PHYSICAL SCIENCE CONCEPTS

SECOND EDITION

Grant W. Mason
Dana T. Griffen
John J. Merrill
James M. Thorne

Editorial Assistance: Madlyn Tanner
Illustrations: Rachel Adams, Jeff Michelsen, Lorraine Mullen
Cover Design: Dave Eliason
Cover Photograph: Brian Kelly
Color Plates: Jeff Hester and Paul Scowen, Arizona State University,
using the wide field and planetary camera 2 on board NASA's
Hubble Space Telescope on April 1, 1995
Layout Design: Bjorn Pendleton
Figures Redesign: Joel Pullan, David Babcock, David Bentley, Bjorn Pendleton

Published by Grant W. Mason
Printed in the United States of America
Brigham Young University Press
ISBN 0-9611938-10-6

13. Waves

It may be surprising to find a chapter on waves used to introduce the study of matter. As we shall see, waves play a very important role in understanding matter. By studying waves we can better understand the nature of light. Light that is emitted from atoms gives us clues about the nature of atoms. If atoms emit light as waves, they will likely be quite different in nature than atoms that emit streams of particles. Thus, the study of waves is an essential element in our study of matter. This chapter will establish some of the vocabulary and identify some of the phenomena that are understood in terms of waves. More familiar waves, such as on the sea or as earthquakes, are also of interest in their own right.

Waves are an important consequence of the elastic properties of materials, as governed by the laws of motion and the laws of force. You are no doubt familiar with surface waves on water. For example, a disturbance in the middle of an otherwise calm pond is transmitted to the sides of the pond and back again. The traveling disturbance is a **wave**.

Another familiar example is a wave on a rope. Imagine two people holding the ends of a rope and one person shaking one end. The traveling disturbance, or wave, moves from one end to the other.

These two waves have several features in common. Each travels through a medium, such as the water surface or the rope, which supports the wave motion. Each medium has an equilibrium shape (level water surface or straight rope), and the wave causes a deviation from that shape. Finally, the medium is either elastic or has some other mechanism for restoring its shape. Internal elastic forces cause a return to equilibrium shape in most instances, but gravity provides the restoring force for waves on the surface of the ocean. These restoring forces cause the wave to be propagated.

It is the disturbance that is propagated from one place to another, not parts of the medium itself (Fig. 13.1). Individual parts of the rope move back and forth as the wave passes, but they always return to their starting point. Pieces of cork floating on the water surface move about as a wave passes, but they remain in one general area and periodically return to their original position. Individual samples of water do the same.

Another common feature of these waves is that each has a source, something that causes the original disturbance. For example, waves result from a stone thrown into the middle of the pond or a person shaking one end of a rope.

Finally, energy is transmitted in wave movement or

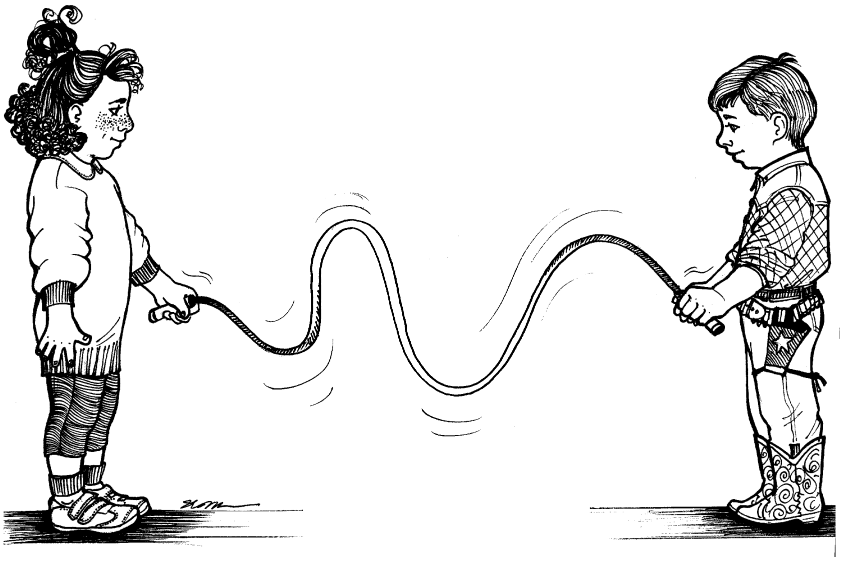

Figure 13.1. What travels along the rope from one person to another?

the motion of the wave. For instance, when the water is disturbed, samples of the water all across the pond are moving up and down, back and forth. These have kinetic energy. (They also experience changes in gravitational potential energy.) Energy has been transferred from the source (the rock striking the water surface) to remote parts of the pond. In the other example, the rope is originally at rest. As the wave passes, individual parts of the rope begin moving; again, kinetic energy travels from the source, through the medium, to the other end of the rope. Features of waves may be summarized as follows:

> A wave is a disturbance, accompanied by energy, that is initiated by a source and that advances through a medium.

Wave motion is responsible for several important processes in nature. Water waves cause erosion, sound travels as a wave in air, and light exhibits many wave properties.

Types of Waves

The water waves with which we are most familiar are called **surface waves**. Such waves can occur on the surfaces of most solids and liquids. Many waves, however, travel through the interior of materials rather than along their surfaces. Sound waves travel through air; earthquake waves pass through the earth; light waves travel through empty space, air, and some solids.

Waves traveling through materials are of two general types: **compression waves** (also called longitudinal waves) and **shear waves** (also called transverse waves). Figure 13.2 shows the initiation and progress of a compression wave. The diagrams represent a homogeneous sample of matter. Imaginary vertical lines divide the sample into units of equal mass. The material is in its original, undisturbed state in Figure 13.2a. A wave begins when the small piston pushes on the material and compresses the material adjacent to the point of contact in Figure 13.2b. (Compressed regions are shaded in the figure.) Since the material is elastic, this compressed, higher-density region immediately expands and compresses the material adjacent to it, as shown in Figure 13.2c. If left undisturbed, this region of compression will be transmitted through the material like a row of dominoes falling in succession.

If the source moves back to its original position, as often happens, the elastic material adjacent to it will expand as in Figure 13.2d. This region of lower density propagates through the material in much the same way as before, following the compressed region through the material. If the source—in this case, the piston—moves back and forth, it causes alternate regions of compression and decompression that travel consecutively through the medium. Such a wave is repeating (or periodic), and is responsible for most wave phenomena.

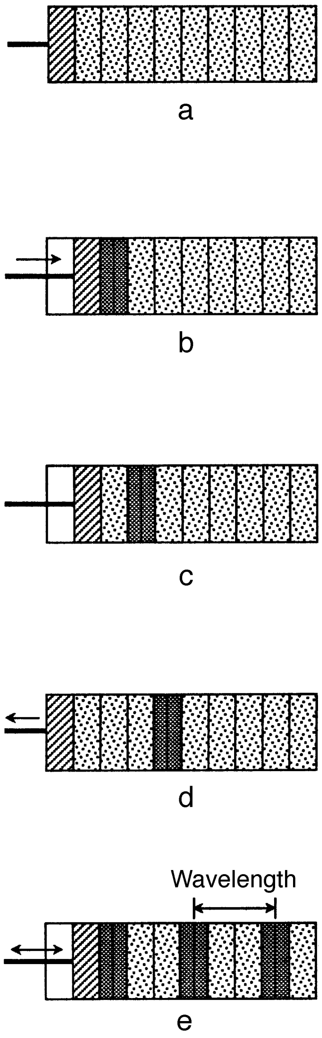

Figure 13.2. Transmission of a compression wave.

Again, the material itself is not transmitted through the medium. Only the disturbance—in this case, compression and decompression—is transmitted.

Sound in air is a compression wave of this type. The source can be any vibrating object in contact with air. As the object vibrates, it causes a series of compressions and decompressions to travel from the source to the receiver. These in turn cause a series of oscillating forces on any object they strike—for example, a human eardrum. As the eardrum vibrates in response to these forces, a series of nerve impulses (themselves a wave of sorts) are transmitted to the brain, where they are interpreted as sound.

The transmission of a shear wave is illustrated in Figure 13.3. The undisturbed material is shown in

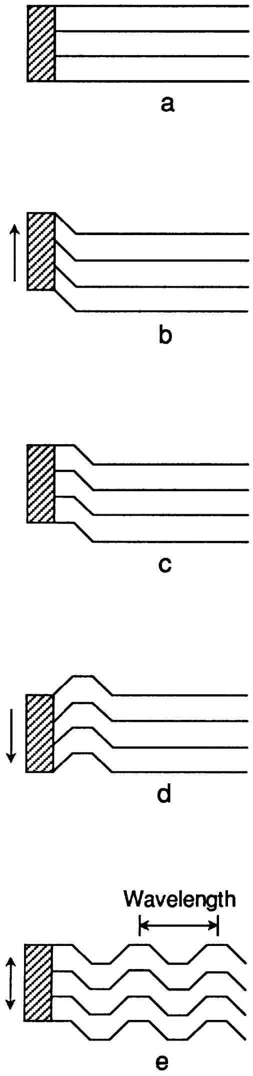

Figure 13.3. Transmission of a shear wave.

Figure 13.3a, where horizontal lines divide the material into units of equal mass. The shear wave is initiated when a source pushes sideways on the surface, dragging the adjacent material with it as shown in Figure 13.3b. If the material is elastic with respect to shear, this displaced material pulls on the material next to it. Once this adjacent material has been displaced, it in turn pulls on the material it touches, and so on through the material as indicated in Figure 13.3c. The disturbance propagates through the material just as in compression, except now the forces and the motions within the material are sideways rather than back and forth.

Now suppose the source of the shear returns to its original position, as in Figure 13.3d. A second disturbance, representing a return to the equilibrium position, is initiated and propagated through the medium. If the source repeats its back-and-forth motion, a repeating wave travels through the medium.

Propagation of this kind of wave occurs only if the material is elastic with respect to shear. If part of the material is displaced sideways, it must pull sideways on the adjacent material and in turn be pulled back toward its equilibrium position. Chapter 10 explained that solids are elastic with respect to shear but that fluids (liquids, gases, and plasmas) are not. All materials, however, are elastic with respect to compression. Thus, all materials transmit compression waves, but only solids transmit shear waves.

Properties of Waves

Four properties—speed, frequency, wavelength, and amplitude—are used to describe waves and to distinguish one from another. The **speed** of a wave is the rate at which the disturbance travels through the medium. The speed of elastic waves often does not depend on the kind of disturbance, but only on the elastic properties and density of the medium. Generally, higher wave speeds occur with larger elastic constants. Also, the speed of a compression wave is always higher than the speed of a shear wave through the same material.

Wave speeds for different materials vary greatly. The speed of sound in air is about 340 meters/second (760 miles/hour) near sea level. Shear earthquake waves travel through solid rock about 10,000 kilometers/hour, while compression waves travel about twice as fast. Light has the fastest speed in nature, 186,000 miles/second (300,000 kilometers/second), about one foot every billionth of a second.

Imagine standing at one point in a wave-transmitting medium such as the ones described above, watching a repeating wave go by. The **frequency** of the wave is the number of disturbances that pass a particular point every second. It is also the number of oscillations of the source that occur each second. For example, our ears are sensitive to the frequencies of sound waves that vary from 20 to 20,000 oscillations per second. Higher frequencies produce higher tones. Earthquake waves have frequencies from 10 to 1000 oscillations per second. Frequencies of radio waves, which are listed on the dial of each receiver, are in the range of a few thousand to several million oscillations per second. The frequency of light determines its color, higher frequency corresponding to the blue end of the spectrum and lower frequency to the red end. Light frequencies are in the range of 10^{15} oscillations per second.

The **wavelength** is the distance between successive disturbances in a repeating wave. Wavelengths are indicated in Figures 13.2e and 13.3e.

Frequency and wavelength for a particular type of wave are always related. High frequency corresponds with short wavelengths and low frequency with long wavelengths (Fig. 13.4). Wave speed is also related to these. Imagine once again watching a repeating wave go by. The frequency indicates how many disturbances go by each second; the wavelength indicates the distance between each pair of disturbances. In one second, the wave will have traveled a distance equal to the product of these two. Thus,

$$\textit{wave speed} = \textit{frequency} \times \textit{wavelength} .$$

Suppose, for example, that a particular wave has a wavelength of 5 meters and a frequency of 30 oscillations per second. That means that 30 waves, each 5 meters long, will pass any point in the medium in one second. The wave must move a distance of 30 times 5 meters, or 150 meters, each second.

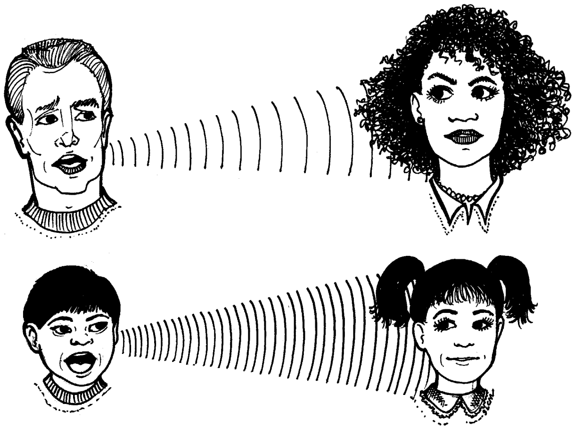

Figure 13.4. Low- and high-pitched sound waves have the same speed. Which has the longer wavelength? Which has the higher frequency?

Wavelengths for sound vary from about 2 centimeters for the highest tones to nearly 20 meters for the lowest tones. The wavelengths of light are short, about 0.00005 (5×10^{-5}) centimeters; the shorter wavelengths correspond to the bluer colors and longer ones to redder colors.

The **amplitude** of a wave is a measure of how large a disturbance is being transmitted. A strong wave has a large amplitude. A loud sound has a large amplitude; a softer one has a smaller amplitude. The amplitude of an elastic wave is the maximum distance that the medium is displaced from equilibrium as the wave passes. Figure 13.5 illustrates amplitude along with frequency and wavelength.

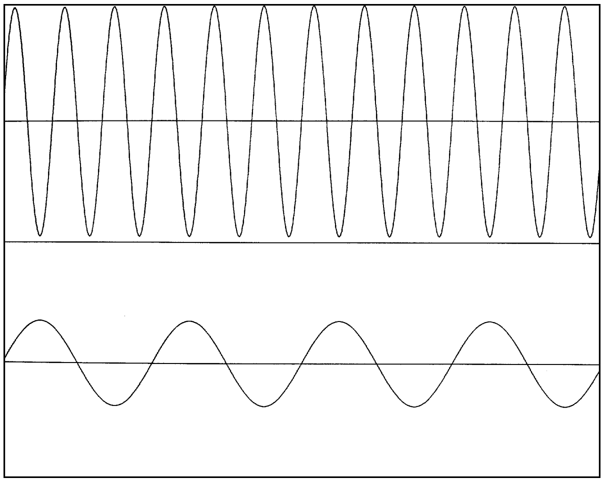

Figure 13.5. Upper: A large amplitude wave of high frequency and short wavelength. Lower: A small amplitude wave of low frequency and long wavelength.

Wave Phenomena

Several kinds of behavior characterize all waves. These illustrate the important role of waves in nature and provide a means of identifying a particular phenomenon as a wave. For example, light and sound exhibit all of these behaviors, a fact that has led scientists to believe that light and sound are waves.

Reflection

Waves “bounce,” or **reflect**, when they encounter

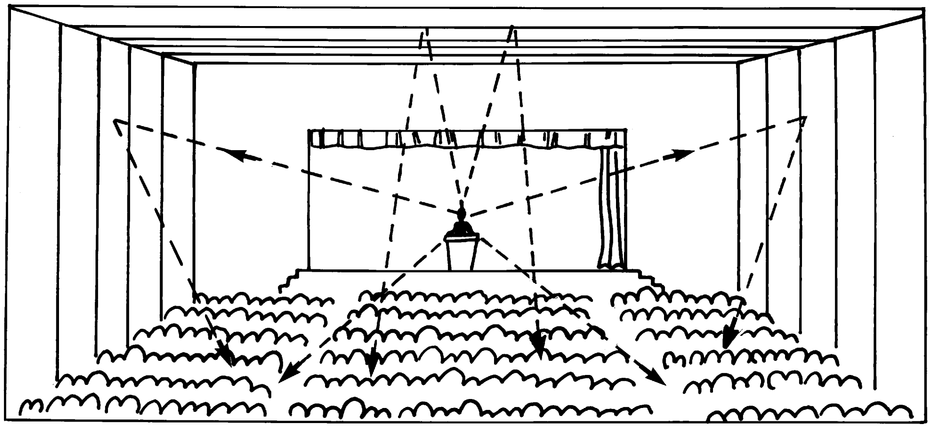

Figure 13.6. Much of the sound you hear in a room is from reflections off the walls and ceiling.

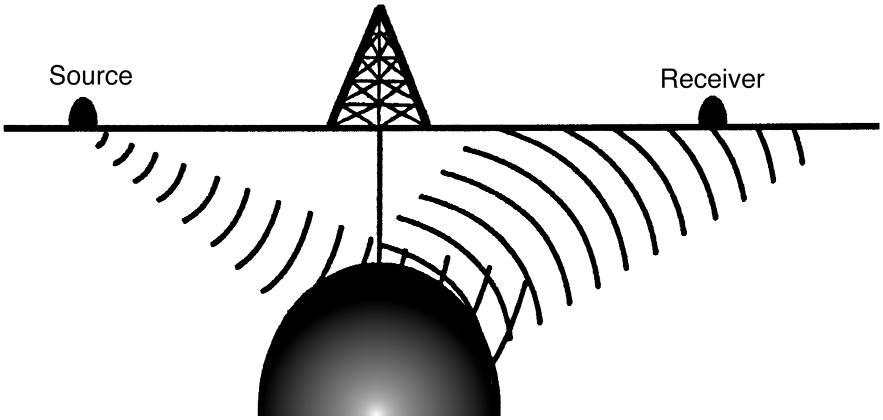

Figure 13.7. Geologists can "see" potential oil-bearing structures by analyzing reflected elastic waves.

abrupt changes in the medium through which they are traveling. Water waves in a bathtub reflect whenever they encounter the tub itself. Reflecting sound waves are responsible for echoes and the acoustical properties of rooms (Fig. 13.6).

We are all familiar with the reflection of light from mirrors, but sometimes we do not realize that reflected light is responsible for our ability to see most things. For example, light from a light bulb shines on a chair. Some of the light is reflected by the chair and reaches our eyes. Our brain analyzes the signals it receives and reaches appropriate conclusions about the location and important characteristics of the chair. Without reflected light we would see almost nothing.

Geologists use earthquake waves to "see" inside the earth in much the same way (Fig. 13.7). The earth is not homogeneous but has a variety of nonuniform structures. Elastic waves initiated by explosives or other means reflect from the boundaries between these structures. The reflected waves later reach the surface where sensitive instruments may detect and measure them. The analysis of these signals is not always simple, but such measurements have given us a considerable amount of information about the earth's interior.

Figure 13.8. A partly submerged stick appears to be bent. Why?

Refraction

Waves often travel from one medium to another in which the wave speed is different. When they change mediums, they often change direction. This phenomenon is called **refraction**.

Light travels more slowly in glass and other transparent materials than it does in air. The changes in direction that occur when light goes into or out of such materials is responsible for the operation of telescopes, microscopes, eyeglasses, and other optical instruments. Faulty depth perception when observing submerged objects is due to the refraction that occurs when light leaves the water surface (Fig. 13.8).

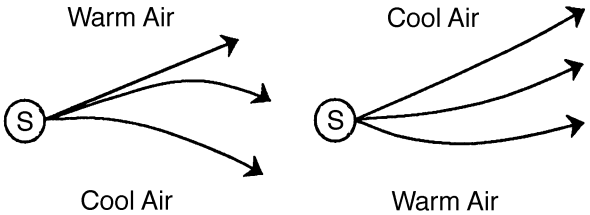

Figure 13.9. Refraction of sound due to cooler and warmer layers of air.

Sound waves are refracted as they move from cooler air to warmer air, or from warmer air to cooler air. Sound travels faster in warmer air than in cooler air. The direction the sound travels is always "bent" toward

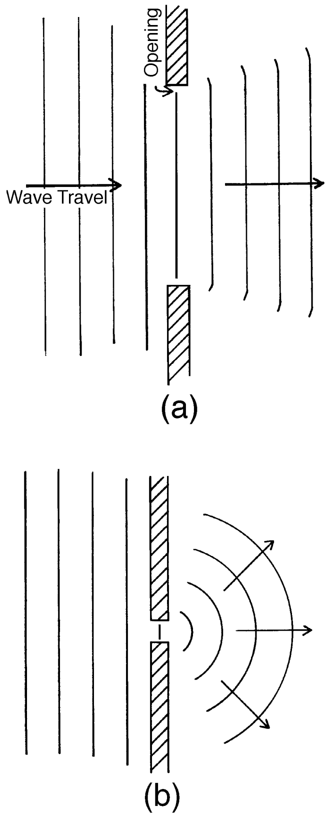

Figure 13.10. Because of diffraction, water waves spread out as they pass through holes. A smaller hole causes more diffraction.

the region of lower wave speed (Fig. 13.9).

A clear example of refraction often can be seen in ocean waves near gently sloping beaches. The wave speed in such cases depends on the depth of the water. As waves move from deeper to more shallow water, their speed becomes slower, and in many cases their directions change as well.

Diffraction

Diffraction refers to the ability of waves to bend around corners and spread whenever they encounter obstacles (Fig. 13.10). Sound can be heard around a corner, even when the source cannot be seen. Water waves spread after they pass through a narrow opening in a breakwater, so that the wave disturbs an area behind the opening that is much broader than the opening itself. In fact, the spreading becomes even more pronounced as the opening becomes smaller.

The amount of diffraction that occurs in a particular situation depends on the relationship between the wavelength and the size of the opening (or obstacle). Diffraction increases when the wavelength is larger than the opening. Diffraction is not readily apparent if the wavelength is a great deal smaller than the hole. For this reason, we do not usually notice the diffraction of light because of its short wavelength. However, if we cause light to pass through a small opening, perhaps by closing our eyelids until only a tiny slit is left through which light may pass, the diffraction of light is easily noticed because the resulting image is blurred.

Interference

Interference occurs whenever two (or more) similar waves travel through the same medium at the same time. The medium responds to both waves at once, being disturbed from equilibrium by an amount that represents the sum of the disturbances caused by the interfering waves.

As an example, imagine that two rocks drop near each other in an otherwise smooth pond (Fig. 13.11). Each rock initiates a set of circular waves across the surface. Both sets of waves seem to pass through each other without changing shape or speed. Both waves, however, pass through some points on the surface at the same time. In these regions they interfere. Where both waves are high at a particular point, the resulting disturbance is twice as high as for either wave alone; where both are low, the water is twice as low. The interference

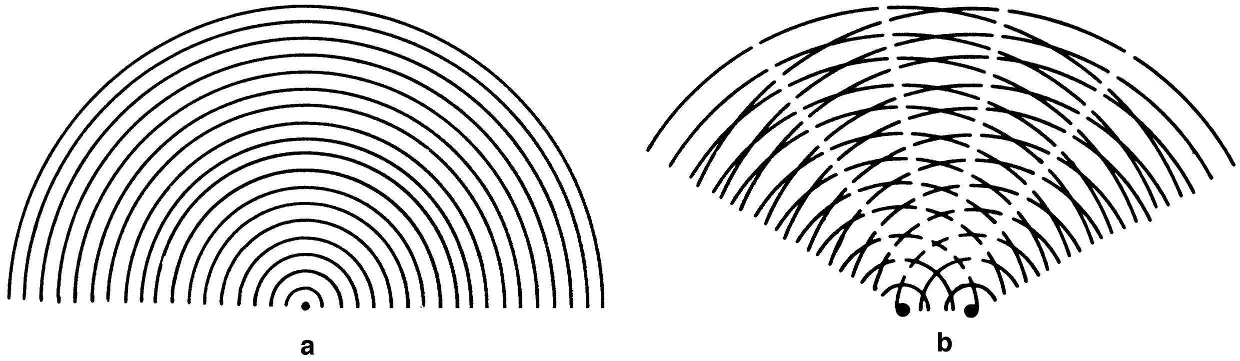

Figure 13.11. (a) A single rock, dropped into a pond, causes circular waves. (b) Two rocks dropped at the same time cause waves that interfere with one another.

at these points, where the two waves add to each other so that the resulting disturbance is greater than for either wave alone, is called **constructive interference**. At other points, however, one wave would cause the water to rise and the other would cause the water to fall. As both waves progress through such points, the medium seems not to be disturbed at all because the two waves cancel each other, resulting in **destructive interference**.

Interesting acoustical effects sometimes occur because of the interference of sound. Sound from a single musical instrument sometimes varies from place to place in a room because the various waves reflected to the listener from different walls interfere with each other. Interference effects due to sounds from two different instruments also occur. Musicians use such interference to tune their instruments by listening for beats caused by alternating constructive and destructive interference between two waves whose frequencies are close, but not identical.

Interference, particularly the possibility of destructive interference, is an important characteristic of waves. Notice in our water wave example that either wave by itself causes a disturbance at all points on the water surface. Every point is disturbed. However, when both waves travel through the medium, some places no longer seem to experience the effects of the wave, whereas other places oscillate more violently than for either wave by itself. Waves can cancel each other at certain places in the medium. Waves are the only phenomenon we know for which this kind of cancellation is possible.

Summary

Waves probably provide the most important means we have of interacting with our environment. Imagine how limited we would be without eyes and ears, let alone the microscopes, telescopes, radio and TV antennas, x-ray devices, and other instruments that depend on waves to enhance our natural senses. Waves, particularly light and its related phenomena, have played a fundamental role in helping to reveal the structure and behavior of all parts of the universe.

Waves are an important mechanism for transmitting energy and information. The waves of our everyday experience are disturbances of a medium. They may be surface waves, compression waves, or shear waves.

Waves are characterized by four properties: speed, frequency, wavelength, and amplitude. The speed of a wave is characterized almost exclusively by the elasticity and density of the medium through which it travels. The wave speed is equal to the product of the frequency and wavelength of the wave.

Wave behavior is characterized by four phenomena: reflection, refraction, diffraction, and interference. Of these, the latter two are most strictly characteristic of waves. Diffraction is the changing of a wave's direction of motion as it encounters objects. Diffraction is most pronounced when the wavelength is about the same as (or longer than) the dimension of the diffracting object. Interference occurs when two or more waves of the same type move through the same medium at the same time. Interference may be constructive or destructive.

STUDY GUIDE
Chapter 13: Waves

A. FUNDAMENTAL PRINCIPLES: No new fundamental principles. Matter set in motion by waves obeys the laws of motion, force, and conservation described in Chapters 3–8.

B. MODELS, IDEAS, QUESTIONS, OR APPLICATIONS

1. What are waves?
2. What types of waves are observed and what are their properties?
3. What is the relationship between the speed of a wave, its frequency, and its wavelength?
4. What phenomena are characteristic of waves?
5. Which of these phenomena cannot be explained in any other way except by assuming they are produced by some kind of waves?

C. GLOSSARY

1. **Amplitude:** A measure of the amount of displacement of the medium from its normal undisturbed position or value by the disturbance of a wave. If the disturbance caused the medium to move 3 inches to each side of its normal rest position, the amplitude of the wave is three inches.
2. **Compression Wave:** A wave in which the disturbance is a compression of the medium.
3. **Constructive Interference:** The enhancing interference that occurs when two waves occupy the same space at the same time and both disturb the medium in the same way so that the disturbance is larger than the disturbance of either wave separately.
4. **Destructive Interference:** The canceling interference that occurs when two waves occupy the same space at the same time and both disturb the medium in opposite ways so that the disturbance is smaller than the disturbance of either wave separately.
5. **Diffraction:** The changing of direction of waves to bend around corners and spread as they encounter obstacles.
6. **Frequency:** For a repeating disturbance, the number of identical disturbances produced per unit time, or, equivalently, the number of disturbances that pass a particular point in space every unit of time.

7. **Interference:** The canceling or enhancing effect that occurs when two waves move through the same space at the same time.
8. **Reflection:** The bouncing of a wave from a surface, such as an echo for sound waves.
9. **Refraction:** The changing of direction of a wave as it passes from one medium to another.
10. **Shear Wave:** A wave in which the disturbance is an elastic deformation perpendicular to the direction of motion of the wave.
11. **Surface Wave:** A wave which propagates over the surface of a medium, such as waves on the surface of a lake.
12. **Wave:** A disturbance or variation that progressively transfers energy from one point to another in a medium. The disturbance may take the form of an elastic deformation, a change in pressure, etc.
13. **Wavelength:** The distance between successive disturbances in a repeating wave.
14. **Wave Speed:** The rate at which the disturbance travels from point to point.

D. FOCUS QUESTIONS

1. What is meant by diffraction of waves? Describe and explain an example of the diffraction of water waves.
2. What is meant by interference of waves? Describe and explain an example of interference produced when two closely spaced sources initiate water waves of the same frequency.

E. EXERCISES

13.1. What travels from one point to another as a wave?

13.2. How do we know that waves carry energy?

13.3. What is a wave?

13.4. What is the difference between compression and shear waves?

13.5. Why are shear waves not propagated through fluids? Why are compression waves propagated through all materials?

13.6. Describe the processes by which compression and shear waves are transmitted through materials. What kind of elastic properties are required in each case?

13.7. Two water waves travel through the same body of water at different times. The crests of one are farther apart than the crests of the other. In which wave would a buoy move up and down more times in one minute? Explain your answer.

13.8. Explain why the frequency, wavelength, and speed of any wave are related to each other.

13.9. Describe what is meant by the terms wavelength, frequency, speed, and amplitude as applied to a wave.

13.10. Red light has a longer wavelength than does blue light. Which has the higher frequency? How do you know?

13.11. Why do we say that diffraction and interference are unique properties of waves? Can you think of other energy transfer mechanisms that exhibit these properties?

13.12. Describe some experimental evidence for the belief that sound is a wave.

13.13. What is meant by the reflection of waves? Describe an example.

13.14. What is meant by the refraction of waves? Describe an example.

13.15. What is meant by the term “diffraction?” Describe an example of the diffraction of water waves.

13.16. What is “wave interference”? Describe an example of the interference of water waves.

13.17. Sketch and describe the pattern observed when two closely spaced sources initiate water waves of the same frequency.

13.18. The direction of wave travel is observed to change as waves move from one medium into another medium because of the different wave speeds in the two media. This wave phenomenon is that of

(a) refraction
(b) diffraction
(c) reflection
(d) interference
(e) superposition.

13.19. Which of the following is (are) an example of a compressional wave?

(a) sound in air
(b) wave going from earth’s surface through center
(c) wave on violin string
(d) both a and c
(e) both a and b.

14. The Properties of Light

With this chapter we continue to study what has become known as the "modern synthesis," or the "20th century scientific revolution." These terms describe the collection of important discoveries made since the last decade of the 19th century. The modern synthesis includes the Special Theory of Relativity, which we have already encountered.

The ideas of the modern synthesis represent major transitions in our understanding of nature, and came about as men and women continued to probe the limits of the universe in several important directions. One of these limits is the investigation of the smallest things possible. As our tools become more refined, we can probe deeper into matter and ask questions that could never be answered (or even asked) at an earlier time. As we shall see, the answers reveal that this inner universe is totally unlike anything we experience in our macroscopic surroundings.

Another one of these limits is speed. How do things behave when they travel at speeds higher than any we normally encounter? Again, the answers are startling because they force us to reexamine our basic premises about time and space.

The fastest thing in nature is light. A careful inspection of its properties is important for what is to follow. Not only is light fascinating in its own right but it also is an important tool to be used in probing and understanding other important phenomena.

Two important constituents of the physical universe are matter and **electromagnetic radiation**. The first—matter—has already received considerable attention. The second—electromagnetic radiation—is a broad class of phenomena that includes visible light.

Electromagnetic radiation and matter interact with each other through the electromagnetic interaction. Because of this interaction, radiation provides many of the important clues that have led to our present understanding of the structure of matter. In fact, we have gone about as far as we can in describing matter itself. Therefore, to proceed further we need to understand some of the details surrounding the nature of light.

Light has always been a puzzle. What is it? What is transmitted from place to place when light "shines"?

The Speed of Light

Light has the highest speed of any known natural phenomenon—about 300,000,000 meters per second (or 186,000 miles/second). Light can travel around the earth in 0.13 second, from the earth to the moon and back again in 2.6 seconds, from the sun to the earth in 8.3 minutes, and across the entire solar system in about 11 hours. The speed of light is about 900,000 times the speed of sound in air, about 30,000 times the speed of the fastest rocket, and about 10,000 times the speed of the earth in its orbit around the sun.

The speed of light is a measuring stick for describing and comparing the immense distances in the outer universe. Such distances may be specified in terms of the time required for light to traverse them. For example, the average earth-to-sun distance can be specified as either 93 million miles or as 8.3 light-minutes. Using this system, the diameter of the solar system is 11 light-hours, and the distance to the nearest visible star, Alpha Centauri, is 4.3 light-years (about 24 trillion miles).

The high speed of light has not been easy to measure until recently. The first indication of its value was suggested by Danish astronomer Olaus Roemer in 1676. He was able to estimate the time taken for light to travel across the solar system by using his observations of the moons of Jupiter as a time reference. However, a more precise value was obtained by Armand Fizeau. He used a toothed wheel such as the one shown in Figure 14.1. In the earliest versions of the experiment, light passed through a gap, traveled 8.63 kilometers to a mirror, was reflected back, and blocked by a tooth which had rotated into its path. Knowing the speed of rotation of the wheel and the size of the gaps between the teeth, Fizeau was able to measure the speed of light.

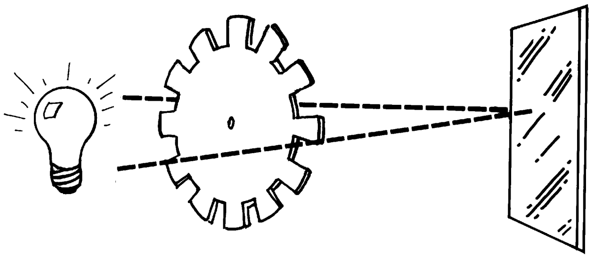

Figure 14.1. A method by which the speed of light can be measured. The wheel advances one tooth while a light pulse travels to the mirror and back.

Modern electronic devices permit the measurement of time intervals shorter than one-billionth of a second, the time that it takes light to travel one foot. Thus, the speed of light can be measured with high precision and must be taken into account in a variety of experiments. The speed of light is believed to be one of the fundamental constants of nature.

An interesting, unexpected feature of light is that its speed seems to be independent of the motion of the source or the observer. The consequences that the independence of the speed of light produced were considered in Chapter 9. Although this independence seems peculiar, it has been demonstrated convincingly in recent years by measuring the speed of radiation emitted by tiny particles accelerated to speeds within a fraction of a percent of the speed of light by modern high-energy accelerators. The speed of the emitted radiation is the same whether the particles are at rest or moving near the speed of light.

The Source of Radiation

Radiation and electric charge are intimately related. In fact, radiation occurs whenever electric charge is accelerated. Radio and television signals are caused by electrons accelerating in radio antennas. Visible light is caused by electrons accelerating in the hot outer layers of the sun or in a hot filament in an electric light bulb. X-rays are caused when fast electrons are suddenly stopped in an x-ray tube.

After leaving its source, radiation exerts forces on electric charges in the matter it encounters. Radio and television signals exert forces on the electrons in a receiving antenna, which causes them to move in a way that can be detected and converted into sound and picture. Visible light interacts with electrons in the retina of the eye or on a piece of photographic film. This causes reactions that are eventually converted to visual information. X-rays interact with electrons in living tissue, initiating biological changes that are responsible for their cancer-curing properties, as well as for their detrimental effects.

The theoretical relationship between electric charge and radiation was discovered by James Maxwell in the decades succeeding 1850. He combined the known laws governing the electromagnetic interaction into a mathematically consistent form now known as **Maxwell's Equations**. He found that the equations predicted waves with properties similar to those already observed for light. For example, the speed of light was accurately predicted by the equations. The correspondence between the theoretically predicted speed and the actually measured speed was a striking confirmation of the theory and of the relationship between electric charge and light. In addition to light, Maxwell's theory predicted other waves with the same speed but with different frequencies and wavelengths. These, too, were experimentally confirmed, and the new technology led to the development of radio, television, and radar.

All of the radiations associated with accelerating electric charge are known as electromagnetic radiation. All travel through empty space where they have the same speed—the speed of light. Therefore, although the forms of electromagnetic radiation differ in many important respects, they are all related.

The Electromagnetic Family

Maxwell's Equations predicted a group of waves associated with electromagnetic interaction. In a vacuum, all of these have the same speed—3×10^8 meters/second—but they differ in wavelength and frequency. This group includes radio waves (AM, FM, television, and microwaves), infrared radiation, visible light, ultraviolet radiation, x-rays, and gamma rays. These are listed in order of increasing frequency and decreasing wavelength (Fig. 14.2 and Color Plate 4).

Notice that visible light, the frequencies to which our eyes are sensitive, constitutes only a small part of this list. All the colors of the spectrum fall in this range, red corresponding to the longer wavelengths (lower frequencies) and blue and violet to the shorter wavelengths (higher frequencies).

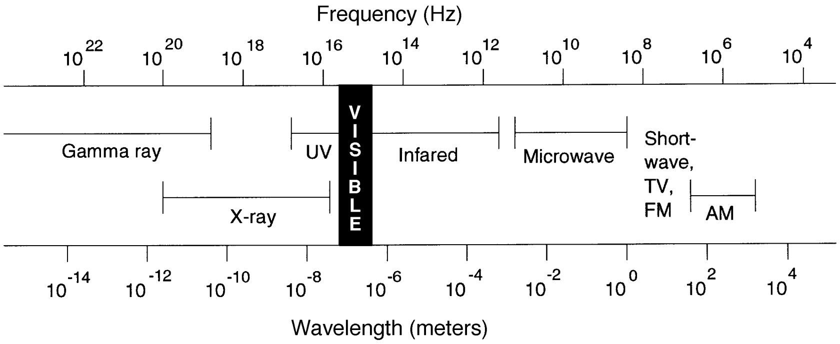

Figure 14.2. The family of electromagnetic waves.

Wave Phenomena of Light

The wave phenomena known as reflection, refraction, diffraction, and interference were described in Chapter 13. These phenomena also occur with all of the electromagnetic radiations. Reflection, for example, is responsible not only for the properties of mirrors but also for the transmission of long-range radio signals bounced from layers in the upper atmosphere. Refraction is used in the design of eyeglasses, microscopes, telescopes, and other optical instruments.

Diffraction, a phenomenon uniquely associated with waves, is the ability of a wave to travel around corners and to spread out after passing through a small opening. Radio waves diffract as they travel around barriers, such as mountains and large buildings, to reach a receiver that would otherwise be hidden from the transmitter.

Diffraction is less obvious with waves of shorter wavelength, such as television or visible light. The amount of diffraction depends on the relationship between the size of the opening or barrier and the wavelength of a wave passing through or around it. For example, if the wavelength is much smaller than the opening, diffraction is insignificant and the wave passes through without being distorted. If the wavelength is about the same size as the opening (or larger), however, diffraction is significant. Appreciable diffraction occurs when waves pass through an opening that is nearly as small as their own wavelength.

Diffraction can be studied experimentally by allowing light to pass through a series of small holes of different sizes onto photographic film, where the size of the images is noted (Fig. 14.3). With holes that are much larger than the wavelength of light, the images show the geometric shadows of the holes. Light seems to travel in straight lines, with no significant bending or diffraction as it passes through the holes. The images become smaller as the holes are made smaller.

However, when the holes become quite small, the nature of the images changes significantly. Diffraction occurs and the images become larger than the holes. If the holes continue to decrease in size, the images become correspondingly larger, the largest images corresponding to the smallest holes. This is what we would expect for diffracting waves.

Interference provides even more convincing evidence for the wave nature of light. Interference happens whenever two similar waves occur simultaneously at the same place. The usual way to obtain two similar

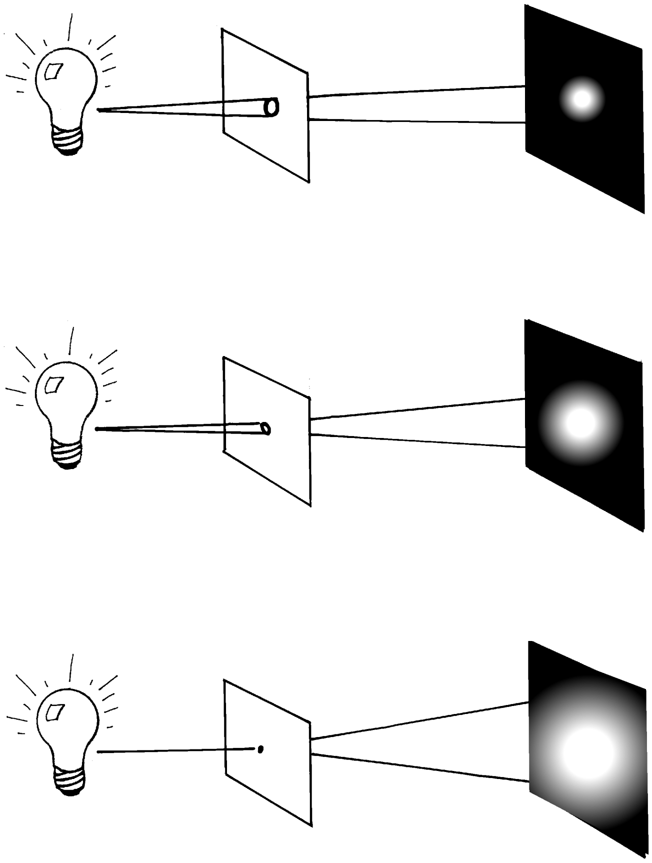

Figure 14.3. The diffraction of light. Why do the images become larger when the holes are made smaller?

light waves is to divide a single wave by partial reflection. When the two waves are recombined, usually by reflecting one in the same direction as the other, interference (which often can be observed) occurs.

A common example demonstrating both interference and diffraction occurs when a distant light source, such as a streetlamp or car light, is viewed through a piece of thin fabric (e.g., a curtain or handkerchief). The source of light appears to be larger than when it is viewed directly. Furthermore, the image is interlaced with alternating light and dark regions. The enlarging is the result of diffraction. Each wave encounters the small space between threads, spreads out behind the cloth, and creates a broad region in which the wave proceeds. The alternating light and dark regions of the image are due to interference. Individual waves that pass through adjacent spaces between threads overlap (because each is spreading out by diffraction) and interfere with each other—sometimes constructively and sometimes destructively. In some situations, it is possible to discern separate colors in the interference pattern. These patterns occur because the locations of regions of constructive interference depend on wavelength.

A more careful experiment may help illustrate the significance of interference. Consider a long, narrow slit through which light passes and falls on a piece of photographic film so that the positions of its arrival can be monitored. The slit is narrow enough so that significant diffraction occurs, and the recorded image is significantly broader than the slit itself (Fig. 14.4).

Suppose a second slit is opened next to the first one. When light passes through only this second slit, the same thing happens as before. Further, if the slits are close enough together, the diffraction patterns overlap.

However, a new feature emerges when light passes through both slits at once. Instead of a more intense image representing the combination of the two single images, the new image is a series of alternating light and dark areas. In some places the two waves result in a stronger wave with a brighter image than before, but in other adjacent places, the two waves combined cancel each other so that no light arrives. The waves interfere constructively to produce the bright lines and destructively to produce the dark lines.

This two-slit interference pattern provides convincing evidence of the wave nature of light. The demonstration is most dramatic at any one of the dark lines, where light arrives from each slit. When only one slit is open, the spot is illuminated and bright. However, when light arrives from both slits, it is canceled. Wave motion is the only phenomenon that exhibits such behavior.

A diffraction grating is a useful application of the same principle. The grating is simply a piece of glass or plastic on which are ruled a large number of linear scratches placed as close together as possible. The undisturbed glass between the scratches acts as a set of slits through which light can pass. Waves passing through individual slits are diffracted so that the waves all overlap. The resulting interference produces bright images in some locations and dark ones elsewhere (Fig. 14.5).

The large number of effective slits, together with their narrow spacing, results in narrow, bright images that are separated by broad, dark regions. In addition, the location of the bright images depends on wavelength; the images show up in one place for red light, another for violet light, and still others for the colors in between. If white light were allowed to pass through such a grating, its constituent colors would be dramatically revealed to the viewer. Such gratings can demonstrate the wavelengths that make up the light.

The Particulate Nature of Light

One of the startling discoveries of the 20th-centu-

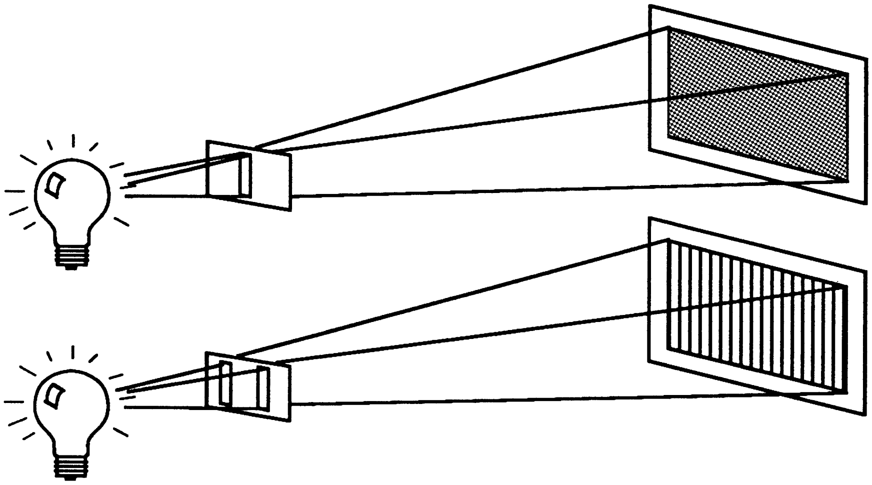

Figure 14.4. Interference of light. How can light from two slits give a dimmer image in some places than light from one slit?

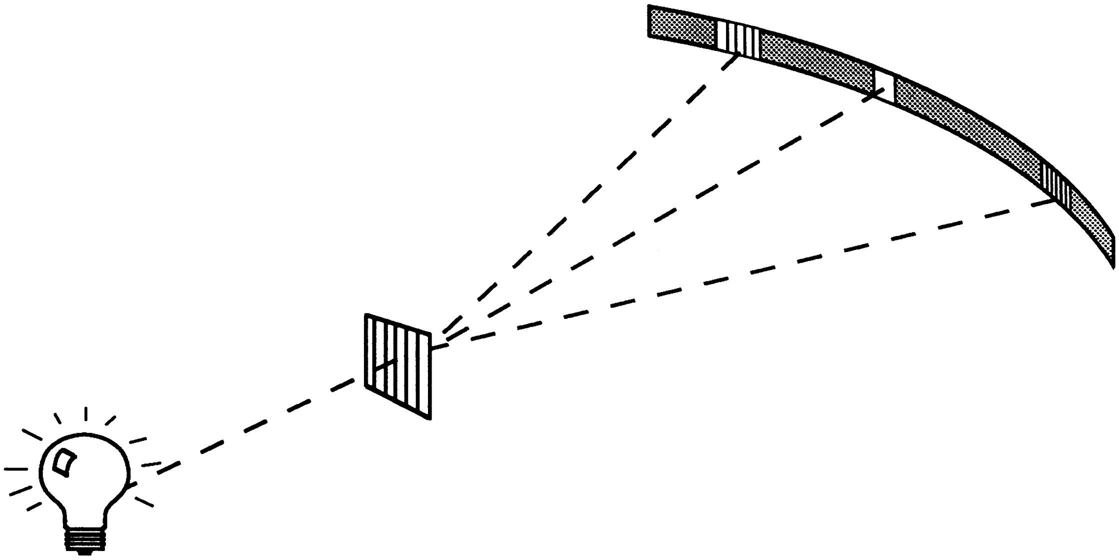

Figure 14.5. A diffraction grating separates light into its component colors by means of interference.

ry scientific revolution is that light not only has wave properties but it also has a particulate nature! It sometimes behaves in ways that can only be explained by assuming that light is a stream of fast particles traveling from the source to the receiver. (Newton was at least partly right after all.)

The simplest experiment revealing the particulate nature of light is to expose black and white film to greatly reduced light using an ordinary camera (Fig. 14.6). Pictures taken in ordinary light show smooth gradations of various shades of gray. The image seems smooth and continuous except for the graininess of the film emulsion. The exposure of the film generally occurs in a short time (0.01 second or so), during which time enough light reaches the film to record an image.

However, let us reduce the light illuminating the scene to be photographed so that 2 or 3 hours is required for sufficient exposure. What kind of image is recorded after 1 minute, 10 minutes, or 30 minutes? How is the final image built up by the incoming light?

If light were simply a wave, the photograph would gradually appear. It would start by being dark all over. Then, as the light arrived, the bright areas would gradually become brighter and the dark areas would not. The image recorded at any time would be the same as the final image, except it would not be as bright or well defined. The image would appear to consist of smooth gradations between various shades of gray.

The actual result is quite different than this. After a few minutes, the recorded image appears to be a random collection of bright dots. As time goes on and more light is admitted, the number of dots increases until the entire photograph gradually is filled in. The difference between the bright and dark places on the recorded image is not that the dots have different shades of gray, but rather that more dots are in the bright areas. All the dots seem to be about the same. The photograph consists of a large collection of dots that together form a picture.

This result cannot be explained in terms of a wave

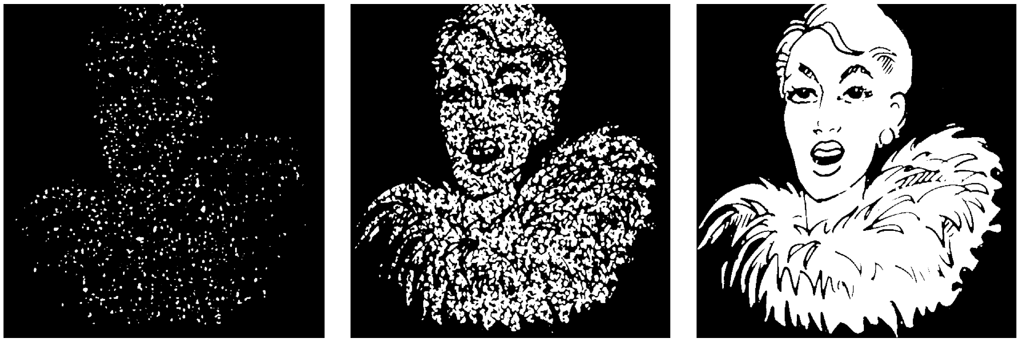

Figure 14.6. The appearance of a photograph if the light level is increased slowly.

model of light; it can be explained only if we assume that light is a stream of particles. Each particle is recorded as it reaches the film, leaving a single dot to reveal its arrival. The photograph assumes the image of the photographed object only when sufficient "particles" of light have arrived.

The existence of such particles of light has been verified by thousands of experiments performed during recent years. The particles themselves are referred to as **photons**. We normally do not notice them because there are so many in even the dimmest light that the signal seems to be continuous and smooth. Only in light beams that are too weak to be seen by the human eye are there few enough photons so that their individual arrival is revealed.

This raises some interesting questions: How many photons are in a particular light beam? How could such a number be estimated? The early scientists working on the problem of light naturally asked these questions. The key to the question turned out to be energy. Measuring the amount of energy arriving per second in any electromagnetic radiation is fairly simple. If the energy carried by single photons were known, calculating the number of photons arriving each second would be possible.

The energy associated with each photon was revealed by carefully reexamining an effect called the **photoelectric effect**, which had been known but not understood for many years (Fig. 14.7).

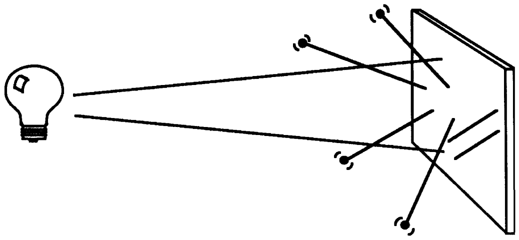

Figure 14.7. The energy of individual photons can be measured by studying electrons emitted from a metal plate when light is absorbed.

Light has the ability to discharge certain negatively charged materials, which is consistent with the general relationship between light and electric charge described earlier. The impinging light simply interacts with the electrons in the charged object, transferring enough energy to them so that they can escape from its surface. So far this is fairly understandable. However, certain disquieting features of this effect defied explanation in terms of light waves. For one thing, the ability of light to discharge an object depends on the color of the light (that is, its frequency). Higher-frequency light discharges an object more effectively. In fact, the effect does not occur at all if the frequency of the light is not high enough, even if the light is intense. The brightest red light cannot discharge most objects, even though a much dimmer ultraviolet light can do so readily.

The implications of these experimental results were understood only when the effect was interpreted in terms of a particulate model of light. In terms of this model, the photoelectric effect occurs when individual photons give up their energy to individual electrons. If the electron gains enough energy in this process, it can escape from the charged object, thereby partly discharging it. If it does not gain sufficient energy to escape, its extra energy quickly becomes thermalized and the object remains charged. This explanation of the effect, together with its dependence on the color of the incident light, also indicates something about the energy of individual photons. Those associated with higher frequency have more energy than those associated with lower frequency. "Violet" photons have enough energy to allow electrons to escape in many situations in which "red" photons do not.

The exact relationship between photon energy and frequency was discovered by measuring the energy of electrons ejected from materials that had absorbed the energy of individual photons. The answer is simple—energy of a photon is exactly proportional to frequency. In algebraic form,

$$energy = h \times frequency\ ,$$

in which h represents a new constant in nature that has come to be called **Planck's constant**, a small number (6.63×10^{-34} in the metric system of units). This means that the energy associated with individual photons is minuscule even at the high frequencies associated with visible light. Billions of billions of photons arrive every second in even the dimmest light.

Even though the energy associated with individual photons is small, it is enough to initiate some important sequences of events. Photoelectric absorption of photons by electrons is the first step in the photographic recording of images, photosynthesis, and vision, to name a few important examples.

Wave-Particle Duality

Now, after examining some of the important experimental evidence that reveals the nature of light, the ancient question still remains: Is light a wave or a stream of particles?

Particles are localized lumps. Waves are spread-out kinds of things. Therefore, they are of an opposite nature. The Principle of Noncontradiction says that of two contrary propositions both cannot be true. In the discussion of light we are faced with a puzzle which threatens to cast doubt on one of our "self-evident" truths that the reason of science is supposedly built on. We started out asking whether light was a particle phenomenon or whether it was a wave phenomenon because these are the only two means we know of conveying energy—as light does. Can light be both? Perhaps it would be better to say that it is neither and try to avoid the conflict with the Principle of Noncontradiction. Light is light. It has characteristics of waves and it has characteristics of particles, but it is something more than either.

This contradictory behavior probably is best exemplified by a simple experiment that combines the features of the two others we have described already. Imagine repeating the two-slit interference experiment with low-intensity light—so low that it takes several hours or days to complete the exposure of the film (Fig. 14.8). This slow exposure allows us to examine how the image of the interference pattern is built up as more and more light reaches the film.

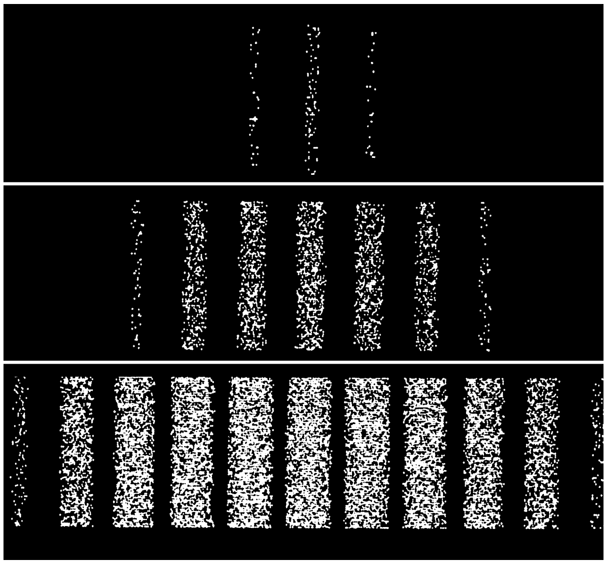

Figure 14.8. The appearance of the two-slit interference pattern as the amount of light is gradually increased.

The initial appearance of the film reveals the particulate nature of the absorbed light. Apparently random dots appear, all with about the same brightness. As the number of dots becomes larger, the alternating bright and dark lines of the interference pattern become clear. These reveal the wave nature of the same light.

Anything that exhibits both wave and particulate properties in this way is said to exhibit wave-particle duality. Such an entity is hard to imagine, but the experimental evidence is conclusive. To describe nature accurately, we must admit that light has these unusual properties.

Summary

Light is part of a group of phenomena collectively known as electromagnetic radiation. All members of the group can be created by accelerating electric charges, usually electrons, and all act on and may be absorbed by electric charges in materials on which they impinge.

Although the details of their creation and interaction with matter vary significantly, all electromagnetic radiations exhibit several unusual properties. They all travel at the same high speed through empty space, and their speed does not depend on the motion of their source or of the receiver. All electromagnetic radiations exhibit wave-particle duality. This means they show properties of both waves and particles. Finally, the energy of individual photons in any electromagnetic radiation may be calculated by multiplying the frequency of the radiation by Planck’s constant.

Historical Perspectives

“Let there be light: and there was light. And God saw the light, that it was good” (Genesis 1:3-4).

Galileo was convinced that light moved at a very great, though not infinite, speed. However, his own efforts to measure its speed by coordinating signals between himself and a colleague stationed on a nearby hilltop were unsuccessful. Some, like René Descartes (1596-1650), believed that light was propagated instantaneously at infinite speed, but it was Olaus Roemer who settled the issue in 1676.

Roemer must have had a sense of humor. He announced to the Paris Academy of Sciences that an expected eclipse of one of the moons of Jupiter would be delayed by 10 minutes. On November 9, 1676, at 45 seconds past 5:25 a.m., astronomers were positioned by the telescopes to observe the eclipse. It finally occurred at 5:35 a.m. However, Roemer waited two weeks before explaining to the baffled astronomers how he had known: It was just that the light from Jupiter varies in travel time from Jupiter to earth, depending on the relative positions of the two in their orbits (Fig. 14.9). His estimate of 22 minutes for light to cross a diameter of the earth’s orbit could have given him a rough estimate of the speed of light. Roemer showed the speed was not infinite.

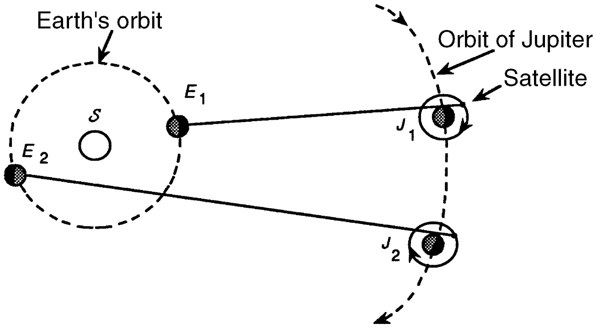

Figure 14.9. Roemer’s method of deducing the velocity of light.

Yet we are still left with the question: What is light? The answers have bounced back and forth through the ages. Is it a stream of particles? Democritus of Abdera (ca. 460-370 B.C., "inventor" of atoms), Isaac Newton (1642-1727), and Albert Einstein (1879-1955) lined up on the side of particles. Is it a disturbance in a medium (a pulse or a wave)? Aristotle (384-322 B.C.), Leonardo da Vinci (1452-1519), René Descartes (1596-1650), and Thomas Young (1773-1829) thought it was a wave phenomenon. To be a wave disturbance, there had to be something to be disturbed, so the proponents of the waves and pulses had to fill space with an invisible, hard-to-detect stuff that was called "ether." Eventually, Newton found a spot between the two extremes by suggesting that the stream of light particles would set the ether into vibratory motion.

Newton, for example, observed that objects placed in a strong beam of light cast very sharp shadows. Waves or pulses could be expected to bend around the edges of such objects in much the same way that sound bends around the edges of things. If light were waves or pulses, there would not be the sharp edges to the shadow. Therefore, Newton reasoned it was likely that light consisted of a stream of particles. Such an idea also explained refraction reasonably well. The particles of light striking an interface between two media were much like tennis balls striking and passing through a piece of tissue paper. The tissue paper would rupture, but the speed of the balls would be altered slightly as they passed through in just such a way that accounts for the refraction.

Newton's followers eventually dropped the idea of the ether altogether and adopted the purely particle theory of light. Generally, Newton's stature insured that the particle theory of light prevailed for a hundred years throughout the 18th century.

In 1801, Newton's idea was challenged by a London physician, Thomas Young, with these words: "Much as I venerate the name of Newton, I am not therefore obliged to believe that he was infallible. I see . . . with regret that he was liable to err, and that this authority has, perhaps, sometimes even retarded the progress of science" (Mason, *A History of the Sciences*, p. 468).

Young continued to think of light as vibrations of the ether and developed the classical two-slit experiment, which produces an interference pattern for light.

Young's case for the wave nature of light was strengthened by the conclusions of a younger colleague, Augustin-Jean Fresnel (1788-1827), who submitted a paper in 1818 on the wave theory of light to a competition sponsored by the Paris Academy of Sciences. One of the judges, Siméon Poisson, was a strong critic of the wave theory and proposed to test a prediction of Fresnel's, which he thought would destroy the theory once and for all. Fresnel's mathematical description of light waves predicted that if a circular disk were placed in a beam of light, a point of constructive interference would form a bright spot on a screen behind the disk. The spot, a result of the diffraction of the waves around the edge of the disk, would be at dead center of the shadow. Poisson was convinced that the spot would not form and that this would be conclusive evidence against the wave theory. Fresnel arranged to conduct the experiment, and to Poisson's surprise and discomfiture the spot appeared!

By the middle of the 19th century, the wave theory of light was well established. By 1849, Armand Hippolyte Louis Fizeau (1819-1896) had made the first terrestrial (i.e., not astronomical) measurement of the speed of light using the toothed wheel described in this chapter. However, the ether was still there and as big a problem as ever. By now the ether had become a kind of elastic rarefied matter through which the planets moved without seeming difficulty. If light were to be a disturbance, then something had to be disturbed, so the ether idea held until James Clerk Maxwell entered the scene.

James Clerk Maxwell (1891-1879) was a brilliant Scotsman from Kirkcudbrightshire who possessed a flair for mathematics. Maxwell drew together into four equations everything that was known about electricity and magnetism. What Maxwell summarized in his equations was an interconnectedness between electricity and magnetism.

Maxwell's Equations described what happens when electric fields and magnetic fields change in time. ("Fields" are the regions of influence which surround electric charges and magnets.) Light could be thought of as a self-sustaining disturbance of the fields themselves. This showed that waves didn't require an ether! Maxwell quickly worked out from his equations how fast these waves would travel through space. He got exactly the speed of light, which by that time had been measured by Fizeau. On December 8, 1864, he delivered his results before the Royal Society: "The agreement of the results seems to show that light . . . is an electromagnetic disturbance propagated through the field according to electromagnetic laws."

Maxwell died of cancer in 1879. Unfortunately, he did not live to see the experiments of Heinrich Hertz in 1888, which generated electromagnetic waves in the laboratory and which ushered in the era of radio and television. He also did not live to see Albert Einstein receive the Nobel Prize in 1923 for his explanation of the photoelectric effect, an explanation which clearly required that light was not waves at all, but a stream of tiny particles.

STUDY GUIDE
Chapter 14: The Properties of Light

A. FUNDAMENTAL PRINCIPLES

1. **Wave-Particle Duality of Electromagnetic Radiation (Light):** Electromagnetic radiation in its finest state is observed as particles (photons), but when unobserved (such as moving from place to place) is described by waves of probability. (The concept of "waves of probability" will be introduced in Chapter 16.)
2. **Principle of Noncontradiction:** See Chapter 1.

B. MODELS, IDEAS, QUESTIONS, OR APPLICATIONS

1. What is electromagnetic radiation? What is its source and what is its speed?
2. Is there evidence to support the view that electromagnetic radiation (light) has a wave nature?
3. Is there evidence to support the view that electromagnetic radiation (light) has a particle aspect?
4. How much energy is there in a photon of light?

C. GLOSSARY

1. **Electromagnetic Radiation:** All of the radiations produced by accelerating electric charge. Electromagnetic radiation is light, both visible and nonvisible.
2. **Maxwell's Equations:** A set of four fundamental laws, expressed in mathematical form, that govern electricity and magnetism and their interrelationship. The Electrical Force Law (see Chapter 4) is included in Maxwell's Equations.
3. **Photoelectric Effect:** Experimental results where low-frequency light does not discharge certain negatively charged materials, but high-frequency light does. The photoelectric effect is evidence for the particle nature of light.
4. **Photons:** Particles of electromagnetic radiation (light).
5. **Planck's Constant:** A fundamental constant of nature that appears in several fundamental relationships associated with wave-particle duality. For example, the energy in a photon equals Planck's constant times the frequency, E = Planck's constant × frequency.

D. FOCUS QUESTIONS

1. In each of the following situations:
   a. Describe what would be observed.
   b. Name and state in your own words the principle, or partial principle, that can explain what would be observed.
   c. Explain what would happen in terms of the principle.
   (1) A light beam from a laser is allowed to pass through two close, narrow slits and then fall on a screen.
   (2) Light from a regular flashlight and then ultraviolet light is shined on a metal surface hooked to a charged electroscope.

E. EXERCISES

14.1. Two rocket ships are approaching each other, each moving at three-fourths the speed of light. Light is emitted by one of them. How fast would this light appear to be moving if its speed were measured by the pilot of the first rocket ship and then by the pilot of the other rocket ship?

14.2. How fast would the light in question 14.1 appear to be moving if its speed were measured by a third person who is standing on the ground watching both rocket ships go by?

14.3. Suppose a truck were traveling at a speed of 50 miles per hour when a ball was thrown forward from the truck at a speed of 20 miles per hour. How fast would the ball be going as measured by a person on the ground watching the truck and ball go by?

14.4. Why are your answers to questions 14.2 and 14.3 so different? If you used the same reasoning in 14.2 as you did in 14.3, the light emitted by the rocket should be seen to be going one and three-fourths the usual speed of light.

14.5. Describe an experiment for measuring the speed of light.

14.6. Our eyes respond differently to red and blue light. Compare the speed, wavelength, and frequency of these two kinds of light.

14.7. Describe an example of the diffraction of light.

14.8. Describe a situation in which interference of light can be observed.

14.9. Describe experiments you might do to convince a skeptic that light has wave properties.

14.10. Describe how the pattern of light passing through a hole onto a screen changes as the hole becomes smaller. Start with a very large hole (say several inches in diameter) and describe what happens until the hole becomes very, very small.

14.11. Sketch and describe the diffraction pattern observed when light passes through a single narrow slit and then falls on a screen.

14.12. Describe what happens to the pattern in Exercise 14.11 when the slit is made even narrower.

14.13. Sketch the interference pattern observed when light passes through two close, narrow slits and then falls on a screen.

14.14. Explain how the pattern described in Exercise 14.13 can be explained.

14.15. Describe the appearance of a photograph taken with low-intensity light. What does this suggest about the nature of light?

14.16. Describe experiments you might do to convince a skeptic that light has particulate properties.

14.17. Is light wavelike or particlelike? Justify your answer by describing some experimental results.

14.18. What is a photon?

14.19. How can the energy associated with individual photons be measured?

14.20. Describe the photoelectric effect and explain how it demonstrates an important aspect of the nature of light.

14.21. Which color of light, blue or red, contains the more energetic photons?

14.22. Which of the following is false regarding red and blue light?
(a) both travel with same speed
(b) both produce interference patterns
(c) both produce diffraction patterns
(d) both have "same energy" photons
(e) they have different wavelengths.

14.23. The particle nature of light is demonstrated by
(a) reflection
(b) refraction
(c) interference
(d) diffraction
(e) photoelectric effect.