some whole number of wavelengths farther from one source than from the other. In other words, the difference in distances $(S_1P - S_2P)$ must equal $n\lambda$, λ being the wavelength and n being zero or any whole number. At any point Q on a *nodal* line, the waves from the two sources arrive exactly *out* *of phase*. This occurs because Q is an odd number of half-wavelengths ($\frac{1}{2}\lambda$, $\frac{3}{2}\lambda$, $\frac{5}{2}\lambda$, etc.) farther from one source than from the other. This condition can be written $S_1Q - S_2Q = (n + \frac{1}{2})\lambda$.

The distance from the sources to a detection point may be much larger than the source separation d. In that case, there is a simple relationship between the node position, the wavelength λ, and the separation d. The wavelength can be calculated from measurements of the positions of nodal lines. (The details of the relationship and the calculation of wavelength are described in the *Student Guide* for this chapter.)

This analysis allows you to calculate from simple measurements made on an interference pattern the wavelength of any wave. It applies to water ripples, sound, light, etc. You will find this method very useful later. One important thing you can do now is find λ for a real case of interference of waves in the laboratory. This practice will help you later in finding the wavelengths of other kinds of waves.

8.7 STANDING WAVES

If you and a partner shake both ends of a taut rope with the same frequency and same amplitude, you will observe an interesting result. The interference of the identical waves coming from opposite ends results in certain points on the rope not moving at all! In between these nodal points, the entire rope oscillates up and down. But there is no apparent propagation of wave patterns in either direction along the rope. This phenomenon is called a *standing wave* or a *stationary wave*. The remarkable thing behind this phenomenon is that the standing oscillation you observe is really the effect of two *traveling* waves.

To see this, let us start with a simpler case. To make standing waves on a rope (or Slinky), there do not have to be two people shaking the opposite ends. One end can be tied to a hook on a wall or to a door knob. The train of waves sent down the rope by shaking one end back and forth will reflect back from the fixed hook. These reflected waves interfere with the new, oncoming waves, and it is this interference that can produce a standing pattern of nodes and oscillation. In fact, you can go further and tie both ends of a string to hooks and pluck (or bow) the string. From the plucked point a pair of waves go out in opposite directions, and are then reflected from the ends. The interference of these reflected waves that travel in opposite directions can produce a standing pattern just as before. The strings of guitars, violins, pianos, and all other stringed instruments act in just this fashion. The energy given to the strings sets up standing waves. Some of

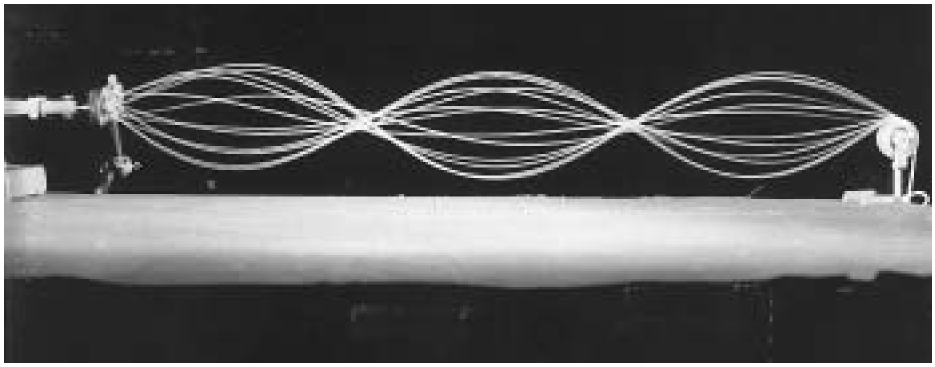


FIGURE 8.19 Time exposure: A vibrator at the left produces a wave train that runs along the rope and reflects from the fixed end at the right. The sum of the oncoming and reflected waves is a standing wave pattern.

the energy is then transmitted from the vibrating string to the body of the instrument; the sound waves sent forth from there are at essentially the same frequency as the standing waves on the string.

The vibration frequencies at which standing waves can exist depend on two factors. One is the speed of wave propagation along the string. The other is the length of the string. A connection between the length of string and the musical tone it can generate was recognized over 2000 years ago, and contributed indirectly to the idea that nature is built on mathematical principles. Early in the development of musical instruments, people learned how to produce certain pleasing harmonies by plucking a string constrained to different lengths by stops. Harmonies result if the string is plucked while constrained to lengths in the ratios of small whole numbers. Thus, the length ratio 2:1 gives the octave, 3:2 the musical fifth, and 4:3 the musical fourth. This striking connection between musical harmony and simple numbers (integers) encouraged the Pythagoreans to search for other numerical ratios or harmonies in the Universe. This Pythagorean ideal strongly affected Greek science, and many centuries later inspired much of Kepler's work. In a general form, the ideal flourishes to this day in many beautiful applications of mathematics to physical experience.

The physical reason for the appearance of harmonious notes and the relation between them were not known to the Greeks. But using the superposition principle, we can understand and define the harmonic relationships much more precisely. First, we must stress an important fact about standing wave patterns produced by reflecting waves from the boundaries of a medium. One can imagine an unlimited variety of waves traveling back and forth. But, in fact, *only certain wavelengths (or frequencies) can produce*

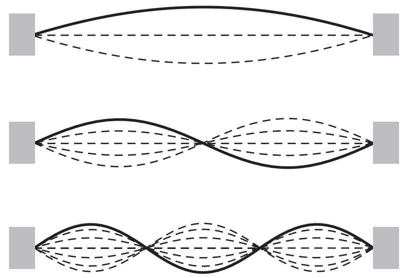


FIGURE 8.20 Standing wave patterns: first three nodes.

standing waves in a given medium. In the example of a stringed instrument, the two ends are fixed and so must be nodal points. This fact puts an upper limit on the length of standing waves possible on a fixed rope of length l. Such waves must be those for which one-half wavelength just fits on the rope ($l = \lambda/2$). Shorter waves also can produce standing patterns, having more nodes. But *always*, some whole number of one-half wavelengths must just fit on the rope, so that $l = n\lambda/2$. For example, in the first of the three illustrations in Figure 8.20, the wavelength of the interfering waves, λ_1, is just $2l$. In the second illustration, λ_2 is $\frac{1}{2}(2l)$; in the third, it is $\frac{1}{3}(2l)$. The general mathematical relationship giving the expression for all possible wavelengths of standing waves on a fixed rope is thus

$$\lambda_n = \frac{2l}{n},$$

where n is a whole number representing the harmonic. Or we can write simply,

$$\lambda_n \propto \frac{1}{n}.$$

That is, if λ_1 is the longest wavelength possible, the other possible wavelengths will be $\frac{1}{2}\lambda_1$, $\frac{1}{3}\lambda_1$, . . . $(1/n)\lambda_1$. Shorter wavelengths correspond to higher frequencies. Thus, *on any bounded medium, only certain frequencies of standing waves can be set up*. Since frequency f is inversely proportional to wavelength, $f \propto 1/\lambda$, we can rewrite the expression for all possible standing waves on a plucked string as

$$f_n \propto n.$$

VIBRATION OF A DRUM

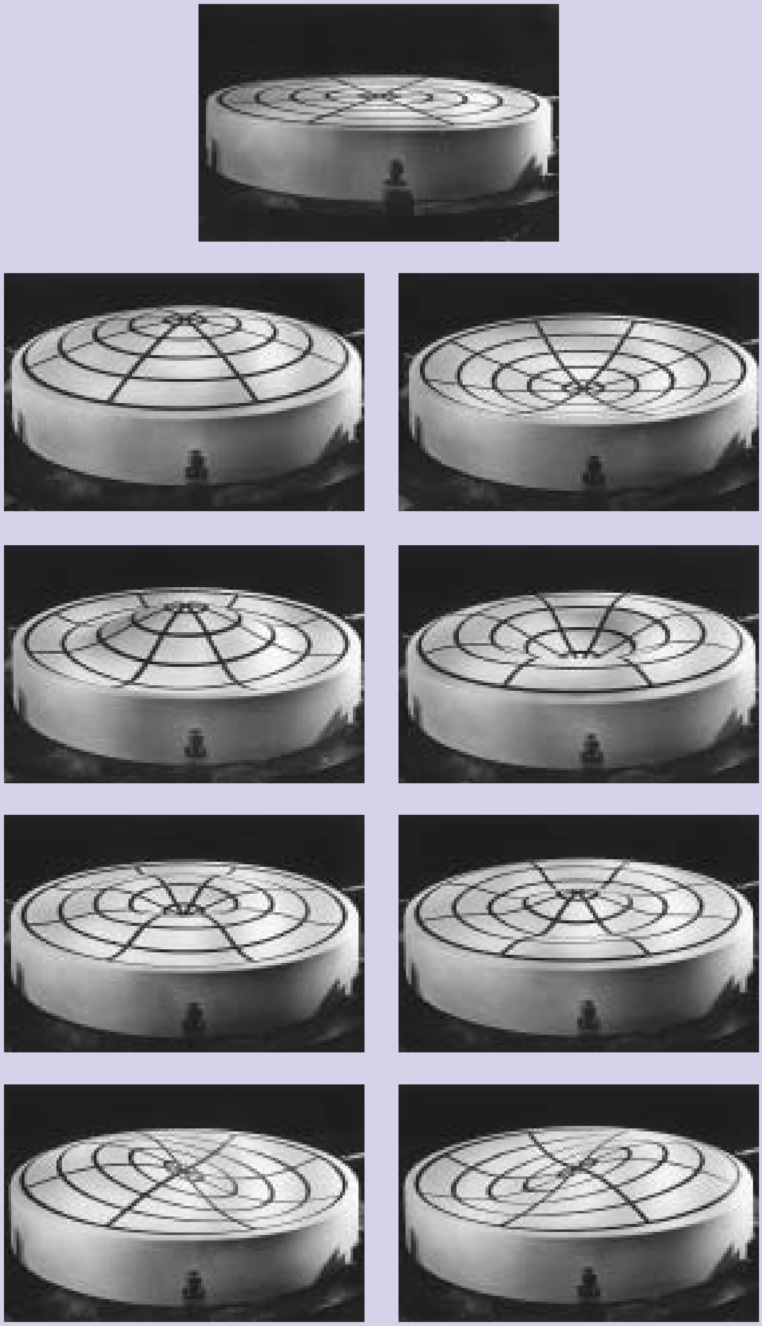


FIGURE 8.21 A marked rubber "drumhead" vibrating in several of its possible modes. Here we see side-by-side pairs of still photographs from three of the symmetrical modes and from an anti-symmetrical mode.

In other circumstances, f_n may depend on n in some other way. The lowest possible frequency of a standing wave is usually the one most strongly present when the string vibrates after being plucked or bowed. If f_1 represents this lowest possible frequency, then the other possible standing waves would have frequencies $2f_1$, $3f_1$, . . . , nf_1. These higher frequencies are called "overtones" of the "fundamental" frequency f_1. On an "ideal" string, there are in principle an unlimited number of such frequencies, but each being a simple multiple of the lowest frequency.

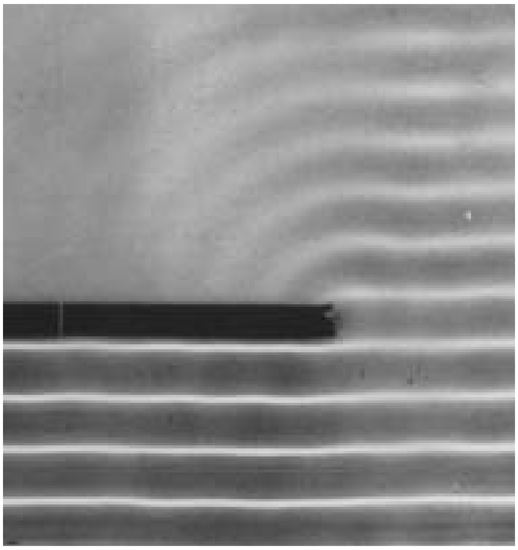
In real media, there are practical upper limits to the possible frequencies. Also, the overtones are not exactly simple multiples of the fundamental frequency; that is, the overtones are not strictly "harmonic." This effect is still greater in systems more complicated than stretched strings. In a flute, saxophone, or other wind instrument, an *air column* is put into standing wave motion. Depending on the shape of the instrument, the overtones produced may not be even approximately harmonic.

As you might guess from the superposition principle, standing waves of different frequencies can exist in the same medium at the same time. A strongly plucked guitar string, for example, oscillates in a pattern which is the superposition of the standing waves of many overtones. The relative oscillation energies of the different instruments determine the "quality" of the sound they produce. Each type of instrument has its own balance of overtones. This is why a violin sounds different from a trumpet, and both sound different from a soprano voice, even if all are sounding at the same fundamental frequency.

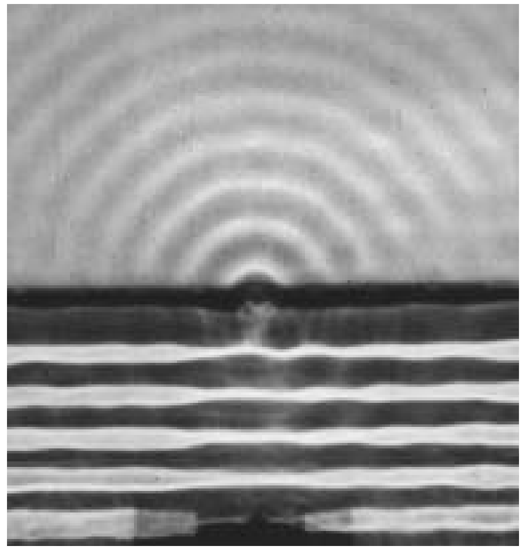
8.8 WAVE FRONTS AND DIFFRACTION

Unlike baseballs, bullets, and other pieces of matter in motion, waves can go around corners. For example, you can hear a voice coming from the other side of a hill, even though there is nothing to reflect the sound to you. You are so used to the fact that sound waves do this that you scarcely notice it. This spreading of the energy of waves into what you might expect to be "shadow" regions is called *diffraction*.

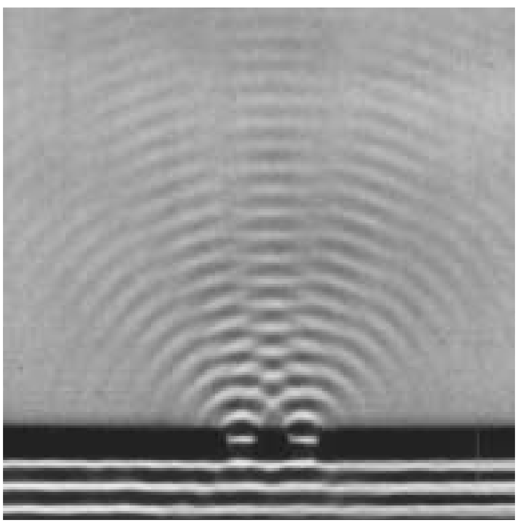
Once again, water waves will illustrate this behavior most clearly. From among all the arrangements that can result in diffraction, we will concentrate on two. The first is shown in the second photograph in Figure 8.22. Straight water waves (coming from the bottom of the second picture) are diffracted as they pass through a narrow slit in a straight barrier. Notice that the slit is less than one wavelength wide. The wave emerges and spreads in all directions. Also notice the *pattern* of the diffracted wave. It is basi-



(a)



(b)



(c)

FIGURE 8.22 (a) Diffraction of water ripples around the edge of a barrier; (b) diffraction of ripples through a narrow opening; (c) diffraction of ripples through two narrow openings.

cally the same pattern a vibrating point source would set up if it were placed where the slit is.

The bottom photograph shows a second barrier arrangement. Now there are two narrow slits in the barrier. The pattern resulting from superposition of the diffracted waves from both slits is the same as that produced by two point sources vibrating in phase. The same kind of result is obtained when many narrow slits are put in the barrier; that is, the final pattern just matches that which would appear if a point source were put at the center of each slit, with all sources in phase.

One can describe these and all other effects of diffraction if one understands a basic characteristic of waves. This characteristic was first stated by Christiaan Huygens in 1678 and is now known as *Huygens' principle*. To understand it one first needs the definition of a *wave front*.

For a water wave, a wave front is an imaginary line along the water's surface, with every point along this line in exactly the same stage of vibration; that is, all points on the line are *in phase*. For example, crest lines are wave fronts, since all points on the water's surface along a crest line are in phase. Each has just reached its maximum displacement upward, is momentarily at rest, and will start downward an instant later.

Since a sound wave spreads not over a surface but in three dimensions, its wave fronts form not lines but surfaces. The wave fronts for sound waves from a very small source are very nearly spherical surfaces, just as the wave fronts for ripples, made by a very small source of waves on the surface of water, are circles.

Huygens' principle, as it is generally stated today, is that *every point on a wave front may be considered to behave as a point source for waves generated in the direction of the wave's propagation*. As Huygens said:

> There is the further consideration in the emanation of these waves, that each particle of matter in which a wave spreads, ought not to communicate its motion only to the next particle which is in the straight line drawn from the [source], but that it also imparts some of it necessarily to all others which touch it and which oppose themselves to its movement. So it arises that around each particle there is made a wave of which that particle is the center.

The diffraction patterns seen at slits in a barrier are certainly consistent with Huygens' principle. The wave arriving at the barrier causes the water in the slit to oscillate. The oscillation of the water in the slit acts as a source for waves traveling out from it in all directions. When there are two slits and the wave reaches both slits in phase, the oscillating water in each slit acts like a point source. The resulting interference pattern is similar to the pattern produced by waves from two point sources oscillating in phase.

Consider what happens behind the breakwater wall as in the aerial photograph of the harbor. By Huygens' principle, water oscillation near the end of the breakwater sends circular waves propagating into the "shadow" region.

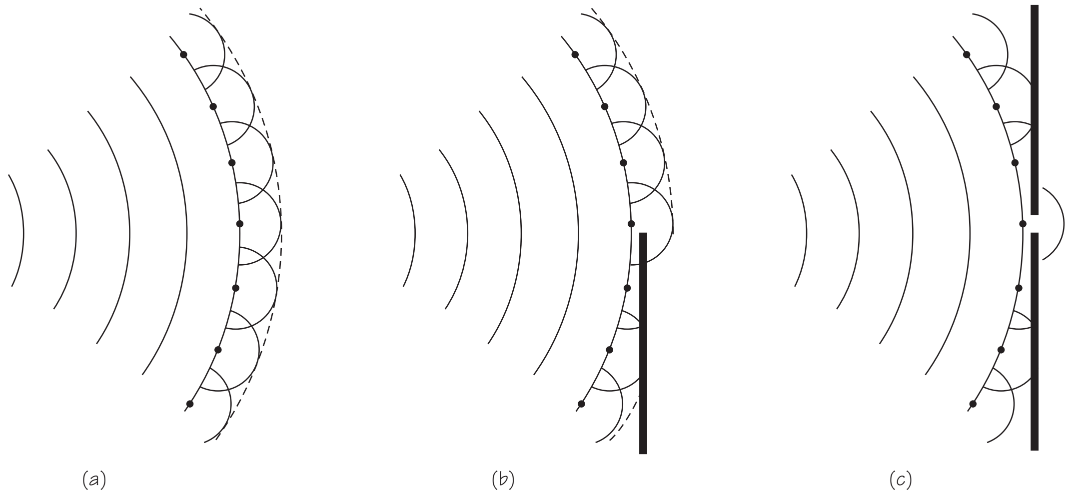


FIGURE 8.23 (a) Each point on a wave front can be thought of as a point source of waves. The waves from all the point sources interfere constructively only along their envelope, which becomes the new wave front. (b) When part of the wave front is blocked, the constructive interference of waves from points on the wave front extends into "shadow" region. (c) When all but a very small portion of a wave front is blocked, the wave propagating away from that small portion is nearly the same as that from a point source.

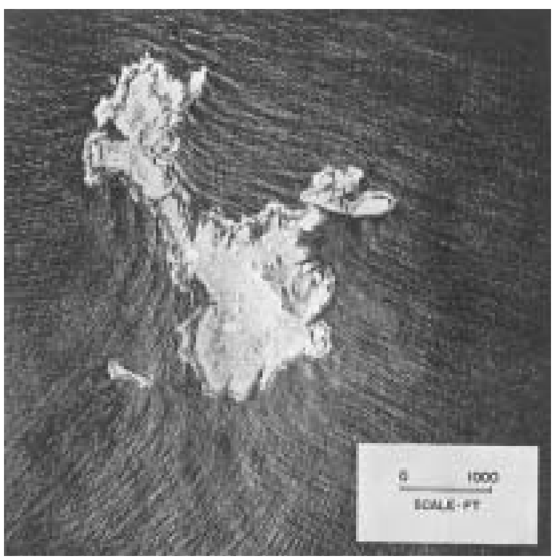


FIGURE 8.24 Reflection, refraction, and diffraction of water waves around an island.

You can understand all diffraction patterns if you keep both Huygens' principle and the superposition principle in mind. For example, consider a slit wider than one wavelength. In this case, the pattern of diffracted waves contains no nodal lines unless the slit width is about λ (see the series of images in Figure 8.25).

Figure 8.26 helps to explain why nodal lines appear. There must be points like P that are just λ farther from side A of the slit than from side B; that is, there must be points P for which distance AP differs from distance BP by exactly λ. For such a point, AP and OP differ by one-half wavelength, $\lambda/2$. By Huygens' principle, you may think of points A and O as in-phase point sources of circular waves. But since AP and OP differ by $\lambda/2$, the two waves will arrive at P completely out of phase. So, according to the superposition principle, the waves from A and O will cancel at point P.

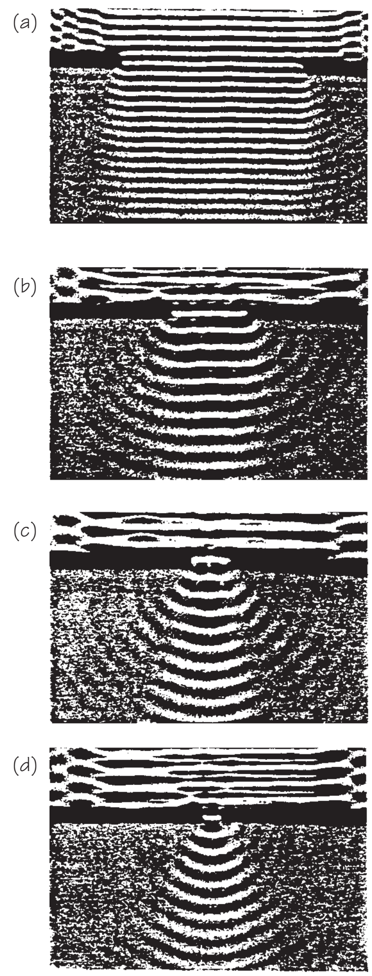


FIGURE 8.25 Single-slit diffraction of water waves with slits of different sizes.

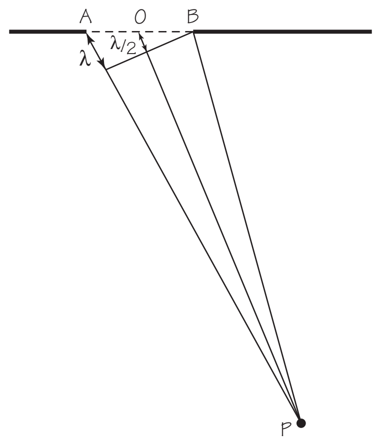


FIGURE 8.26 Diagram of a single slit showing how nodal lines appear (see text).

This argument also holds true for the pair of points consisting of the first point to the right of A and the first to the right of O. In fact, it holds true for *each* such matched pair of points, all the way across the slit. The waves originating at each such pair of points all cancel at point P. Thus, P is a nodal point, located on a nodal line. On the other hand, if the slit width is less than λ, then there can be *no* nodal point. This is obvious, since no point can be a distance λ farther from one side of the slit than from the other. Slits of widths less than λ behave nearly as point sources. The narrower they are, the more nearly their behavior resembles that of point sources.

One can compute the wavelength of a wave from the interference pattern set up where diffracted waves overlap. (See the *Student Guide* for such a calculation.) This is one of the main reasons for interest in the interference of diffracted waves. By locating nodal lines formed beyond a set of slits, you can calculate λ even for waves that you cannot see. Moreover, this

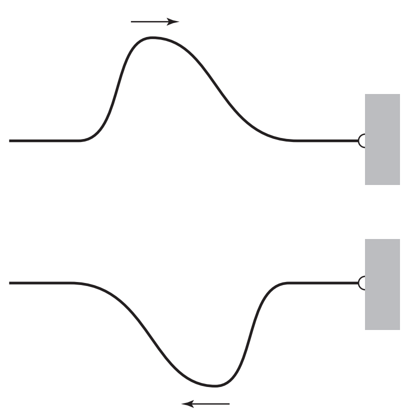


FIGURE 8.27 Wave on rope reflected from a wall to which it is attached.

is one very important way of identifying a series of unknown rays as consisting of either particles or waves.

For two-slit interference, the larger the wavelength compared to the distance between slits, the more the interference pattern spreads out. That is, as λ increases or d decreases, the nodal and antinodal lines make increasingly large angles with the straight-ahead direction. Similarly, for single-slit diffraction, the pattern spreads when the ratio of wavelength to the slit width increases. In general, diffraction of longer wavelengths is more easily detected. Thus, when you hear a band playing around a corner, you hear the bass drums and tubas better than the piccolos and cornets, even if they actually are playing equally loudly.

8.9 REFLECTION

You have seen that waves can pass through one another and spread around obstacles in their paths. Waves also are reflected, at least to some degree, whenever they reach any boundary of the medium in which they travel. Echoes are familiar examples of the reflection of sound waves. All waves share the property of being capable of reflection. Again, the superposition principle will help understand what happens when reflection occurs.

Suppose that one end of a rope is tied tightly to a hook securely fastened to a massive wall. From the other end, a pulse wave is sent down the rope toward the hook. Since the hook cannot move, the force exerted by the rope wave can do no work on the hook. Therefore, the energy carried in the wave cannot leave the rope at this fixed end. Instead, the wave bounces back, is *reflected*, ideally with the same energy.

What does the wave look like after it is reflected? The striking result is that the wave seems *to flip upside down* on reflection. As the wave comes in from left to right and encounters the fixed hook, it pulls up on it. By Newton's third law, the hook must exert a force on the rope in the opposite direction while reflection is taking place. The details of how this force varies in time are complicated, but the net effect is that an inverted wave of the same form is sent back down the rope.

The three sketches in Figure 8.28 show the results of reflection of water waves from a straight wall. You can check whether the sketches are accurate by trying to reproduce the effect in a sink or bathtub. Wait until the water is still, then dip your fingertip briefly into the water, or let a drop fall into the water. In the upper part of the sketch, the outer crest is approaching the barrier at the right. The next two sketches show the po-

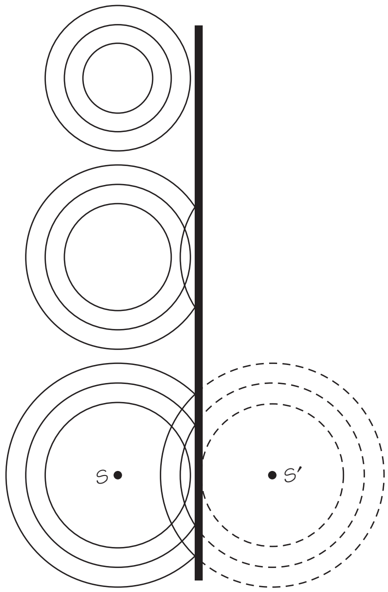


FIGURE 8.28 Two-dimensional circular wave reflecting from a wall.

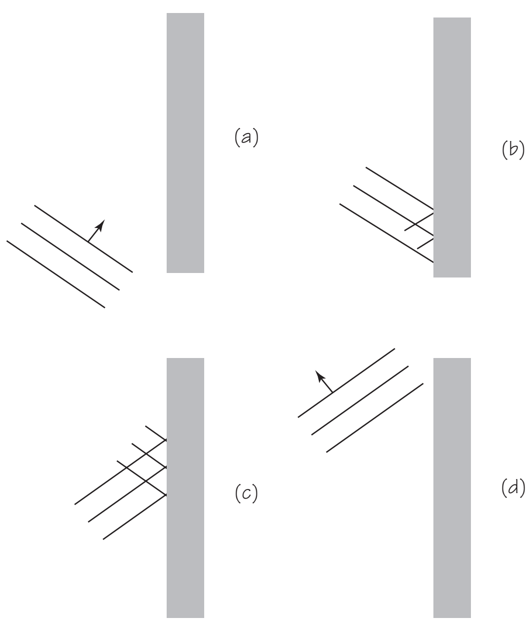


FIGURE 8.29 Two-dimensional plane wave reflecting from a wall.

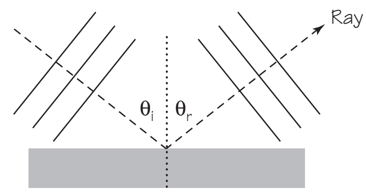


FIGURE 8.30 Angles of incidence and reflection.

sitions of the crests after first one and then two of them have been reflected. Notice the dashed curves in the last sketch. They show that the reflected wave appears to originate from a point S′ that is as far behind the barrier as S is in front of it. The imaginary source at point S′ is called the *image* of the source S.

Reflection of circular waves is studied first, because that is what you usually notice first when studying water waves. But it is easier to see a general principle for explaining reflection by observing a straight wave front, reflected from a straight barrier. The ripple-tank photograph (Figure 8.32a) shows one instant during such a reflection. (The wave came in from the upper left at an angle of about 45°.) The sketches below indicate in more detail what happens as the wave crests reflect from the straight barrier.

The description of wave behavior is often made easier by drawing lines perpendicular to the wave fronts. Such lines, called *rays*, indicate the direction of propagation of the wave. Notice Figure 8.30 for example. Rays have been drawn for a set of wave crests just before reflection and just after reflection from a barrier. The straight-on direction, perpendicular to the reflecting surface, is shown by a dotted line. The ray for the *incident*

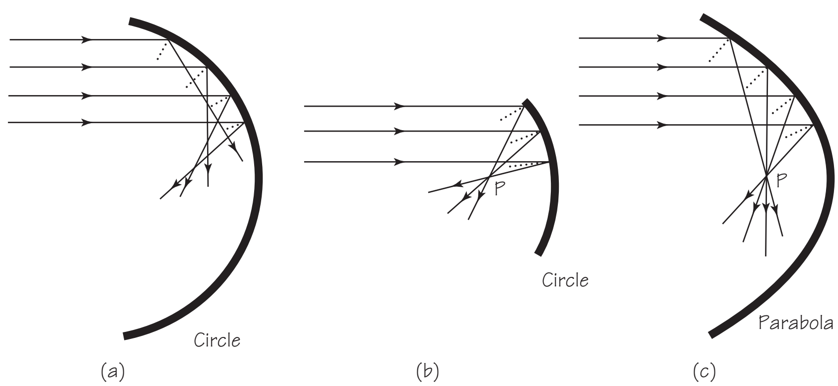
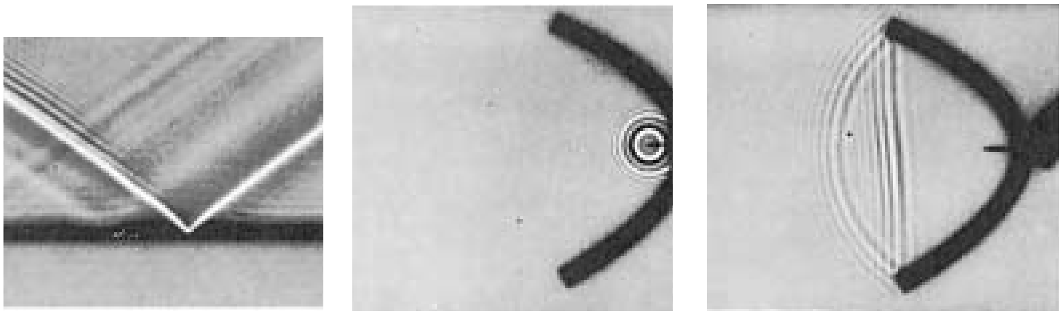


FIGURE 8.31 Rays reflecting from concave surfaces (circular and parabolic).



(a) (b) (c)

FIGURE 8.32 (a) Reflection of a water wave from a wall; (b) and (c) ripple tank photographs showing how circular waves produced at the focus of a parabolic wall are reflected from the wall into straight waves.

crests makes an angle θ_i with the straight-on direction. The ray for the *reflected* crests makes an angle θ_r with it. The *angle of reflection* θ_r is equal to the *angle of incidence* θ_i; that is,

$$\theta_r = \theta_i.$$

This is an experimental fact, which you can easily verify.

Many kinds of wave reflectors are in use today. One can find them in radar antennae or infrared heaters. Figure 8.31 (a) and (b) shows how straight-line waves reflect from two circular reflectors. A few incident and reflected rays are shown. (The dotted lines are perpendicular to the barrier surface.) Rays reflected from the half-circle (a) head off in all directions. However, rays reflected from a small segment of the circle (b) come close to meeting at a single point. A barrier with the shape of a parabola (c) focuses straight-line *rays*, quite precisely at a point—which is to say that a parabolic surface reflects *plane waves* to a sharp focus. An impressive example is a radio telescope. Its huge parabolic surface reflects faint radio waves from space to focus on a detector. Another example is provided by the dish used for satellite TV reception.

The wave paths indicated in the sketches could just as well be reversed. For example, spherical waves produced at the focus become plane waves when reflected from a parabolic surface. The flashlight and automobile headlamp are familiar applications of this principle. In them, white-hot wires placed at the focus of parabolic reflectors produce almost parallel beams of light.

RADAR WAVES AND TECHNOLOGY

One of the highly useful wave phenomena we shall encounter in Chapter 12 is the propagation and reflection of electromagnetic waves, such as light and microwaves. An example of the latter, as a preview of the general usefulness of the idea of wave propagation, is Radar.

Radar (an acronym for Radio Detection and Ranging) is an electromagnetic sensor for detecting, locating, tracking, and identifying various kinds of objects at various distances. The most popular form of radar signal is made up of short continual pulses, and the shorter the width of this pulse, the more accurate the radar is at locating the target

Radar, developed during World War II, is credited with being the key technology that prevented a victory by the German air force, especially during its bombing campaign on cities in England. It shifted the course of the war, and forever changed the face of military, astronomical, and weather technology.

Radar is now used for innumerable tasks, all of which require some form of detection at distance: police detection of speeders, air traffic controllers following the path of aircraft, satellite detection of topography on Earth and on other bodies in the solar system—all utilize the basic principles of radar. These principles rest on two fundamental effects of radio waves, the echo effect and the Doppler shift.

The echo is a very familiar phenomenon—shout out your name in a large empty room and the walls seem to shout it back. This type of echo results from the reflection of sound waves off a surface. The same effect can be obtained with radio waves, which travel at the speed of ordinary (visible) light in space. A pulse of radio waves sent out from an antenna will reflect from any object it hits, and part of the wave will return to where it originated. The time it takes between the emission of the pulse and the reception of the reflected part of the pulse can be used to determine the distance between the point and the reflecting surface. Thus the radar stations in England could be alerted that a hostile aircraft was present even if it was still far away, and fighter planes could scramble to fight off the expected attack.

The Doppler shift, also common in everyday life, occurs when waves of any kind are emitted or reflected by a moving body. (Everyone has experienced it as the shift in frequency of a car horn or a train whistle while in motion.) If waves sent out from a point are reflected by a moving body, the returning waves will appear to have a higher frequency as the object moves toward the original point, and a lower frequency as the object moves away from it. Therefore measuring the Doppler shift of reflected waves can be used to determine quickly the speed and direction of the reflecting surface.

Since these principles apply to sound waves, it is possible to make a "sound radar," or Sonar. That device works well enough in water, and has been used with great success to detect and trace submarines. But sonar is impractical for use in the air, because there, ordinary sound waves travel less far, and their echo would be too faint to be useful in precise detections.

After a radar transmitter has sent out a short burst, or pulse, of radio waves, the transmitter shuts off and a receiver is turned on, measuring the time and Doppler shift of the detected reflection. From monitoring the movement of cars on Route 1 to mapping the surface of Venus, radar has given us a new way to see the world.

In a standard radar system there is a transmitter, which produces a signal in the form of electromagnetic energy that is sent to the

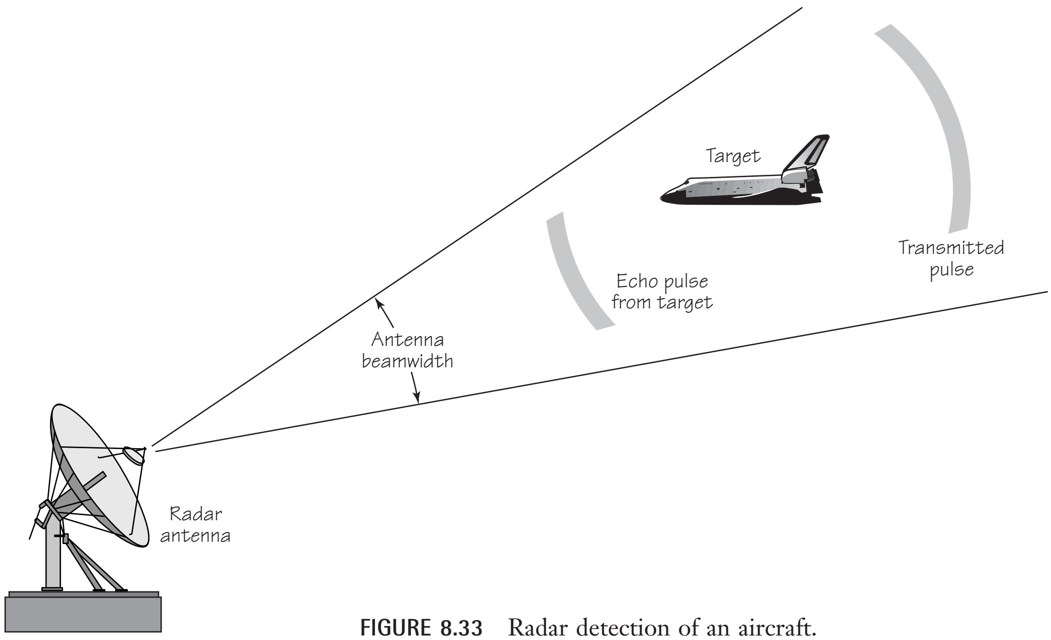


FIGURE 8.33 Radar detection of an aircraft.

antenna. A radar antenna is commonly a parabolic reflector, with a small antenna placed at the center of the parabola to illuminate the surface of the reflector. The electromagnetic energy is radiated from this surface in the form of a narrow beam. When this electromagnetic beam passes over a target, the object reflects an amount of the radiated energy back to the radar, where a receiver filters and amplifies the echoes. The single processor then differentiates the signals obtained from a target from those produced by clutter, such as atmospheric effects. A computer then processes this information and the output is displayed on a monitor. With the information that is provided by the radar it is possible to calculate the location of the target in terms of range and angular direction.

Development of Radar

The scientific origins of radar can be found in the work of the German physicist Heinrich Hertz. Hertz showed, as Maxwell's equations had predicted, that radio waves exist, and in the same way as light waves, are reflected from metallic objects. However, not until the 1930s did radar become a focus for scientific research, largely in response to the fear of war. The most important needs of a radar transmitter are often conflicting. For example, to guarantee the greatest accuracy a transmitter must be powerful and have a wide bandwidth, but at the same time it cannot be too heavy or too large, to fit into an aircraft or ship. One of the main objectives for researchers working on radar during World War II was to solve these conflicts by developing a system that was small enough to fit in fighter aircraft but worked at higher frequencies.

The benefits of using microwaves, waves of wavelength 1 m or less, in radar technology had been recognized for some time. They included greater accuracy, increased efficiency at reducing clutter, and an expanded potential

RADAR WAVES AND TECHNOLOGY (*Continued*)

for discriminating between targets. The cavity magnetron, which was invented in Britain in 1939 at the University of Birmingham, opened up the possibility of using microwaves and was small enough to fit in the palm of a hand. In 1940, as part of a transatlantic scientific exchange, a prototype of the magnetron was sent to America where it soon became the basis for some of the most important work on radar during World War II. As a direct spin-off of this exchange, a new laboratory, known as the Radiation Laboratory, was founded at the Massachusetts Institute of Technology that helped to develop more than 150 radar systems between 1940 and 1950.

Current Uses of Radar Technology

Radar technology is utilized today in many different ways. Armed forces all over the world continue to use radar as a detector of aircraft and ships, as they did in World War II. However, it is now also used to distinguish many different kinds of targets, to control and guide weapons, and to provide information on the damage caused by these weapons. Sophisticated weather forecasting techniques are also highly dependent on radar technology in the form of remote sensing. Radar technology is also crucial to civilian air traffic control, where it provides information on air traffic and weather conditions, as well as a tool for guiding pilots in unfavorable weather conditions.

Further Reading

R. Buderi, *The Invention that Changed the World* (New York: Touchstone Books, 1998).

8.10 REFRACTION

What happens when a wave propagates from one medium to another medium in which its speed of propagation is different? Look at the simple situation pictured in Figure 8.35. Two one-dimensional pulses approach a boundary separating two media. The speed of the propagation in medium 1 is greater than it is in medium 2. Imagine the pulses to be in a light rope (medium 1) tied to a relatively very heavy rope (medium 2). Part of each pulse is reflected at the boundary. This reflected component is flipped upside down relative to the original pulse. (Recall the inverted reflection at a hook in a wall discussed earlier. The heavier rope here tends to hold the boundary point fixed in just the same way.) But what happens to that part of the wave that continues into the second medium?

As shown in the figure, the transmitted pulses are closer together in medium 2 than they are in medium 1. The reason is that the speed of the pulses is less in the heavier rope. So the second pulse, while still in the light

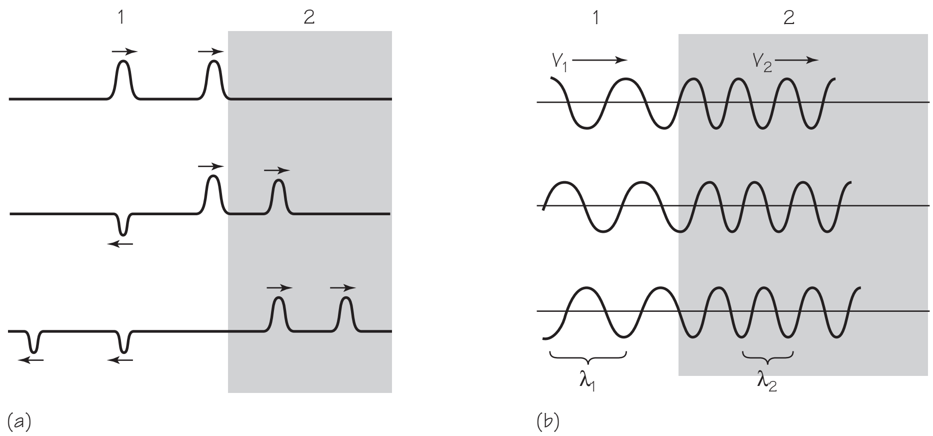


FIGURE 8.34 (a) Pulses encountering a boundary between two different media. (b) continuous wave train crossing the boundary between two different media. In both cases, the speed of propagation is less in medium 2.

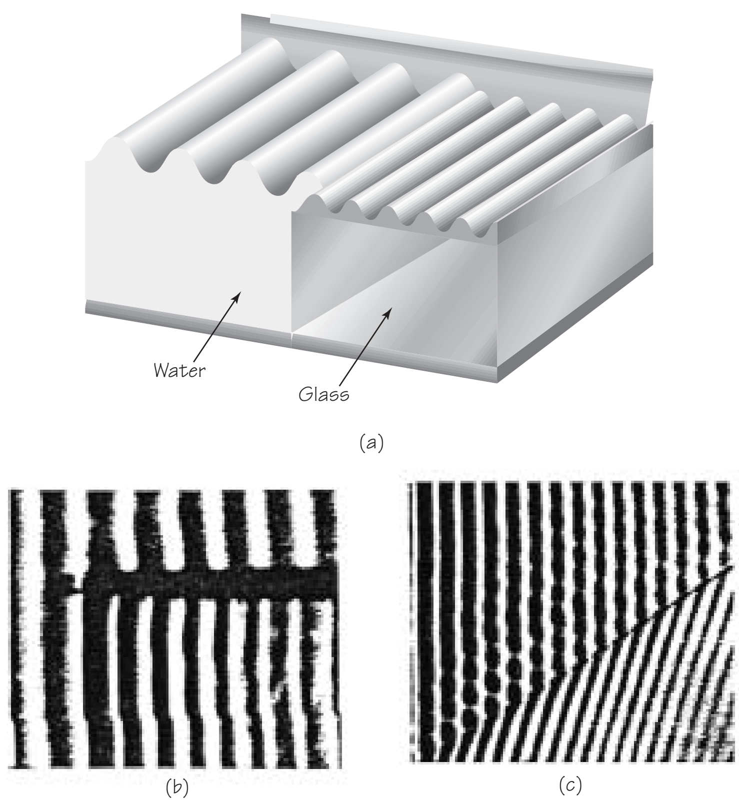


FIGURE 8.35 (a) Cross section of waves in a ripple tank; (b) ripples on water (coming from the left) encounter the shallow region over the corner of a submerged glass plate; (c) ripples on water (coming from the left) encounter a shallow region over a glass plate placed at an angle to the wave fronts.

rope, is catching up with the one that is already in the heavy rope. For the same reason, each separate pulse is itself squeezed into a narrower form; that is, when the front of a pulse has entered the region of less speed, the back part of it is still moving ahead with greater speed.

Something of the same sort happens to a periodic wave at such a boundary. This situation is pictured in Figure 8.35b. For the sake of simplicity, assume that all of the wave is transmitted and none of it is reflected. Just as the two pulses were brought closer and each pulse was squeezed and narrowed, the periodic wave pattern is squeezed together, too. Thus, the wavelength λ_2 of the transmitted wave is shorter than the wavelength λ_1 of the incoming, or incident, wave.

Although the wavelength changes when the wave passes across the boundary, the frequency of the wave cannot change. If the rope is unbroken, the pieces immediately on either side of the boundary must go up and down together. The frequencies of the incident and transmitted waves must, then, be equal. We can simply label both of them *f*.

The wavelength, frequency, and speed relationship for both the incident and transmitted waves can be written separately

$$\lambda_1 f = v_1 \qquad \text{and} \qquad \lambda_2 f = v_2.$$

Dividing one of these equations by the other and eliminating *f*:

$$\frac{\lambda_1}{\lambda_2} = \frac{v_1}{v_2}.$$

This equation tells us that the ratio of the wavelengths in the two media equals the ratio of the speeds.

The same sort of thing happens when water ripples cross a boundary. Experiments show that the ripples move more slowly in shallower water. A piece of plate glass is placed on the bottom of a ripple tank to make the water shallower there. This creates a boundary between the deeper and shallower part (medium 1 and medium 2). Figure 8.35a shows the case where this boundary is parallel to the crest lines of the incident wave. As with rope waves, the wavelength of water waves in a medium is proportional to the speed in that medium.

Water waves offer a possibility not present for rope waves. The crest lines can approach the boundary at any angle, not only head-on. Photograph (c) shows such an event. A ripple-tank wave approaches the boundary at an angle. The wavelength and speed, of course, change as the wave passes across the boundary. The *direction* of the wave propagation also changes. As each

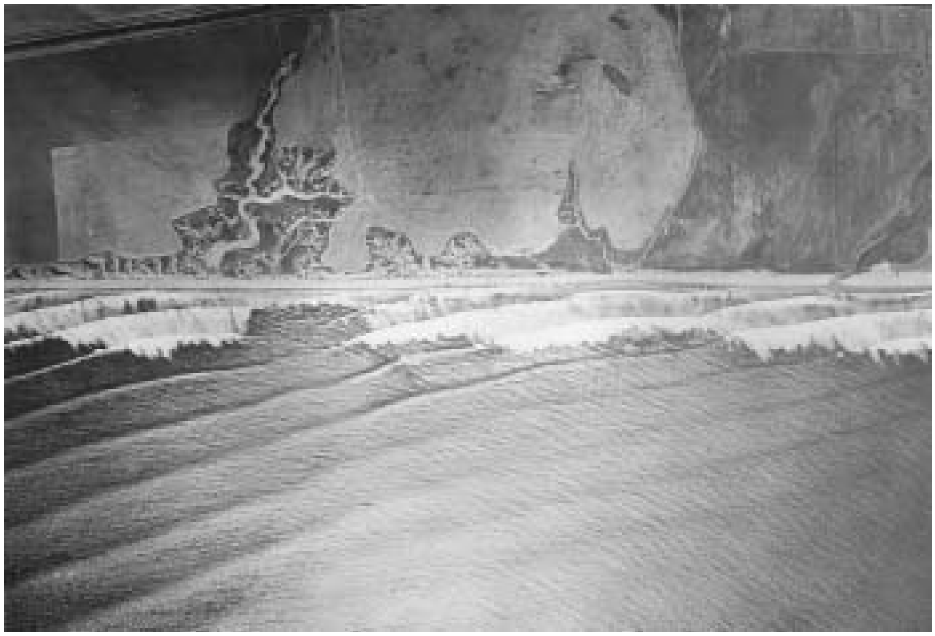


FIGURE 8.36 Aerial photograph of the refraction of ocean waves approaching shore.

part of a crest line in medium 1 enters medium 2, its speed decreases, and it starts to lag behind. In time, the directions of the whole set of crest lines in medium 2 are changed from their directions in medium 1.

This phenomenon is called *refraction*. Refraction occurs whenever a wave passes into a medium in which the wave velocity is different. In this case, the wave fronts are turned (refracted) so that they are more nearly parallel to the boundary. (See Figures 8.35a and 8.35b.) This accounts for something that you may have noticed if you have been at an ocean beach. No matter in what direction the waves are moving far from the shore, when they come near the beach that slopes gently into the deeper water, their crest lines are nearly parallel to the shoreline. A wave's speed is steadily reduced as it moves into water that gets gradually more shallow. So the wave is refracted continuously as if it were always crossing a boundary between different media, as indeed it is. The refraction of sea waves, coming from one direction, can be so great that wave crests can curl around a very small island with an all-beach shoreline and provide surf on all sides.

The slowing of starlight by increasingly dense layers of the atmosphere produces refraction that changes the apparent position of the star.

8.11 SOUND WAVES

Sound waves are mechanical disturbances that propagate through a medium, such as the air. Typically, sound waves are *longitudinal* waves, producing changes of density and pressure in the medium through which they travel. The medium can be a solid, liquid, or gas. If the waves strike the ear, they cause the ear drum to vibrate, which produces a signal in the acoustic nerve that can produce the sensation of hearing. The biology and psychology of hearing, as well as the physics of sound, are important to the science of acoustics. Here, of course, we will concentrate on sound as an example of wave motion. Sound has all the properties of wave motion considered so far. It exhibits reflection, refraction, diffraction, and the same relations among frequency, wavelength, and propagation speed and interference. Only the property of polarization is missing, because sound waves are longitudinal, not transverse. In addition, sound waves travel faster in cold air than in hot air because of the increased density of the medium, air, when it is cold.

Vibrating sources for sound waves may be as simple as a tuning fork or as complex as the human larynx with its vocal cords. Tuning forks and some electronic devices produce a steady "pure tone." Most of the energy in such a tone is in simple harmonic motion at a single frequency. Frequency is often measured in units of hertz (Hz), where 1 Hz is one cycle (or oscillation) per second; 1 Hz = 1/s. (There is no unit for "cycle.")

The normal human ear can hear sound waves with frequencies between about 20 Hz and 15,000 Hz. Dogs can hear over a much wider range (15 Hz–50,000 Hz). Bats, porpoises, and whales generate and respond to frequencies up to about 120,000 Hz.

Loudness (or "volume") of sound is, like pitch, a psychological variable. Loudness is strongly related to the *intensity* of the sound. Sound intensity is a physical quantity. It is defined in terms of the energy carried by the wave and is usually measured in the number of watts per square centimeter transmitted through a surface perpendicular to the direction of motion of a wave front. The human ear can perceive a vast range of intensities of sound. Figure 8.37 illustrates this range. It begins at a level of 10^{-16} W/cm^2 (relative intensity = 1). Below this "threshold" level, the normal ear does not perceive sound. It is customary to measure loudness in decibels (db). The number of decibels is 10 times the exponent in the relative intensity of the sound. Thus, a jet plane at takeoff, making a noise of 10^{14} relative intensity, is said to emit noise at the 140-db level.

Levels of noise intensity about 10^{12} times threshold intensity can be felt as an uncomfortable tickling sensation in the normal human ear. Beyond

Relative intensity	*Sound*
1	Threshold of hearing
10^1	Normal breathing
10^2	Leaves in a breeze
10^3	
10^4	Library
10^5	Quiet restaurant
10^6	Two-person conversation
10^7	Busy traffic
10^8	Vacuum cleaner
10^9	Roar of Niagara Falls
10^{10}	Subway train
10^{11}	
10^{12}	Propeller plane at takeoff
10^{13}	Machine-gun fire
10^{14}	Small jet plane at takeoff
10^{15}	
10^{16}	Wind tunnel
10^{17}	Space rocket at lift-off

FIGURE 8.37 Loudness chart.

that, the sensation changes to pain and may damage the unprotected ear. Since many popular music concerts produce, in an auditorium, steady sound levels at this intensity (and above it for the performers), there are many cases of impaired hearing among people extensively exposed to such sound.

Often the simplest way of reducing noise is by *absorbing* it after it is produced but before it reaches your ears. Like all sound, noise is the energy of back and forth motion of the medium through which the noise travels. Noisy machinery can be muffled by padded enclosures in which the energy of noise is changed to heat energy, which then dissipates. In a house, a thick rug on the floor can absorb 90% of room noise. (A foot of fresh fluffy snow is an almost perfect absorber of noise outdoors. Cities and countrysides are remarkably hushed after a snowfall.)

It has always been fairly obvious that sound takes time to travel from source to receiver. By timing echoes over a known distance, the French mathematician Marin Mersenne in 1640 first computed the speed of sound in air. It took another 70 years before William Derham in England, comparing the flash and noise from cannons across 20 km, came close to the modern measurements. Sound in air at sea level at 20°C moves at about 344 m/s. As for all waves, the speed of sound waves depends on the properties of the medium: the temperature, density, and elasticity. Sound waves generally travel faster in liquids than in gases, and faster still in solids. In seawater, their speed is about 1500 m/s; in steel, about 5000 m/s; in quartz, about 5500 m/s.

Interference of sound waves can be shown in a variety of ways. In a large hall with hard, sound-reflecting surfaces, there will be "dead" spots. At these spots, sound waves coming together after reflection tend to cancel each other. Acoustic engineers must consider this in designing the shape, position, and materials of an auditorium. Another interesting and rather dif-

FIGURE 8.38 Boston Symphony concert hall.

ferent example of sound interference is the phenomenon known as *beats*. When two notes of slightly different frequency are heard together, they interfere. This interference produces beats, a rhythmic pulsing of the sound. Piano tuners and string players use this fact to tune two strings to the same pitch. They simply adjust one string or the other until the beats disappear.

Refraction of sound by different layers of air explains why you sometimes cannot hear the thunder after seeing lightning. Similar refraction of sound occurs in layers of water of different temperatures. Geologists use the refraction of sound waves to study the Earth's deep structure and to locate fossil fuels and minerals. Very intense sound waves are set up in the ground (as by dynamite blasts). The sound waves travel through the Earth and are received by detection devices at different locations. The path of the waves, as refracted by layers in the Earth, can be calculated from the relative intensities and times of sound received. From knowledge of the paths, estimates can be made of the composition of the layers.

As mentioned, diffraction is a property of sound waves. Sound waves readily bend around corners and barriers to reach the listener within range.

Sound waves reflect, as do rope or water waves, wherever they encounter a boundary between different media. The architectural features called "whispering galleries" show vividly how sound can be focused by reflection from curved surfaces. All these effects are of interest in the study of acoustics. Moreover, the proper acoustical design of public buildings is now recognized as an important function by all good architects.

So far in this chapter, you have studied the basic phenomena of mechanical waves, ending with the theory of sound propagation. The explanations of these phenomena were considered the final triumph of Newtonian mechanics as applied to the transfer of energy of particles in motion. Most of the general principles of acoustics were discovered in the 1870s. Since then, perhaps its most important influence on modern physics has been its effect on the imagination of scientists. The successes of acoustics encouraged them to take seriously the power of the wave viewpoint, even in fields far from the original one—the mechanical motion of particles that move back and forth or up and down in a medium.

We now turn to an especially important type of wave phenomenon—light.

B. LIGHT

8.12 WHAT IS LIGHT?

The conviction that the world and everything in it consists of *matter in motion* drove scientists prior to the twentieth century to search for mechanical models for light as well as heat; that is, they tried to imagine how the effects of light, heat, and other phenomena could be explained in detail as the action of material objects. For example, consider the way light bounces off a mirror. A model for this effect might picture light as consisting of particles of matter that behave somewhat like tiny ping-pong balls. On the other hand, light exhibits interference and diffraction, suggesting a model involving waves. Such mechanical models were useful for a time, but in the long run proved far too limited. Still, the search for these models led to many new discoveries, which in turn brought about important changes in science, technology, and society.

In most basic terms, light is a form of energy. The physicist can describe a beam of light by stating measurable values of its speed, wavelength or frequency, and intensity. But to scientists, as to all people, "light" also means brightness and shade, the beauty of summer flowers and fall foliage, of red sunsets, and of the canvases painted by masters. These are different ways

FIGURE 8.39 Roman temple in Evora, Portugal. Light beams travel in straight lines, as shown by the shadow lines.

of appreciating light. One way concentrates on light's measurable aspects, an approach enormously fruitful in physics and technology. The other way concerns aesthetic responses to viewing light in nature or art. Still another way of considering light deals with the biophysical process of vision.

These aspects of light are not easily separated. Thus, in the early history of science, light presented more subtle and more elusive problems than did most other aspects of physical experience. Some Greek philosophers believed that light travels in straight lines at high speed and contains particles that stimulate the sense of vision when they enter the eye. For centuries after the Greek era, this particle model survived almost intact. Around 1500, Leonardo da Vinci, noting a similarity between sound echoes and the reflection of light, speculated that light might have a wave character.

A decided difference of opinion about the nature of light emerged among scientists of the seventeenth century. Some, including Newton, favored a model largely based on the idea of light as a stream of particles. Others, including Huygens, supported a wave model. By the late nineteenth century, there appeared to be overwhelming evidence in support of the wave model. This part of the chapter will deal with the question: *How accurate is a wave model in explaining the observed behavior of light*? The wave model will be taken as a hypothesis, and the evidence that supports it examined. Remember that any scientific model, hypothesis, or theory has two chief functions: to explain what is known, and to make predictions that can be tested experimentally. Both of these aspects of the wave model will be discussed. The result will be rather surprising. The wave model turns out to work splendidly to this day for all properties of light known before the twentieth century. But in Chapter 13 you will find that for some purposes a particle model must be used. Then in Chapter 15 *both* models will be combined, merging two apparently conflicting theories.

The ancient opinion, later proved by experiment, that light travels in straight lines and at high speed has been mentioned. The daily use of mirrors shows that light can also be reflected. Light can also be refracted, and it shows the phenomena of interference and diffraction, as well as other phenomena characteristic of waves, such as dispersion, polarization, and scattering. All of these characteristics lent strong support to the wave model of light.

8.13 PROPAGATION OF LIGHT

There is ample evidence that light travels in straight lines. A shadow cast by an object intercepting sunlight has well-defined outlines. Similarly, sharp shadows are cast by smaller sources closer by. The distant Sun and the nearby small source are approximate *point* sources of light. Such point sources produce sharp shadows.

Images can also demonstrate that light travels in straight lines. Before the invention of the modern camera with its lens system, a light-tight box with a pinhole in the center of one face was widely used. As the *camera obscura* (meaning "dark chamber" in Latin), the device was highly popular in the Middle Ages. Leonardo da Vinci probably used it as an aid in his sketching. In one of his manuscripts he says that "a small aperture in a window shutter projects on the inner wall of the room an image of the bodies which are beyond the aperture." He includes a sketch to show how the straight-line propagation of light explains the formation of an image.

It is often convenient to use a straight line to represent the direction in which light travels. The pictorial device of an infinitely thin *ray* of light is useful for thinking about light. But no such rays actually exist. A light beam

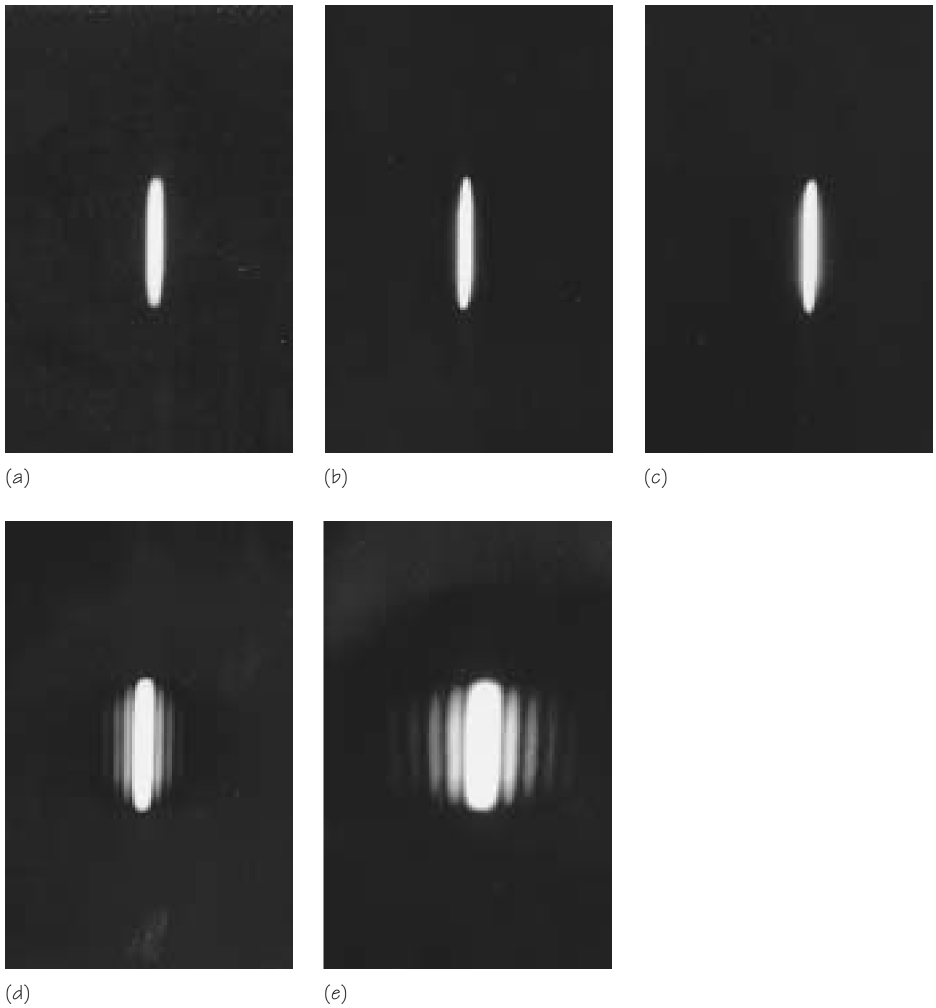


FIGURE 8.40 An attempt to produce a "ray" of light. To make the pictures, a parallel beam of red light was directed through increasingly narrow slits to a photographic plate. Of course, the narrower the slit, the less light gets through. This was compensated for by longer exposures in these photographs. The slit widths were (a) 1.5 mm; (b) 0.7 mm; (c) 0.4 mm; (d) 0.2 mm; and (e) 0.1 mm.

emerging from a good-sized hole in a screen is as wide as the hole. You might expect that if you made the hole extremely small, you would get a very narrow beam of light, ultimately just a single ray. This is not the case. Diffraction effects, such as those observed for water and sound waves, appear when the beam of light passes through a small hole. So an infinitely thin ray of light, although it is pictorially useful, cannot be produced in practice. But the idea can still be used in order to *represent the direction* in which a train of waves in a beam of light is traveling.

The beam of light produced by a laser comes as close as possible to the ideal case of a thin, parallel bundle of rays. As you will find in Chapter 14, light is often produced by the action of electrons within the atoms of its source. Lasers are designed in such a way that their atoms produce light in unison with one another, rather than individually and at random, as in other sources of light. As a result, light from a laser can yield a total beam of considerable intensity, and one that is much more nearly monochromatic—that is, of a single color—than light from any conventional source. In addition, since the individual wavelets from the atoms of a laser are produced simultaneously, they are able to interfere with each other constructively to produce a beam of light that is narrow and very nearly parallel. In fact, such light spreads out so little that thin beams emitted by lasers on Earth, when directed at the surface of the Moon 400,000 km away, have been found to produce spots of light only 1 m in diameter on the Moon.

Given that light can be considered to travel in straight lines, can we tell how fast it goes? Galileo discussed this problem in his *Two New Sciences* (published in 1638). He pointed out that everyday experiences might lead one to conclude that light propagates instantaneously. But these experiences, when analyzed more closely, really show only that light travels much faster than sound. For example, "when we see a piece of artillery fired, at a great distance, the flash reaches our eyes without lapse of time; but the sound reaches the ear only after a noticeable interval."

But how do you really know whether the light moved "without lapse of time" unless you have some accurate way of measuring the lapse of time? Galileo went on to describe an experiment by which two people standing on distant hills flashing lanterns might measure the speed of light. He concluded that the speed of light is probably finite, not infinite. Galileo, however, was not able to estimate a definite value for it.

Experimental evidence was first successfully related to a finite speed for light by a Danish astronomer, Ole Rœmer. Detailed observations of Jupiter's satellites had shown an unexplained irregularity in the times recorded between successive eclipses of the satellites by the planet. Such an eclipse was expected to occur at 45 s after 5:25 a.m. on November 9, 1676 (Julian calendar). In September of that year, Rœmer announced to the Academy of Sciences in Paris that the observed eclipse would be 10 min late. On November 9, astronomers at the Royal Observatory in Paris carefully studied the eclipse. Though skeptical of Rœmer's mysterious prediction, they reported that the eclipse did occur late, just as he had foreseen.

Later, Rœmer revealed the theoretical basis of his prediction to the baffled astronomers at the Academy of Sciences. He explained that the originally expected time of the eclipse had been calculated from observations made when Jupiter was near the Earth. But now Jupiter had moved farther away. The delay in the eclipse occurred simply because light from the area around Jupiter takes time to reach the Earth. Obviously, this time interval must be greater when the relative distance between Jupiter and the Earth in their orbits is greater. In fact, Rœmer estimated that it takes about 22 min for light to cross the Earth's own orbit around the Sun.

Shortly after this, the Dutch physicist Christian Huygens used Rœmer's data to make the first calculation of the speed of light. Huygens combined Rœmer's value of 22 min for light to cross the Earth's orbit with his own estimate of the diameter of the Earth's orbit. (This distance could be estimated for the first time in the seventeenth century, in good part as a result of the advances in astronomy described in Chapter 2.) Huygens obtained a value for the speed of light in space which, in modern units, is about 2×10^8 m/s. This is about two-thirds of the currently accepted value. The error in Huygens' value was due mainly to Rœmer's overestimate of the time interval. Scientists now know that it takes light only about 16 min to cross the Earth's orbit.

The speed of light has been measured in many different ways since the seventeenth century. The development of electronic devices in the twentieth century allowed very precise measurements, making the speed of light one of the most precisely measured physical constants known today. Because of the importance of the value of the speed of light in modern physical theories, physicists continue to improve their methods of measurement.

The most precise recent measurements indicate that the speed of light in vacuum is 2.99792458×10^8 m/s. The uncertainty of this value is thought to be about 1 m/s, or 0.000001%, the precision being limited only by the precision to which lengths can be measured (times can be measured to several orders of magnitude greater precision). The speed of light is usually represented by the symbol c; for most purposes it is sufficient to use the approximate value $c = 3 \times 10^8$ m/s. Indeed, there has been general agreement not to pursue endlessly the search for greater accuracy, and some physicists have accepted the speed of light (in vacuum) to be *by definition* 2.9979×10^8 m/s.

8.14 REFLECTION AND REFRACTION

What does each model of light predict will happen when light traveling in one medium (e.g., air) hits the boundary of another medium (e.g., glass)? The answers to this question depend on whether a particle or a wave the-

The incident, reflected, and refracted rays are all in the same plane, a plane perpendicular to the surface.

ory of light is used. Here is an opportunity to test which theory is better.

Reflection and refraction from the wave viewpoint were discussed in Sections 8.9 and 8.10. Recall the results obtained there and apply them to light:

1. A ray may be taken as the line drawn perpendicular to a wave's crest lines. Such a ray represents the direction in which a train of waves is traveling.
2. In reflection, the angle of incidence (θ_i) is equal to the angle of reflection (θ_r).
3. Refraction involves a change of wavelength and speed of the wave as it passes into another medium. When the speed decreases, the wavelength decreases, and the ray bends in a direction toward a line perpendicular to the boundary. This bending toward the perpendicular is observed, for example, when a ray of light passes from air to glass.

What about explaining the same observations by means of the particle model? To test this model, first consider the nature of the surface of glass. Though apparently smooth, it is actually a wrinkled surface. A powerful microscope would show it to have endless hills and valleys. If particles of light were at all similar to little balls of matter, then on striking such a wrinkled surface they would scatter in all directions. They would not be reflected and refracted as noted above. Therefore, Newton argued, there must actually be "some feature of the body which is evenly diffused over its surface and by which it acts upon the ray without immediate contact." Obviously, in the case of reflection, the acting force would have to be one that

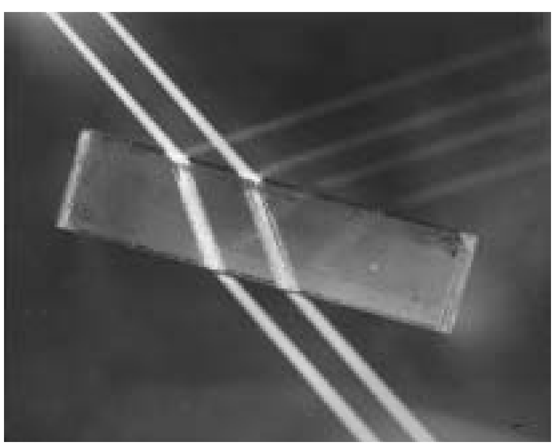
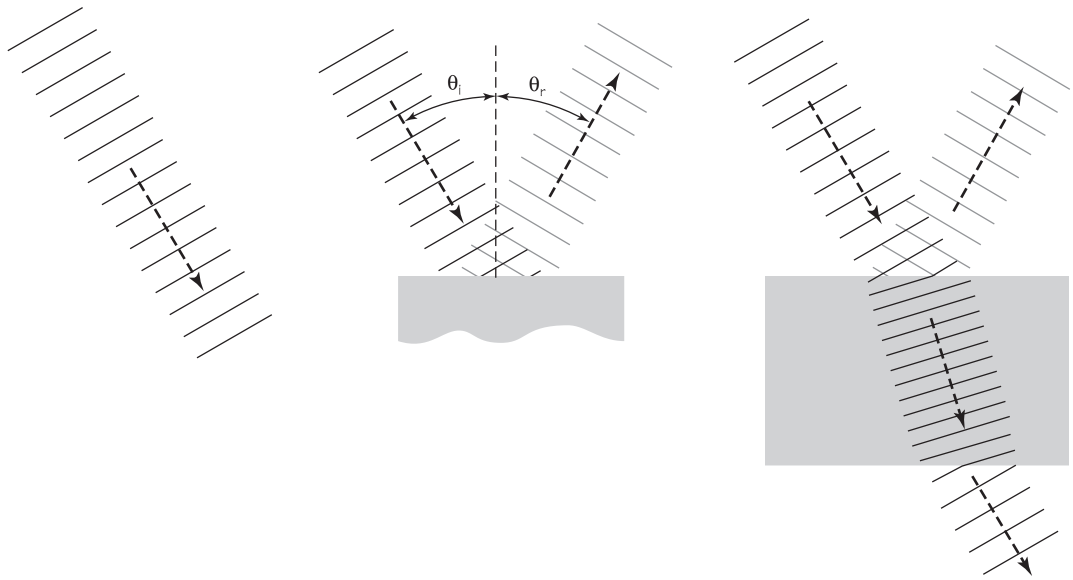


FIGURE 8.41 Two narrow beams of light, coming from the upper left, strike a block of glass. Can you account for all the observed effects?



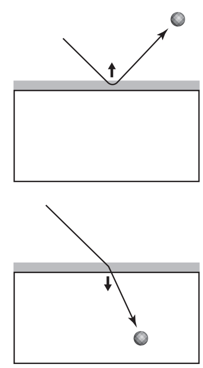


FIGURE 8.42 Diagrams illustrating reflection and refraction of light, viewed as waves and particles.

repelled the particles of light. Similarly, a force that attracted light particles instead of repelling them could explain refraction. As a particle of light approached a boundary of another medium, it would first have to overcome the repelling force. If it did that, it would then meet an attractive force in the medium that would pull it into the medium. Since the attractive force would be a vector with a component in the direction of the particle's original motion, the particle's speed would increase. If the ray of particles were moving at an oblique angle to the boundary, it would change direction as it entered the medium, bending toward the line perpendicular to the boundary. Notice that to make this argument we have had to make an assumption about the size of Newton's light "particles." The particles must be at least as small as the irregularities in the surface of a mirror. Similarly, a concrete wall is quite rough, but a tennis ball rebounds from such a wall almost exactly as light reflects from a mirror.

According to the *particle* model, therefore, you can make the following statements about reflection and refraction:

1. A ray represents the direction in which the particles are moving.
2. In reflection, the angles of incidence and reflection are equal. This prediction can be derived by applying the law of conservation of momentum to particles repelled by a force as shown on the last sketch.
3. Refraction involves a change of speed of the particles as they enter another medium. In particular, when an attractive power acts, *the speed increases*, and the ray is bent into the medium.

Compare these features of the particle model with the corresponding features of the wave model. The only difference is in the predicted speed for a refracted ray. You *observe* that a ray is bent toward the perpendicular line when light passes from air into water. The particle theory *predicts* that light has a *greater* speed in the second medium. The wave theory *predicts* that light has a *lower* speed.

You might think that it would be fairly easy to devise an experiment to determine which prediction is correct. All one has to do is measure the speed of light after it has entered water and compare it with the speed of light in air. But in the late seventeenth and early eighteenth centuries, when Huygens was arguing the wave model and Newton a particle model, no

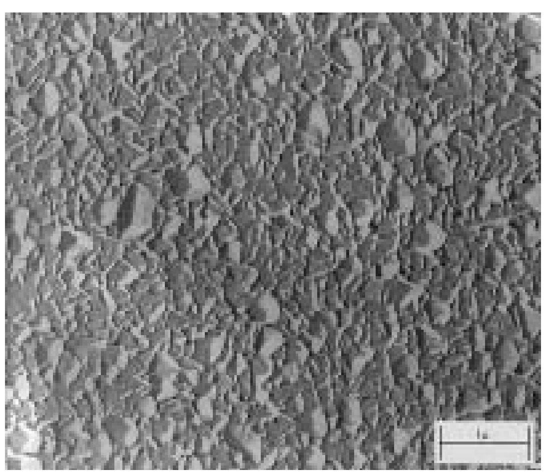


FIGURE 8.43 The surface of a mirror, as shown by a scanning electron microscope. The surface is a 3-micron thick aluminum film. The magnification here is nearly 26,000 times (one micron = 10^{-6} m).

such experiment was possible. The only available way of measuring the speed of light was an astronomical one. Not until the middle of the nineteenth century did Armand H.L. Fizeau and Jean B.L. Foucault measure the speed of light in water. *The results agreed with the predictions of the wave model*: The speed of light is less in water than in air.

The Foucault–Fizeau experiments of 1850 were widely regarded as driving the last nail in the coffin of the Newtonian particle theory of light, for, by the time these experiments were done, most physicists had already accepted the wave model for other reasons. Some of these stemmed from the work of the English scientist Thomas Young, to whom we now turn.

8.15 INTERFERENCE AND DIFFRACTION

Early in the nineteenth century, when Newton's prestige still contributed greatly to the support of the particle theory of light, Thomas Young revived the wave theory of light. In experiments made between 1802 and 1804, Young found that light shows the phenomenon of *interference* de-

FIGURE 8.44 Thomas Young (1773–1829) was an English linguist, physician, and expert in many fields of science. At the age of 14, he was familiar with Latin, Greek, Hebrew, Arabic, Persian, French, and Italian, and later was one of the first scholars successful at decoding Egyptian hieroglyphic inscriptions. He studied medicine in England, Scotland, and Germany. While still in medical school, he made original studies of the eye and later developed the first version of what is now known as the three-color theory of vision. Young also did research in physiology on the functions of the heart and arteries and studied the human voice mechanism, through which he became interested in the physics of sound and sound waves. Young then turned to optics and showed that many of Newton's experiments with light could be explained in terms of a simple wave theory of light. This conclusion was strongly attacked by some scientists in England and Scotland who were upset by the implication that Newton might have been wrong.

scribed in general for transverse waves in Section 8.6. The particle theory of light could not easily explain the interference patterns produced by light. Young's famous "double-slit experiment" provided convincing evidence that light does have properties that are explainable only in terms of waves.

Young's experiment should be done in the laboratory, rather than only talked about; we will describe it only briefly here. Basically, it involves splitting a single beam of light into two beams in order to ensure that they are in phase. The split beams are then allowed to overlap, and the two wave trains interfere, constructively in some places and destructively in others. To simplify the interpretation of the experiment, assume that it is done with light that has a single definite wavelength λ.

Young used a black screen with a small hole punched in it to produce a narrow beam of sunlight in a dark room. In the beam he placed a second black screen with two narrow slits cut in it, close together. Beyond this screen he placed a white screen. The light coming through each slit was diffracted and spread out into the space beyond the screen. The light from each slit interfered with the light from the other, and the interference pattern showed on the white screen. Where interference was constructive, there was a bright band on the screen. Where interference was destructive, the screen remained dark.

It is remarkable that Young actually found, by experiment, numerical values for the very short wavelength of light (see the *Student Guide Calculation* for this chapter). Here is his result:

> From a comparison of various experiments, it appears that the breadth of the undulations constituting the extreme red light must be supposed to be, in air, about one 36 thousandth of an inch [7×10^{-7} m], and those of the extreme violet about one 60 thousandth [4×10^{-7} m].

In announcing his result, Young took special pains to forestall criticism from followers of Newton, who was generally considered a supporter of the particle theory. He pointed out that Newton himself had made several statements favoring a theory of light that had some aspects of a wave theory. Nevertheless, Young was not taken seriously. It was not until 1818, when the French physicist Augustin Fresnel proposed his own mathematical wave theory, that Young's research began to get the credit it deserved. Fresnel also had to submit his work for approval to a group of physicists who were committed to the particle theory. One of them, the mathematician Simon Poisson, tried to refute Fresnel's wave theory of light. If it really did describe the behavior of light, Poisson said, a very peculiar thing ought to happen when a small solid disk is placed in a beam of light. Dif-

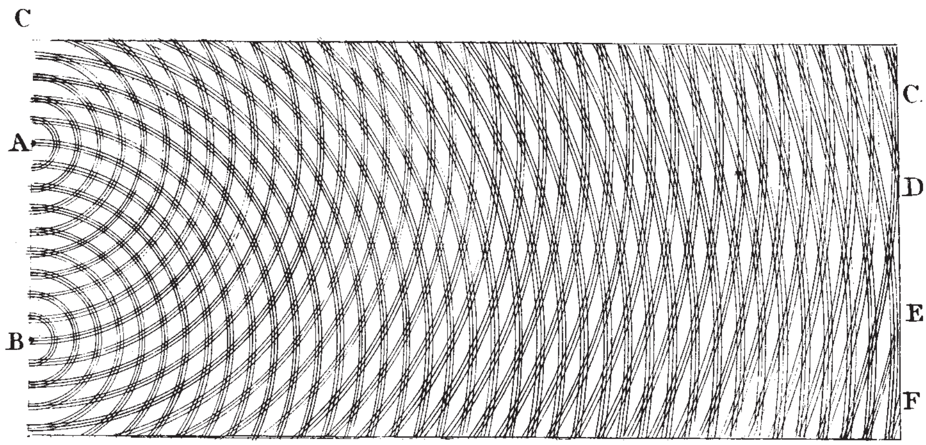


FIGURE 8.45 Thomas Young's original drawing showing interference effects in overlapping waves. The alternate regions of reinforcement and cancellation in the drawing can be seen best by placing your eye near the right edge and sighting at a grazing angle along the diagram.

fraction of some of the light waves all around the edge of the round disk should lead to constructive interference, producing a bright spot in the center of the disk's shadow on a white screen placed behind the disk. But the particle theory of light allowed no room for ideas such as diffraction and constructive interference. In addition, such a bright spot had never been reported, and even the very idea of a bright spot in the center of a shadow seemed absurd. For all of these reasons, Poisson announced that he had refuted the wave theory.

Fresnel accepted the challenge, however, and immediately arranged for Poisson's seemingly ridiculous prediction to be tested by experiment. The result was that a bright spot *did* appear in the center of the shadow!

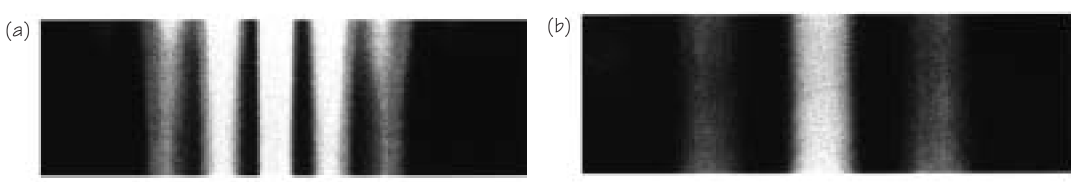


FIGURE 8.46 (a) A double-slit fringe pattern. When white light is used in Young's experiment, each wavelength produces its own fringe pattern slightly shifted from the others. The result is a central white band surrounded by fringes that are increasingly colored. (b) When the separation between slits, a, is decreased, the distance of the fringes from the central axis increases and the fringes broaden. All of this can be seen easily with an ordinary long-filament display light bulb, viewed through the space between two straight fingers.

FIGURE 8.47 Augustin Jean Fresnel (1788–1827) was an engineer of bridges and roads for the French government. In his spare time, he carried out extensive experimental and theoretical work in optics. Fresnel developed a comprehensive wave model of light that successfully accounted for reflection, refraction, interference, and polarization. He also designed a lens system for lighthouses that is still used today.

Thereafter, increasing numbers of scientists realized the significance of the Young double-slit experiment and the "Poisson bright spot." By 1850, the wave model of light was generally accepted; physicists had begun to concentrate on working out the mathematical consequences of this model and applying it to the different properties of light.

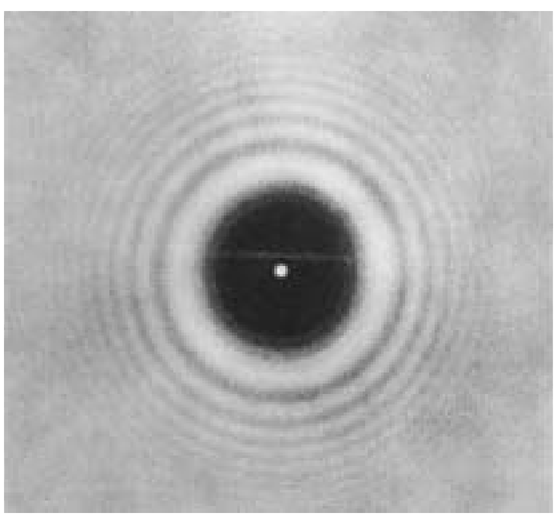


FIGURE 8.48 Diffraction pattern caused by an opaque circular disk, showing the Poisson bright spot in the center of the shadow. Note also the bright and dark fringes of constructive and destructive interference.

FIGURE 8.49 Katherine Burr Blodgett (1898–1979). Dr. Blodgett developed "invisible" glass by applying 44 layers of a one-molecule thick transparent liquid soap to glass to reduce reflections from its surface. Today, nearly all camera lenses and optical devices have non-reflective coatings on their surfaces which facilitate the efficient passage of light.

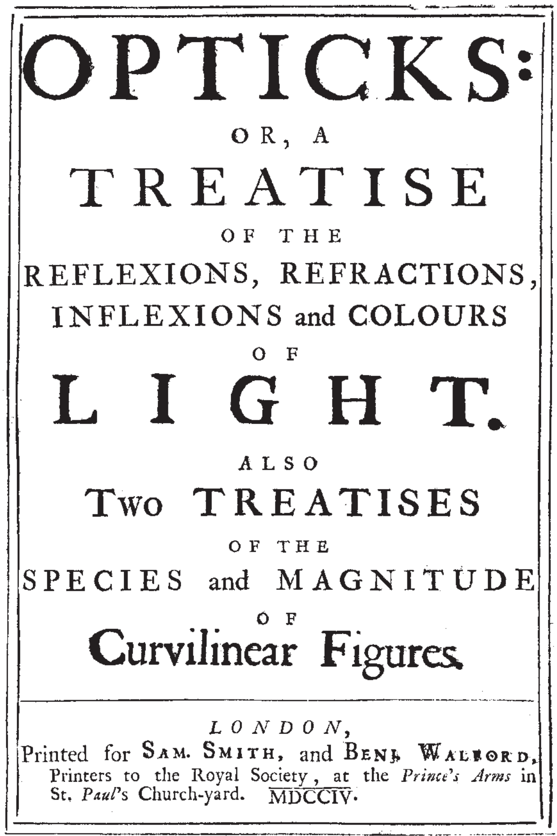
8.16 WHAT IS COLOR?

The coloring agents found in prehistoric painting and pottery show that humans have appreciated color since earliest times. But no scientific theory of color was developed before the time of Newton. Until then, most of the accepted ideas about color had come from artist–scientists like da Vinci, who based their ideas on experiences with mixing pigments.

Unfortunately, the lessons learned in mixing pigments rarely apply to the mixing of different-colored light beams. In ancient times, it was thought that light from the Sun was "pure." Color resulted from adding impurity, as was considered to be the case when a beam of "pure light" was refracted in glass and emerged with colored fringes.

Newton became interested in colors even while he was still a student at Cambridge University. In 1672, at the age of 29, Newton published a theory of color in the *Philosophical Transactions* of the Royal Society of London. This was his first published scientific paper. He wrote:

> In the beginning of the Year 1666, at which time I applyed myself to the grinding of Optick glasses of other figures than *Spherical*, I procured me a Triangular glass-Prisme, to try therewith the celebrated *Phaenomena* of *Colours*. And in order thereto haveing darkened my chamber, and made a small hole in my window-shuts, to



OPTICKS:
OR, A
TREATISE
OF THE
REFLEXIONS, REFRACTIONS,
INFLEXIONS and COLOURS
OF
LIGHT.
ALSO
Two TREATISES
OF THE
SPECIES and MAGNITUDE
OF
Curvilinear Figures.

LONDON,
Printed for SAM. SMITH, and BENJ. WALFORD,
Printers to the Royal Society, at the *Prince's Arms* in
St. *Paul's* Church-yard. MDCCIV.

FIGURE 8.50 Title page from the first edition of Newton's *Opticks* (1704), in which he described his theory of light.

> let in a convenient quantity of the Suns light, I placed my Prisme at his entrance, that it might be thereby refracted to the opposite wall. It was at first a very pleasing divertisement, to view the vivid and intense colours produced thereby. . . .

The cylindrical beam of "white" sunlight from the circular opening passed through the prism and produced an elongated patch of colored light on the opposite wall. This patch was violet at one end, red at the other, and showed a continuous gradation of colors in between. For such a pattern of colors, Newton invented the name *spectrum*.

But, Newton wondered, *where do the colors come from*? And why is the image spread out in an elongated patch rather than circular? Newton passed the light through different thicknesses of the glass, changed the size of the hole in the window shutter, and even placed the prism outside the window.

None of these changes had any effect on the spectrum. Perhaps some unevenness or irregularity in the glass produced the spectrum, Newton thought. To test this possibility, he passed the colored rays from one prism through a second similar prism turned upside down. If some irregularity in the glass caused the beam of light to spread out, then passing this beam through the second prism should spread it out even more. Instead, the second prism, when properly placed, brought the colors *back together* fairly well. A spot of *white* light was formed, as if the light had not passed through either prism.

By such a process of elimination, Newton convinced himself of a belief that he probably had held from the beginning: *White light is composed of colors*. The prism does not manufacture or add the colors; they were there all the time, but mixed up so that they could not be distinguished. When white light passes through a prism, each of the component colors is refracted at a different angle. Thus, the beam is spread into a spectrum.

As a further test of this hypothesis, Newton cut a small hole in a screen on which a spectrum was projected. In this way, light of a single color could be separated out and passed through a second prism. He found that the second prism had no further effect on the color of this beam, though it refracted the beam more. That is, once the first prism had done its job of separating the colored components of white light, the second prism could not change the color of the components.

Summarizing his conclusions, Newton wrote:

> Colors are not *Qualifications of Light* derived from Refraction or Reflection of natural Bodies (as 'tis generally believed) but Original and Connate Properties, which in divers Rays are divers. Some Rays are disposed to exhibit a Red Colour and no other; some a Yellow and no other, some a Green and no other, and so of the rest. Nor are there only Rays proper and particular to the more Eminent Colours, but even to all their intermediate gradations.

Apparent Colors of Objects

So far, Newton had discussed only the colors of rays of light. In a later section of his paper he raised the important question: Why do objects appear to have different colors? Why is the grass green, a paint pigment yellow or red? Newton proposed a very simple answer:

> That the Colours of all Natural Bodies have no other Origin than this, that they . . . Reflect one sort of Light in greater plenty than another.

Most colors observed for real materials are "body" colors, produced by selective absorption of light which penetrates a little beyond the surface before being scattered back. This explains why the light transmitted by colored glass has the same color as the light reflected from it. Thin metallic films, however, have "surface" color, resulting from selective regular reflection. Thus, the transmitted light will be the complement of the reflected light. For example, the light transmitted by a thin film of gold is bluish–green, while that reflected is yellow.

In other words, a red paint pigment looks red to us because when white sunlight falls on it, the pigment absorbs most of the rays of other colors of the spectrum and reflects mainly the red to our eyes.

According to Newton's theory, color is not a property of an object by itself. Rather, color depends on how the object reflects and absorbs the various colored rays that strike it. Newton backed up this hypothesis by pointing out that an object may appear to have a different color when a different kind of light shines on it. For example, consider a pigment that reflects much more red light than green or blue light. When illuminated by white light, it will reflect mostly the red component of the white light, and so will appear red. But if it is illuminated with blue light, there is no red there for it to reflect, and it can reflect only a very little of the blue light. Thus, it will appear to be dark and perhaps dimly blue. (However, Newton was not suggesting that the rays themselves possess color, only that they raise the sensation of color in the eye, or the mind.)

Reactions to Newton's Theory

Newton's theory of color met with violent opposition at first. Other British scientists, especially Robert Hooke, objected on the grounds that postulating a different kind of light for each color was unnecessary. It would be simpler to assume that the different colors were produced from pure white light by some kind of modification. For example, the wave front might be twisted so that it is no longer perpendicular to the direction of motion.

Newton was aware of the flaws in Hooke's theory, but he disliked public controversy. In fact, he waited until after Hooke's death in 1703 to publish his own book, *Opticks* (1704), in which he reviewed the properties of light and his many convincing experiments on light.

Newton's *Principia* was a more important work from a purely scientific viewpoint. But his *Opticks* had also considerable influence on the literary world. This was in part because the work was written in English rather than in Latin and because the book contained little mathematics. English poets gladly celebrated the discoveries of their country's greatest scientist. Most poets, of course, were not deeply versed in the details of Newton's theory of gravity. The technical aspects of the geometric axioms and proofs in the *Principia* were beyond most of its readers. Although some students, including young Thomas Jefferson, learned their physics out of that book, translations and popularized versions soon appeared. But Newton's theory of colors and light provided good material for poetic fancy, as in James Thomson's, "To the Memory of Sir Isaac Newton" (1727):

> . . . First the flaming red,
> Springs vivid forth; the tawny orange next;
> And next delicious yellow; by whose side
> Fell the kind beams of all-refreshing green.
> Then the pure blue, that swells autumnal skies,
> Ethereal played; and then, of sadder hue,
> Emerged the deepened indigo, as when
> The heavy-skirted evening droops with frost;
> While the last gleamings of refracted light
> Died in the fainting violet away.

Leaders of the nineteenth-century Romantic movement in literature and the German "Nature Philosophers" did not think so highly of Newton's theory of color. The scientific procedure of dissecting and analyzing natural phenomena by experiments was distasteful to them. They preferred to speculate about the unifying principles of all natural forces, hoping somehow to grasp nature as a whole. The German philosopher Friedrich Schelling wrote in 1802:

> Newton's *Opticks* is the greatest illustration of a whole structure of fallacies which, in all its parts, is founded on observation and experiment.

The German poet Goethe (mentioned in Chapter 4) rejected Newton's theory of colors and proposed his own theory, based upon his own direct observations as well as passionate arguments. Goethe insisted on the purity of white light in its natural state, rejecting Newton's argument that white light is a mixture of colors. Instead, he suggested, colors may be produced by the interaction of white light and its opposite—darkness. Goethe's observations on the psychology of color perception were of some value to science. But his theory of the physical nature of color could not stand up under further detailed experiment. Newton's theory of the colors of the spectrum remained firmly established.

8.17 WHY IS THE SKY BLUE?

Newton suggested that the apparent colors of natural objects depend on which color is most strongly reflected or scattered to the viewer by the object. In general, there is no simple way of predicting from the surface structure, chemical composition, etc., what colors a substance will reflect or scatter. However, the blue color of the clear sky can be explained by a fairly simple argument.

As Thomas Young showed experimentally (Section 8.15), different wavelengths of light correspond to different colors. The wavelength of light may be specified in units of *nanometers* (abbreviated nm; 1 nm = 10^{-9} m) or, alternatively, in Ångstroms (Å), named after Anders Jonas Ångstrom, a Swedish astronomer who, in 1862, used spectroscopic techniques to detect the presence of hydrogen in the Sun. One angstrom (symbol Å) is equal to 10^{-10} m. The range of the spectrum visible to humans is from about 400 nm (4000 Å) for violet light to about 700 nm (7000 Å) for red light.

Small obstacles can scatter the energy of an incident wave of any sort in all directions, and the amount of scattering depends on the wavelength. This fact can be demonstrated by simple experiments with water waves in

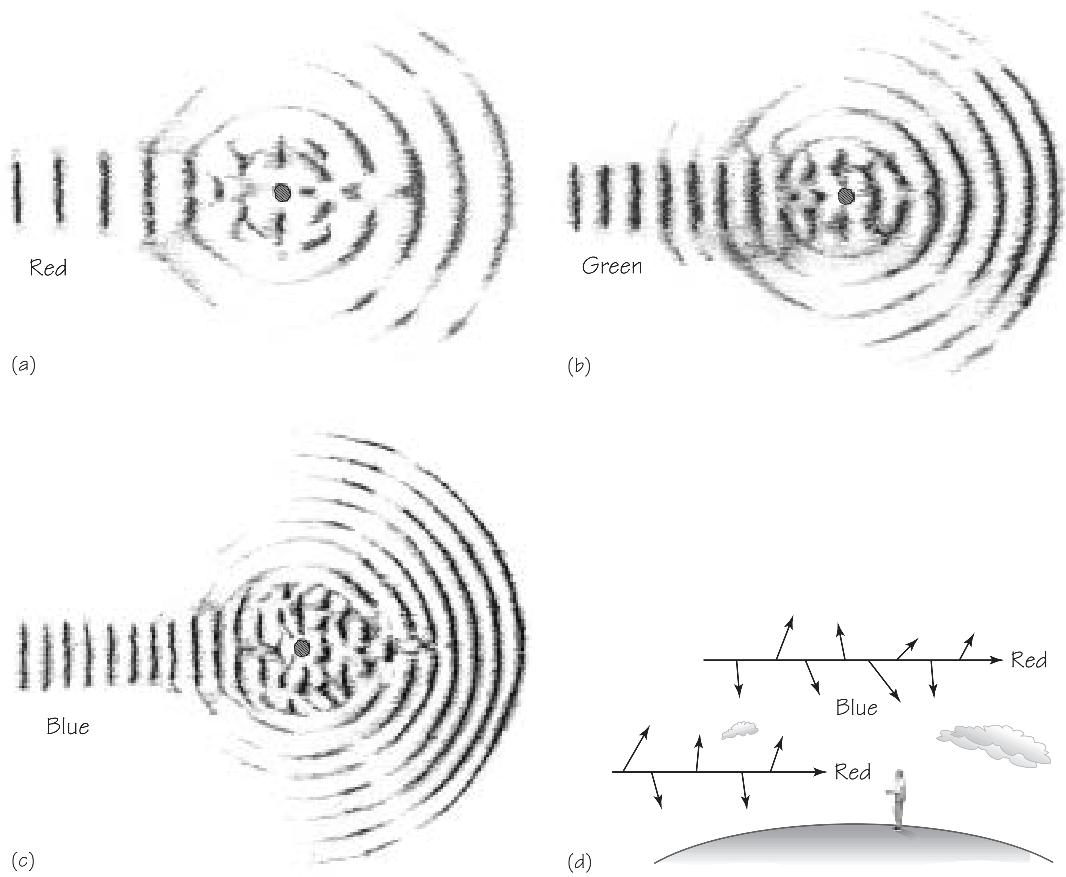


FIGURE 8.51 If you look at a sunset on a hazy day, you receive primarily unscattered colors, such as red, whereas if you look overhead, you will receive primarily scattered colors, the most dominant of which is blue.

a ripple tank. As a general rule, *the larger the wavelength is compared to the size of the obstacle, the less the wave is scattered by the obstacle*. For particles smaller than one wavelength, the amount of scattering of light varies inversely with the fourth power of the wavelength. For example, the wavelength of red light is about twice the wavelength of blue light. Therefore, the scattering of red light is only about one-sixteenth as much as the scattering of blue light.

Now it is clear why the sky is blue. Light from the sun is scattered by separate molecules of vapor, particles of dust, etc., in the air above, all of which are usually very small compared to the wavelengths of visible light. Thus, on a clear day light of short wavelengths (blue light) is much more strongly scattered by the particles than is light of longer wavelengths, and so-to-speak fills the firmament from end to end. When you look up into a clear sky, it is mainly this scattered light that enters your eyes. The range of scattered short wavelengths (and the color sensitivity of the human eye) leads to the sensation of blue. On the other hand, suppose you look at a sunset on a hazy day. You receive directly from the Sun a beam that has had the blue light almost completely scattered out in all directions, while the longer wavelengths have *not* been scattered out. So you perceive the Sun as reddish.

If the Earth had no atmosphere, the sky would appear black, and stars would be visible by day. In fact, starting at altitudes of about 16 km, where the atmosphere becomes quite thin, the sky does look black, and stars can be seen during the day, as astronauts have found.

If light is scattered by particles considerably larger than one wavelength (such as water droplets in a cloud), there is not much difference in the scattering of different wavelengths. So we receive the mixture we perceive as white.

The blue–gray haze that often covers large cities is caused mainly by particles emitted by internal combustion engines (cars, trucks) and by industrial plants. Most of these pollutant particles are invisible, ranging in size from 10^{-6} m to 10^{-9} m. Such particles provide a framework to which gases, liquids, and other solids adhere. These larger particles then scatter light and produce haze. Gravity has little effect on the particles until they become very large by collecting more matter. They may remain in the atmosphere for months if not cleaned out by repeated rain, snow, or winds. The influences of such clouds of haze or smog on the climate and on human health are substantial.

8.18 POLARIZATION

Hooke and Huygens proposed that light is in many ways like sound, that is, that light is a wave propagated through a medium. Newton could not accept this proposal and argued that light must also have some particle-like properties, in addition to its wave nature. He noted two properties of light that, he thought, could not be explained unless light had particle properties. First, a beam of light is propagated in space in straight lines, while waves such as sound spread out in all directions and go around corners. This objection could not be answered until early in the nineteenth century, when Thomas Young measured the wavelength of light and found how extremely small it is. Even the wavelength of red light, the longest wavelength of the visible spectrum, is less than one-thousandth of a millimeter. As long as a beam of light shines on objects or through holes of ordinary size (a few millimeters or more in width), the light will appear to travel in straight lines. As we saw, diffraction and scattering effects do not become strikingly evident until a wave passes over an object or through a hole whose size is about equal to or smaller than the wavelength.

Newton based his second objection on the phenomenon of "polarization" of light. In 1669, the Danish scientist Erasmus Bartholinus discovered that crystals of Iceland spar (calcite) could split a ray of light into two rays. Writing or small objects viewed through the crystal looked double.

Newton thought this behavior could be explained by assuming that light is made up of particles that have different "sides," for example, rectangular cross sections. The double images, he thought, represent a sorting out of light particles that had entered the medium with different orientations.

Around 1820, Young and Fresnel gave a far more satisfactory explanation of polarization, using a modified wave theory of light. Before then, scientists had generally assumed that light waves, like sound waves, must be *longitudinal*. Young and Fresnel showed that if light waves are *transverse*, this could account for the phenomenon of polarization.

In a transverse wave of a mechanical type, the motion of the medium itself, such as a rope, is always perpendicular to the direction of propagation of the wave. This does not mean that the motion of the medium is always in the same direction. In fact, it could be in any direction in a plane perpendicular to the direction of propagation. However, if the motion of the medium *is* mainly in one direction (e.g., vertical), the wave is *polarized*. Thus, a polarized wave is really the simplest kind of transverse wave. An unpolarized transverse wave is more complicated, since it is a mixture of various transverse motions. All of this applies to light waves, which do not need a medium in which to propagate.

Scientific studies of polarization continued throughout the nineteenth century. For instance, the

Ordinary light, when scattered by particles, shows polarization to different degrees, depending on the direction of scattering. The eyes of bees, ants, and other animals are sensitive to the polarization of scattered light from the clear sky. This enables a bee to navigate by the Sun, even when the Sun is low on the horizon or obscured. Following the bees' example, engineers have equipped airplanes with polarization indicators for use in Arctic regions.

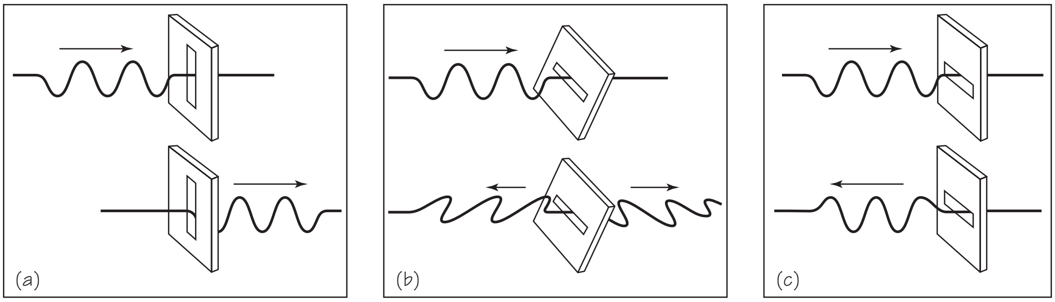


FIGURE 8.52 The same short-wave train on the rope approaches the slotted board in each of the three sketches. Depending on the orientation of the slot, the train of waves (a) goes entirely through the slot; (b) is partly reflected and partly transmitted with changed angles of rope vibration; or (c) is completely reflected.

way in which Iceland spar separates an unpolarized light beam into two polarized beams is sketched in Figure 8.53. Practical applications, however, were frustrated, mainly because polarizing substances like Iceland spar were scarce and fragile. One of the best polarizers was the synthetic crystal "herapathite," or sulfate of iodo-quinine. The needle-like herapathite crystals absorb light that is polarized in the direction of the long crystal axis and absorb very little of the light polarized in a direction at 90° to the long axis.

Herapathite crystals were so fragile that there seemed to be no way of using them. But in 1928, Edwin H. Land, while still a freshman in college, invented a polarizing plastic sheet he called "Polaroid." His first polarizer was a plastic film in which many small crystals of herapathite were embedded. When the plastic was stretched, the needle-like crystals lined up in one direction. Thus, they all acted on incoming light in the same way.

Some properties of a polarizing material are easily demonstrated. For example, you can obtain two polarizing sheets from the lenses of a pair of polarizing sunglasses, or from the "three-dimensional" eyeglasses used in Imax theatres. Hold one of the lenses in front of a light source. Then look at the first lens through the second one. Rotate the first lens. You will notice that, as you do so, the light alternately brightens and dims. You must rotate the sheet through an angle of 90° to go from maximum brightness to maximum dimness.

How can this effect be explained? The light that strikes the first lens, or polarizing sheet, is originally unpolarized, that is, a mixture of waves polarized in different directions. The first sheet transmits only those waves that are polarized in one direction, and it absorbs the rest. The transmitted wave going toward the second sheet is now polarized in one direction. Whenever this direction coincides with the direction of the long molecules

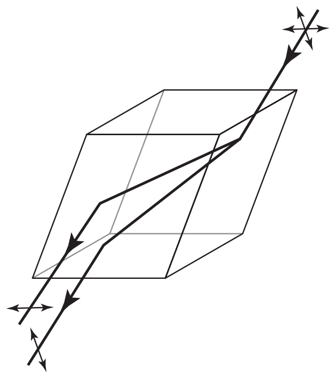


FIGURE 8.53 Double refraction by a crystal of Iceland spar. The "unpolarized" incident light can be thought of as consisting of two polarized components. The crystal separates these two components, transmitting them through the crystal in different directions and with different speeds.

in the second sheet, the wave will not be absorbed by the second sheet (i.e., the wave will set up vibrations within the molecules of the crystals which will transmit most of its energy). However, if the direction is *perpendicular* to the long axis of the crystal molecules, the polarized light will not go through the second sheet but instead will be absorbed.

In conclusion, we see that interference and diffraction effects required a wave model for light. To explain polarization phenomena, the wave model was made more specific; polarization could be explained only if the light waves are transverse waves. Altogether, this model for light explains very satisfactorily all the characteristics of light considered so far.

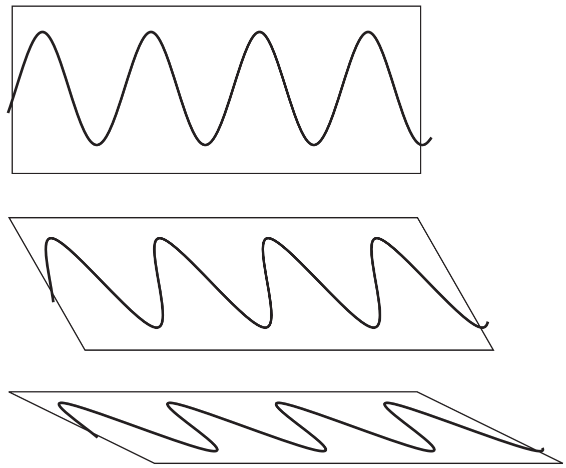
8.19 THE ETHER

One factor seems clearly to be missing from the wave model for light. Earlier in this chapter we defined waves as disturbances that propagate in some substance or "medium," such as a rope or water. What is the medium for the propagation of light waves?

Is air the medium for light waves? No, because light can pass through airless space, as it does between the Sun or other stars and the Earth. Even before it was definitely known that there is no air between the Sun and the Earth, Robert Boyle had tried the experiment of pumping almost all of the air out of a glass container. He found that the objects inside remained visible.

A wave is a disturbance, and it was difficult to think of a disturbance without specifying what was being disturbed. So it was natural to propose that a medium for the propagation of light waves existed. This hypothetical medium was called the *ether*. The word "ether" was originally the name

FIGURE 8.54 Polarized waves.



for Aristotle's fifth element, the pure transparent fluid that filled the heavenly sphere and was later called "quintessence." In the seventeenth and eighteenth centuries, the ether was imagined to be an invisible fluid of very low density. This fluid could penetrate all matter and fill all space. It might somehow be associated with the "effluvium" (something that "flows out") that was imagined to explain magnetic and electric forces. But light waves must be transverse in order to explain polarization, and transverse waves usually propagate only in a *solid* medium. A liquid or a gas cannot transmit transverse waves for any significant distance for the same reason that you cannot "twist" a liquid or a gas. So nineteenth-century physicists assumed that the ether must be a solid.

As stated in Section 8.3, the speed of propagation increases with the stiffness of the medium, and decreases with its density. The speed of propagation of light is very high compared to that of other kinds of waves, such as sound. Therefore, the ether was thought to be a very stiff solid with a very low density. Yet it seems absurd to say that a stiff, solid medium (ether) fills all space. The planets move through space without slowing down, so apparently they encounter no resistance from a stiff ether. And, of course, you feel no resistance when you move around in a space that transmits light freely.

Without ether, the wave theory of light seemed improbable. But the ether itself had absurd properties. Until early in this century, this problem remained unsolved, just as it had for Newton. We shall shortly see how, following Einstein's modification of the theory of light, the problem was solved.

SOME NEW IDEAS AND CONCEPTS

diffraction
ether
frequency
Huygens' principle
in phase
interference
longitudinal wave
medium
nodal lines
out of phase
period
polarization
propagation
ray
spectrum
superposition principle
transverse wave
wave
wave front
wavelength

AN IMPORTANT EQUATION

$v = f\lambda$.

AN IMPORTANT UNIT

1 Hz = 1/s.

FURTHER READING

G. Holton and S.G. Brush, *Physics, The Human Adventure* (Piscataway, NJ: Rutgers University Press, 2001), Chapter 23.

D. Park, *The Fire within the Eye: A Historical Essay on the Nature and Meaning of Light* (Princeton, NJ: Princeton University Press, 1997).

J. Hecht, *City of Light: The Story of Fiber Optics*. Sloan Technology Series (New York: Oxford University Press, 1999).

STUDY GUIDE QUESTIONS

A. WAVES

8.1 What Is a Wave?

1. How would you answer the question, What is a wave?

8.2 The Properties of Waves

1. What kinds of mechanical waves can propagate in a solid?
2. What kinds of mechanical waves can propagate in a fluid?
3. What kinds of mechanical waves can be polarized?
4. Suppose that a mouse runs along under a rug, causing a bump in the rug that travels with the mouse across the room. Is this moving disturbance a propagating wave?

8.3 Wave Propagation

1. What is transferred along the direction of wave motion?
2. On what two properties of a medium does wave speed depend?
3. If a spring is heated to make it less stiff, does it carry waves faster or slower? If the boxcars in a train are unloaded and empty, does the longitudinal start-up wave travel faster or slower?

8.4 Periodic Waves

1. Of the variables *frequency*, *wavelength*, *period*, *amplitude*, and *polarization*, which ones describe:
   (a) *space* properties of waves?
   (b) *time* properties of waves?
2. A vibration of 100 Hz (cycles per second) produces a wave:
   (a) What is the wave frequency?
   (b) What is the period of the wave?
   (c) If the wave speed is 10 m/s, what is the wavelength?
3. If points X and Y on a periodic wave are one-half period "out of phase" with each other, which of the following must be true?
   (a) X oscillates at half the frequency at which Y oscillates.
   (b) X and Y always move in opposite directions.
   (c) X is a distance of one-half wavelength from Y.

8.5 When Waves Meet

1. Two periodic waves of amplitudes A1 and A2 pass through a point P. What is the greatest possible displacement of P?
2. What is the displacement of a point produced by two waves together if the displacements produced by the waves separately at that instant are $+5$ cm and -6 cm, respectively? What is the special property of waves that makes this simple result possible?

8.6 A Two-Source Interference Pattern

1. Are nodal lines in interference patterns regions of cancellation or of reinforcement?
2. What are antinodal lines? antinodal points?

3. Nodal points in an interference pattern are places where:
   (a) the waves arrive "out of phase";
   (b) the waves arrive "in phase";
   (c) the point is equidistant from the wave sources;
   (d) the point is one-half wavelength from both sources.
4. Under what circumstances do waves from two in-phase sources arrive at a point out of phase?

8.7 Standing Waves

1. When two identical waves of the same frequency travel in opposite directions and interfere to produce a standing wave, what is the motion of the medium at:
   (a) the nodes of the standing wave?
   (b) the places between nodes (called antinodes or loops) of the standing wave?
2. If the two interfering waves have the same wavelength λ, what is the distance between the nodal points of the standing wave?
3. What is the wavelength of the longest traveling waves that can produce a standing wave on a string of length l?
4. Can standing waves of *any* frequency higher than that of the fundamental be set up in a bounded medium?

8.8 Wavefronts and Diffraction

1. What characteristic do all points on a wave front have in common?
2. State Huygens' principle in your own words.
3. Can there be nodal lines in a diffraction pattern from an opening less than one wavelength wide? Explain.
4. What happens to the diffraction pattern from an opening as the wavelength of the wave increases?
5. Can there be diffraction without interference? interference without diffraction?

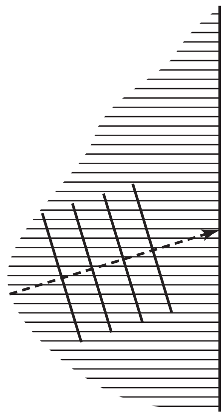
8.9 Reflection

1. What is a "ray"?
2. What is the relationship between the angle at which a wave front strikes a barrier and the angle at which it leaves?
3. What shape of reflector can reflect parallel wave fronts to a sharp focus?
4. What happens to wave fronts originating at the focus of such a reflecting surface?

8.10 Refraction

1. If a periodic wave slows down on entering a new medium, what happens to:
   (a) its frequency?
   (b) its wavelength?
   (c) its direction?

2. Complete the sketch below to show roughly what happens to a wave train that enters a new medium beyond the vertical line in which its speed is greater.



8.11 Sound Waves

1. List five wave behaviors that can be demonstrated with sound waves.
2. Can sound waves be polarized? Explain.

B. LIGHT

8.12 What Is Light?

1. How would you answer the question in the title above?

8.13 Propagation of Light

1. Can a beam of light be made increasingly narrow by passing it through narrower and narrower slits? What property of light does such an experiment demonstrate?
2. What reason did Rœmer have for thinking that the eclipse of a particular satellite of Jupiter would be observed later than expected?
3. What was the most important outcome of Rœmer's work?

8.14 Reflection and Refraction

1. What evidence showed conclusively that Newton's particle model for light could not explain all aspects of refraction?
2. If light has a wave nature, what changes take place in the speed, wavelength, and frequency of light on passing from air into water?

8.15 Interference and Diffraction

1. How did Young's experiments support the wave model of light?
2. In what way is diffraction involved in Young's experiments?

3. What phenomenon did Poisson predict on the basis of Fresnel's wave theory? What was the result?
4. What does the Poisson–Fresnel debate tell about the way science grows?
5. Recall from discussions earlier in the text how difficult it often is for new scientific ideas to be accepted.
   (a) List the cases, just by names.
   (b) Some people object to science as being "too dogmatic" and unchallengeable. Do these cases help or undermine such asssertions?

8.16 What Is Color?

1. How would you answer the question "What is color"?
2. How did Newton show that white light was not "pure"?
3. Why could Newton be confident that, say, green light was not itself composed of different colors of light?
4. How would Newton explain the color of a blue shirt?
5. Why was Newton's theory of color attacked by the Nature Philosophers?

8.17 Why Is the Sky Blue?

1. Why is the sky blue?
2. How does the scattering of light waves by tiny obstacles depend on the wavelength?
3. What would you expect the sky to look like on the Moon? Why?

8.18 Polarization

1. What two objections did Newton have to a pure wave model?
2. Of the phenomena we have discussed, which ones agree with the wave model of light?

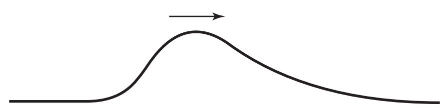
8.19 The Ether

1. Why did scientists assume that there existed an "ether" that transmitted light waves?
2. What remarkable property must the ether have if it is to be the mechanical medium for the propagation of light?

DISCOVERY QUESTIONS

1. On the basis of the evidence presented in this chapter, can light be considered to consist of particles or of waves? Give evidence in support of your answer.

2. The drawing below represents a pulse that propagates to the right along a rope. What is the shape of a pulse propagating to the left that could for an instant cancel this one completely?



3. What shape would the nodal regions have for sound waves from two loudspeakers that emit the same sound?
4. Explain why it is that the narrower a slit in a barrier is, the more nearly it can act like a point source of waves.
5. If light is also a wave, why have you not seen light being diffracted by the slits of a picket fence, or diffracted around the corner of a house?
6. If the frequency of a wave traveling in a medium is increased, what will happen to its speed? What determines the speed of waves in a medium?
7. How can sound waves be used to map the floors of oceans?
8. Waves reflect from an object in a definite direction only when the wavelength is small compared to the dimensions of the object. This is true for sound waves as well as for any other. What does this tell you about the sound frequencies a bat must generate if it is to catch a moth or a fly? Actually, some bats can detect the presence of a wire about 0.12 mm in diameter. Approximately what frequency would that require?
9. Suppose the reflecting surfaces of every visible object were somehow altered so that they completely absorbed any light falling on them; how would the world appear to you?
10. Because of atmospheric refraction, you see the Sun in the evening some minutes after it is really below the horizon, and also for some minutes before it is actually above the horizon in the morning.
    (a) Draw a simple diagram to illustrate how this phenomenon occurs.
    (b) What would sunset be like on a planet with a very thick and dense (but still transparent) atmosphere?
11. Using the phenomena of diffraction and interference, show how the wave theory of light can explain the bright spot found in the center of the shadow of a disk illuminated by a point source.
12. It is a familiar observation that clothing of certain colors appears different in artificial light and in sunlight. Explain why.
13. To prevent car drivers from being blinded by the lights of approaching automobiles, polarizing sheets could be placed over the headlights and windshields of every car. Explain why these sheets would have to be oriented in the same way on every vehicle and must have their polarizing axis at 45° to the vertical.
14. A researcher has discovered some previously unknown rays emitted by a radioactive substance. She wants to determine if the rays are made up of waves or particles. Design a few experiments that she could use to answer her question.

15. When Wilhelm Roentgen discovered X rays, which we now know to have a wavelength of the order of 10^{-10} m, he could not decide by experiment whether X rays were particles or waves. Why do you think he might have had that difficulty?

Quantitative

1. (a) What is the speed of sound in air if middle C (256 Hz) has a wavelength of 1.34 m?
   (b) What is the wavelength in water of middle C if sound waves travel at 1500 m/s in water?
   (c) What is the period of a wave sounding middle C in air? in water?
2. Assuming that light is a wave phenomenon, what is the wavelength of green light if the first node in a diffraction pattern is found 10 cm from the center line at a distance of 4 m from the slits which have a separation distance of 2.5×10^{-3} cm?
3. A convenient unit for measuring astronomical distances is the light year, defined as the distance that light travels in 1 year. Calculate the number of meters in a light year to two significant figures.
4. Suppose a space vehicle had a speed one-thousandth that of light. How long would it take to travel the 4.3 light years from Earth to the closest known star other than the Sun, alpha Centauri? Compare the speed given for the space vehicle with the speed of approximately 10 km/s maximum speed (relative to the Earth) that a space capsule reaches on an Earth–Mars trip.
5. Calculate how much farther than expected Jupiter must have been from Earth when Rœmer predicted a 10-min delay for the eclipse of 1676.
6. Green light has a wavelength of approximately 5×10^{-7} m (500 nm). What frequency corresponds to this wavelength? Compare this frequency to the carrier frequency of the radio waves broadcast by a radio station you listen to.