

Chapter 7:

Wave Models for

Sound and Light



Marin Mersenne (1588-1648). The scientific movement in France was characterized by a tradition of informal gatherings of interested scientists. One such informal group was held together by the personality of Marin Mersenne, a friar in the Palais Royale. Mersenne and his students disseminated the discoveries of Galileo, popularized the Cartesian coordinate frame, and publicized the work of such men as Pascal. Moreover, Mersenne succeeded (where Galileo had failed) in identifying the path of a falling body as having the shape of a parabola.

In this chapter we will return to the discussion of sound and light that we began in Chapter 5. This time we will describe both phenomena from the point of view of the wave model. As we already explained in Section 1.1, the history of models for light was full of controversy and the currently accepted models are still undergoing change. By contrast, the understanding of sound as wave motion dates to the seventeenth century and has advanced steadily with significant contributions by many physicists and mathematicians.

7.1 Applications of wave theory to sound

Early history. Sound and motion had been associated with one another since ancient days, but Galileo was the first person to note clearly the connection between the frequency of vibration of a sound source and the pitch of the note that was produced. This, in spite of the fact that musical instruments had existed for millennia!

Early experiments on the speed of sound. Many of the early experiments reveal a simplicity, an ingenuity, and occasionally a misconception that are charming. Thus, Galileo's idea originated in his scraping a knife at various speeds over the serrated edge of a coin. The first measurements of the speed of sound were made by timing the interval between the flash and sound of a distant gun being fired. A value of the speed very close to the present 344 meters per second was found. It was also noticed that sound travels faster in water (experiments were conducted in Lake Geneva, Switzerland) and in steel wires than in air.

Frequency of sound. Marin Mersenne, sometimes called the "father of acoustics," was the first individual to measure the frequency associated with the musical note emitted by a particular organ pipe. He tuned a short brass wire to the same musical note (and therefore the same frequency) as the organ pipe by hanging on weights to adjust the tension. Then he repeated the experiment with wire of the same material and thickness, and under the same tension, but 20 times as long. This wire vibrated so slowly that he could count ten vibrations per second. Because the material, thickness and tension of the two wires were identical, the wave speed along the two wires was the same. The relationship between frequency and wavelength (Eq. 6.3, $f = v/\lambda$) shows that, if v is constant, the frequency is *inversely proportional* to wavelength. (To review inverse proportions see Appendix A.2.) Thus Mersenne concluded that the original short wire (and the organ pipe) had executed 200 vibrations per second, 20 times as many as the long wire.

Medium for sound propagation. One of the big questions that had to be resolved was whether sound needed a medium. Vacuum pumps had been invented about the middle of the seventeenth century, and it was a simple matter to suspend an alarm clock or a bell in a jar to be evacuated. Unfortunately, a decade was required before Robert Boyle (1627-1691) successfully observed that the alarm in the jar could not be heard outside when the jar did not contain air. Other investigators had arrived at the contrary conclusion, perhaps because they had failed to remove

the air completely enough, or perhaps because the bell's support conducted the sound to the observers.

By the time of Isaac Newton, the wave model for sound as vibration of an elastic medium was generally accepted. In fact, it was so well accepted that the differences between sound and light, which we described in Section 5.1, convinced Newton that light could not also be a wave phenomenon (see Section 7.2)!

TABLE 7.1 SPEED OF SOUND IN SOLIDS, LIQUIDS, AND GASES

<i>Material</i>	<i>Speed (m/sec)</i>
<i>metals:</i>	
<i>aluminum</i>	5100
<i>brass</i>	3500
<i>copper</i>	3560
<i>gold (soft)</i>	1740
<i>iron</i>	5000
<i>lead</i>	1230
<i>brick</i>	3650
<i>glass</i>	5000
<i>marble</i>	3800
<i>paraffin</i>	1300
<i>rubber</i>	54
<i>liquids:</i>	
<i>alcohol</i>	1240
<i>water</i>	1460
<i>gases (room temperature):</i>	
<i>air</i>	344
<i>carbon dioxide</i>	277
<i>helium</i>	960
<i>hydrogen</i>	1360

Speed of sound. In Section 6.1 we described the conditions for wave motion in terms of the oscillator model for the wave medium. The two key factors were the inertia of the oscillators making up the medium and the interaction among them. The gasbag model for air and the MIP model for solids and liquids represent these materials as composed of subsystems that have inertia and interact with one another. Sound waves, therefore, propagate in all materials, but with a predicted speed that is high if the oscillators have low inertia and/or strong interaction and low if the conditions are opposite. Values for the speed of sound in various materials are listed in Table 7.1.

According to the MIP model, hard materials, in which there is strong interaction between oscillators, should exhibit a higher sound velocity than "soft" materials. You can see a trend compatible with your expectation; rubber, lead, paraffin, and water have a relatively low sound speed, while glass, iron, and aluminum have a high sound speed.

Speed of sound in gases. Gases are more difficult to include in the comparison, because both the interaction and the inertia in these low-density materials are much smaller than in liquids and solids, and these two differences may compensate for one another. From the fact that the sound speed in gases is lower than that in solids or liquids, you can conclude that the reduced interaction strength is more significant than the reduced inertia. This analysis of sound speed in gases is an example where the model does not lead to an unambiguous prediction, but where the model and experimental data may be combined to yield more insight into the properties of matter.

Frequency of musical notes. The wave model explains musical notes of different pitch as vibrations of different frequency. This relation was first investigated quantitatively by Mersenne. The presently accepted standard frequency is 440 vibrations per second for the "middle A" note. The entire musical scale is divided into octaves, which are two notes with a frequency ratio of two to one. Thus, various A notes have vibration frequencies of 110 per second, 220 per second, 440 per second, 880 per second, and so on. In Western music since about 1800 the octave interval is generally divided into twelve notes ("semitones"). The frequency ratio of adjacent semitones is slightly less than 1.06. In other words, each semitone has a frequency almost 6% larger than the next lower semitone. The notes in one octave and their frequencies are listed in Table 7.2. All frequencies in the table are multiples of the standard A-440 frequency. You can calculate the frequencies of the corresponding notes in higher or lower octaves by successively doubling or halving the frequencies in the table.

TABLE 7.2 PROPERTIES OF SOUND WAVES FOR MUSICAL NOTES

Note	Frequency (f , /sec) (approximate)	Frequency ratio to C note (approximate)	Wavelength in air (λ , m) (= $344/f$, approx.)
C (middle C)	262	1/1	1.31
C# = D ^b	277	-	-
D	294	-	-
D# = E ^b	311	-	-
E	330	5/4	1.04
F	349	4/3	0.99
F# = G ^b	370	-	-
G	392	3/2	0.88
G# = A ^b	415	8/5	0.83
A (standard)	440	5/3	0.78
A# = B ^b	466	-	-
B	494	-	-
C	523	2/1	0.66

Equation 7.1

$$v = f \lambda,$$

$$\text{or, } \lambda = \frac{v}{f}$$

$$\text{or, } f = \frac{v}{\lambda}$$

EXAMPLE:

$$v = 344 \text{ m/sec,}$$

$$f = 262 \text{ /sec}$$

$$\lambda = \frac{344}{262} \text{ m} = 1.31 \text{ m}$$

Wavelengths of sound waves. Air is, of course, the most important medium for the transmission of sound on earth. You can calculate the wavelengths, λ , in air of musical notes from their frequency (f , Table 7.2, second column) and the known sound speed, v , in air (344 m/sec from Table 7.1), by using the equation $v = f \lambda$ in the form $\lambda = v/f$ (Eq. 7.1, from Eq. 6.3b). The results are included in Table 7.2, fourth column. It is clear that audible sound waves, especially the ones used in speech, have a wavelength comparable to the size of the human body and to objects in our environment. This result (wavelengths of a few feet) is not surprising—as explained above (Section 6.2), the lengths of organ pipes range from a few inches to many feet, which is also the approximate size of the wavelengths of the notes they produce.

The magnitude of wavelengths of audible sound in air explains, in the context of the wave theory, why it is impossible to form a sharp acoustic image of the placement and shape of primary sound sources or reflectors. We pointed out in Section 6.4 that obstacles whose size is comparable to the wavelength diffract waves most strongly. Diffraction by persons, furniture, doors, and buildings, therefore, bends the sound waves so much that their direction and intensity is related only remotely to the placement of the primary sound sources and the reflecting surfaces. Sound transmits certain information about the primary source, for instance, intensity, pitch, and duration, but no sharp image of the location of the sound sources. Only in a clear space, and with the help of both ears, which receive somewhat different information (stereophonic), can we determine the position of sound sources in even an approximate way.

Musical instruments. In Section 6.2 we explained standing waves in an organ pipe and on a violin string as standing waves on tuned systems. The musical octave is simply related to the musical intervals between notes that can exist in a tuned system. For illustration, the various notes generated by standing waves in an organ pipe of 0.657-meter

TABLE 7.3 STANDING WAVES IN AN ORGAN PIPE WITH LENGTH (L) = 0.657 METER

Wave-length (meters) (λ)	Fre-quency (/sec) ($f = v/\lambda$ $= 344/\lambda$)	Note on mus- ical scale
1.31=2 L	262	C
0.66=2/2 L	524	C'*
0.44=2/3 L	785	G'*
0.33=2/4 L	1047	C''*
0.26=2/5 L	1309	~E''†
0.22=2/6 L	1571	G''*

* C' indicates a note exactly one octave above middle C with frequency = $2 \times 262 = 524$; C'' indicates a note exactly two octaves above middle C with frequency = $4 \times 262 = 1048$. G', G'' and E'' are defined similarly with respect to G and E in Table 7.2.

† The note with frequency of 1309 corresponds only approximately with E''.

length are listed in Table 7.3. The lowest frequency wave (longest wavelength) has nodes at both ends of the pipe with half the wavelength equal to the length of the pipe, or a full wavelength equal to $2L$ (first line of Table 7.3). The frequency is determined from Eq. 7.1, $f = v/\lambda = 344/1.32 = 262$ /sec. This wave is known as the fundamental; it has the lowest frequency possible on this system. Other waves (overtones) must also have nodes at the ends of the pipe, but additional half wavelengths can be fitted within the length of the pipe; this determines the remaining wavelengths (and higher frequencies) in Table 7.3, as explained in Sect. 6.2 (Eqs. 6.4 and 6.5).

Stringed instruments. We will explain stringed instruments (such as the guitar and violin) using the wave model. A single vibrating string does not transfer energy and sound effectively to the air; therefore, all stringed instruments require amplification and/or a well-designed sound chamber (the instrument's hollow body), which acts as a coupling element (Section 4.3) to the air. The sound chamber is passive in the sense that it does not affect the transfer of energy, but it is very important in determining the "quality" of the sound we hear. The best instruments are made from wood; the specific characteristics of the wood and its finish (the surface of which actually transfers the sound to the air) are critical.

In a guitar or violin, the lengths of all the strings (and thus the wavelengths of the sounds traveling along the strings) are determined by the length of the instrument and, therefore, are all the same. For the instrument to be able to produce a sufficiently wide range of pitches, the various strings, played at full length, must, therefore, vibrate at different frequencies. Waves of equal wavelengths but different frequencies must travel at different wave speeds along the various strings (Equation 7.1, $v = f\lambda$). Differing speeds means the various strings must have different inertia (weight or density) and/or a different strength of interaction (tension) along the string.

The first column of Table 7.4 lists the notes sounded by the six strings of a guitar when vibrating at full length; the second column lists the frequencies of these notes. To "tune" the strings so they vibrate at

TABLE 7.4 GUITAR WITH STRINGS 0.65 METER LONG ($= 1/2 \lambda$)

Note sounded by string (at full length)	Frequency (f, /sec) (from Table 7.2)	Wave speed on string (v, m/sec) ($= f \lambda$) ($= f \times 1.3\text{m}$)	Wavelength in air (λ , m) ($= v_{\text{air}}/f$)
E	82.5	107	4.17
A	110	-	-
D	147	-	2.34
G	196	-	-
B	247	-	-
E	330	429	1.04

exactly the correct frequency, the player turns the pegs, slightly adjusting the tension and thus the wave speed.

We can use the information in Table 7.4 to find the actual speed of the waves on the strings. The strings are all 0.65m long, so there must be nodes at both ends; thus half the wavelength must be 0.65m, and $\lambda = 1.30$ m. Putting this and the frequency into Equation 7.1 yields the wave speed on the string (Table 7.4, third column). Alternatively, using the frequency plus the speed of sound *in air* in Eq. 7.1 gives the wavelength in air (fourth column). Note that it is easy to forget that the wave speed (v) in Eq. 7.1 depends on the medium (sound or air). You should be careful to use the appropriate value, depending upon the medium (the substance that is actually vibrating and carrying the wave).

Other sound phenomena. We began the discussion of sound in Chapter 5 with the unexpressed operational definition of sound, "sound is what people can hear." It is now appropriate to redefine sound with a formal definition, as displacement waves in a medium, and thereby to extend the concept of sound beyond the limitations of the human ear. As a matter of fact, the human ear is capable of detecting sound waves only between frequencies of approximately 20 and 20,000 vibrations per second, with a great deal of variation among individuals. Lower-frequency vibrations are sensed as rapid knocking, while higher-frequency vibrations are not detected at all, except possibly as pain if they are very intense. Nevertheless, these other waves do occur naturally and/or have been exploited technologically.

Ultrasonics. Ultrasonics refers to sounds with frequencies too high for the human ear. Therefore, ultrasonic sound waves have a much shorter wavelength than audible sound, only about 0.01 meter or less. Ordinary size obstacles therefore diffract ultrasonic sound waves much less than audible sound; hence ultrasonic sound waves can be directed into narrow beams that are reflected by environmental objects. The reflected beam furnishes information about the position of the reflecting object.

Sonar is a method for locating objects under water using ultrasonic sound waves. A high frequency sound source emits wave pulses at a frequency of 20,000 vibrations per second or more; a detector records the reflected pulses (echoes). The relative position (direction and distance) of the reflecting object is determined from the direction of the reflected pulse and the time delay of its arrival after the original pulse was emitted. Sonar depth gauges, which measure the distance to the ocean floor by the time delay of reflected pulses, are now standard equipment on many pleasure boats and commercial craft.

In an industrial application of the sonar principle, sound with several million vibrations per second is used to locate flaws in steel pieces, rubber tires, and so on. The flaw is an irregularity that reflects sound waves and can thereby be detected.

The sonar principle has also been applied in many beneficial ways to health care, most notably to form images of a developing human fetus within the mother's womb. The baby's tissues and bones reflect the sound waves, and computer-assisted detectors can then, amazingly

enough, produce an image from the reflected waves and display it on a conventional TV monitor. Naturally the potential effects of the sound waves on the human body must be investigated carefully and, so far, such effects have been found to be negligible.

The bat is an unusual mammal that can use the sonar principle to locate objects and avoid obstacles in dark spaces (such as caves and bellies). A bat can make sounds with frequencies close to 100,000 vibrations per second. Bats use these sounds to perform amazing feats locating tiny insects (their food) while flying in pitch darkness.

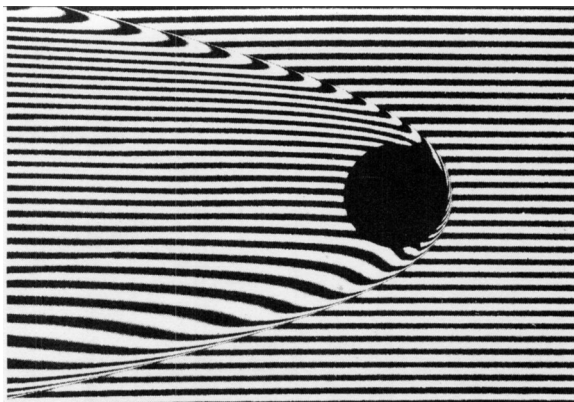
Sub-audible waves. At the other end of the sound spectrum from ultrasonic waves are waves with sub-audible frequency. Most interesting to the scientist are seismic waves, which are generated by the movement of large bodies of rock during earthquakes. The frequencies of seismic waves are in the range of a few vibrations per minute (0.1 per second). There are two kinds of seismic waves, which differ in the direction of the oscillator displacement relative to the direction of propagation. One kind, called the primary wave, travels about 6500 meters per second in the earth's crust, twice as fast as the other kind, called the secondary wave.

Seismic waves are the best source of information about the interior of the earth. They are refracted inside the earth because their speed in various layers is greater or less than it is at the surface. The earth therefore acts like a huge, complicated lens whose properties are inferred from the geographic distribution of seismic waves emitted in earthquakes. One inference is that the material changes abruptly at a depth of about 50 kilometers. This change, which defines the boundary of the earth's crust, is called the Mohorovicic discontinuity ("Moho" for short).

Shock waves. The final item we will take up in this section is shock waves, which are a form of sound with extremely large amplitude and very sudden onset. Whenever an object moves with supersonic speed (faster than the speed of sound in the surrounding air or other medium), the air is displaced very abruptly. What happens then is analogous to what happens at the bow of a speedboat that pushes the water aside



Figure 7.1 A shock wave created by a plastic sphere traveling through air at ten times the speed of sound.



suddenly. The sudden displacement of the air by the moving object cannot communicate itself to other parts of the air in the form of sound waves, because sound travels too slowly. For example, at the front of the moving object, the sound can't get "ahead" of the object because the object itself is moving faster than sound.

Consequently, there is a very large change of air pressure, the ordinary wave model breaks down, and the frequently destructive shock wave is formed (Fig. 7.1). Supersonic airplanes generate shock waves (sonic boom) in air very much in the way the speedboat generates shock waves on the water surface. The boom is caused by the sudden increase in air pressure. Explosions also generate shock waves. The very hot material near the site of the explosion expands into the surrounding material with a speed faster than the speed of sound in that material.

7.2 Application of the wave model to light

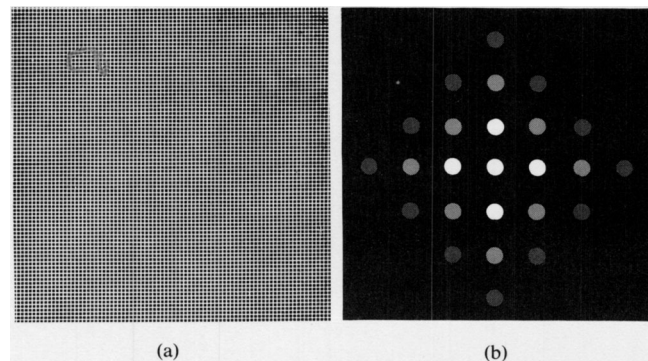
The wavelength of light. Your observation of an interference pattern when you looked through a piece of cloth at a distant light source (Section 5.1) seems to be understandable only with a wave model for the light (Figure 7.2). When you apply the wave model to your everyday experience with light, you conclude, from the absence of noticeable diffraction under ordinary circumstances, that the wavelength of light must be much smaller than the size of the objects around you. Only when you looked through finely woven fabric were the effects of diffraction noticeable, and even then they were quite small.

You can understand the appearance of the interference pattern by thinking of the threads in the fabric as forming two diffraction gratings, one with its slits and barriers at right angles to those of the other one.

Figure 7.2 A handkerchief serves as diffraction grating (Fig. 5.3).

(a) Thread pattern of a handkerchief.

(b) Diagram of the interference pattern from a distant lamp observed through a handkerchief.



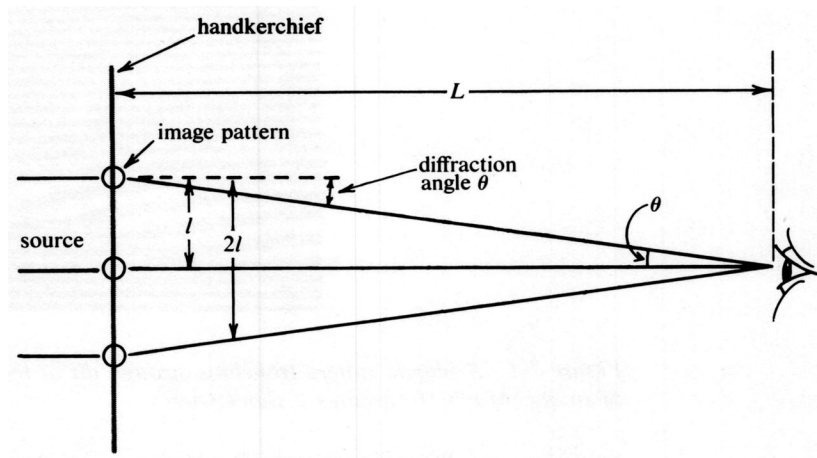


Figure 7-3 Measuring the wavelength of light with a handkerchief held at arm's length, a distant light source, and a ruler (example included for illustration).

- (1) Measure arm length: $L \approx 70 \text{ cm} = 700 \text{ mm}$.
- (2) Measure the spacing of the three bright image spots at a distance of one arm's length: $2l \approx 3 \text{ mm}$.
- (3) Use Eq. A-6 to calculate:

$$\sin \theta \approx \frac{l}{L} \approx \frac{1.5}{700} \approx 2 \times 10^{-3}$$

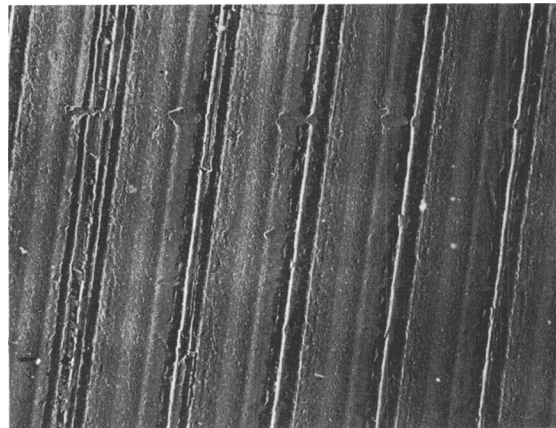
- (4) Measure the "slit distance" of the handkerchief, which has three threads per millimeter (use a magnifier):

$$d \approx 1/3 \text{ mm} \approx 0.3 \text{ mm} = 3 \times 10^{-4} \text{ m}$$

- (5) Calculate the wavelength (Eq. 6-13):

$$\lambda = d \sin \theta \approx 3 \times 10^{-4} \times 2 \times 10^{-3} \text{ m} = 6 \times 10^{-7} \text{ m}$$

Figure 7.4 Electron microscope photograph of a diffraction grating.



The first machines for making the slits in a grating were designed and built by Henry Rowland of Johns Hopkins University at the end of the nineteenth century; his gratings, made by scribing many precise scratches on metal or glass, were expensive and prized scientific tools. Nowadays, very inexpensive gratings are manufactured by impressing the rulings on a sheet of plastic, in much the same way that CDs or auto parts are stamped out from a master mould.

The interference of the light diffracted by the vertical threads produces images of the source displaced in the horizontal direction. The horizontal threads diffract the light to produce images that are displaced in the vertical direction. The combination of both then results in the checkerboard array of images that is observed (Fig. 7.2). How a simple measurement can be used to calculate the wavelength of visible light is explained in Fig. 7.3. The wavelength is indeed very short, only about 6×10^{-7} meters.

Diffraction gratings. Diffraction gratings for the study of light have to be made with a spacing between slits that is comparable to the wavelength. Then the light is diffracted at angles that can be observed easily. A commercial diffraction grating is a transparent sheet with many narrow scratches on its surface (Fig. 7.4). The scratches, which are too small to be seen, are slight obstacles to the propagation of light. The narrow regions between the scratches therefore act as narrow slits. Most of the light incident on the grating passes through unaffected. A small portion of the light, however, is diffracted by the many slits and emerges traveling in a direction at an angle to the incident light. As was shown in Section 6.4, Eq. 6.13 relates the diffraction angle to the distance between slits and the wavelength of the light. Light of

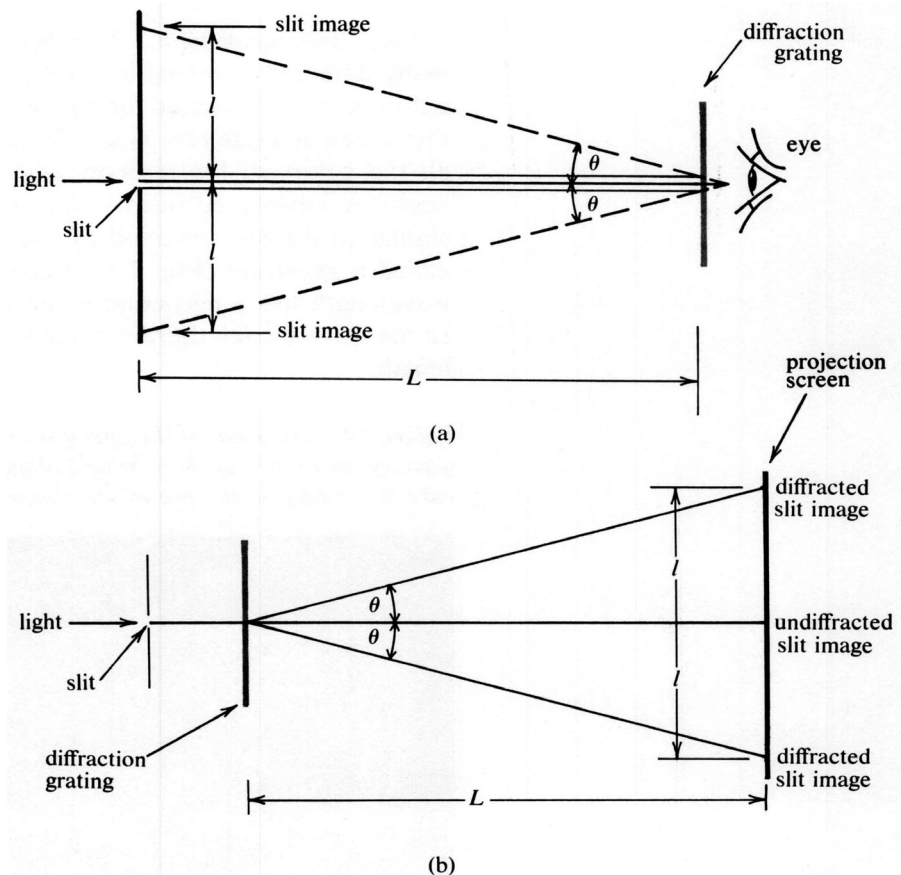


Figure 7.5 Observation of the light that comes from a slit and passes through a diffraction grating.

(a) Viewing the diffracted light directly.

(b) Projecting the diffracted light on a screen.

Equation 6-13

wavelength (meters) λ
 distance between slits
 (meters) d
 diffraction angle θ

$$\sin \theta = \frac{\lambda}{d}$$

Equation 7-2

(Symbols defined in Fig. 7-5.)

$$\sin \theta = \frac{l}{\sqrt{l^2 + L^2}} \approx \frac{l}{L}$$

Equation 7-3

$$\frac{\lambda}{d} = \frac{1}{\sqrt{l^2 + L^2}} \approx \frac{l}{L}$$

short wavelength, therefore, is diffracted through a smaller angle than light of long wavelength.

To observe the diffracted light, you may either look through the grating at the light source or let the diffracted light impinge on a screen at a substantial distance behind the grating (Fig. 7.5). A shield with a slit is usually placed in front of the grating to act as a narrow rectangular light source whose diffracted images can be recognized easily by their shape. You can use the measurements to calculate the diffraction angle (Eq. 7.2) or you can calculate the wavelength directly (Eq. 7.3).

If the wavelength is very much smaller than the grating spacing, then the diffraction angle is very small and you cannot observe the diffracted light separately from the undiffracted light because the two images of the slit overlap. For good observations, the grating spacing must be almost as small as the wavelength of light. The manufacture of such gratings clearly requires precision apparatus.

Color and wavelength. If a beam of white light, which includes light of many different wavelengths strikes a diffraction grating, the various wavelengths emerge at different angles and thus strike a screen (as shown in Fig. 7.5) at different locations. What your eye observes on the screen, however, is a display of all the colors of the rainbow side by side (as shown in Fig. 7.6). Such a display of light, similar to the one obtained by Newton with a prism (Section 5.2), is called a *spectrum*. Each portion of the light with a single wavelength has a particular color and is called monochromatic light. In the wave model, therefore, *color of light is associated with its wavelength*.

The wavelength of visible light ranges around the value we reported above from the crude experiment with the handkerchief. The association of color and wavelength is given in Table 7.5. As shown in the Table, the wavelength range of visible light is actually quite narrow (from 4 to 7×10^{-7} m). This seems somewhat paradoxical: the colors detectable by the human eye seem, intuitively, to span a huge range (think about the number of colors available in a paint store, or, even more impressive, the complex shades and hues discovered by the Impressionist painters), yet this extraordinary complexity is confined within such a narrow range of wavelengths! However, on reflection,

Figure 7.6 Diagram of the spectrum of light, with an indication of the wavelength ranges of the various colors. The transitions are gradual and vary depending on the eye of the observer

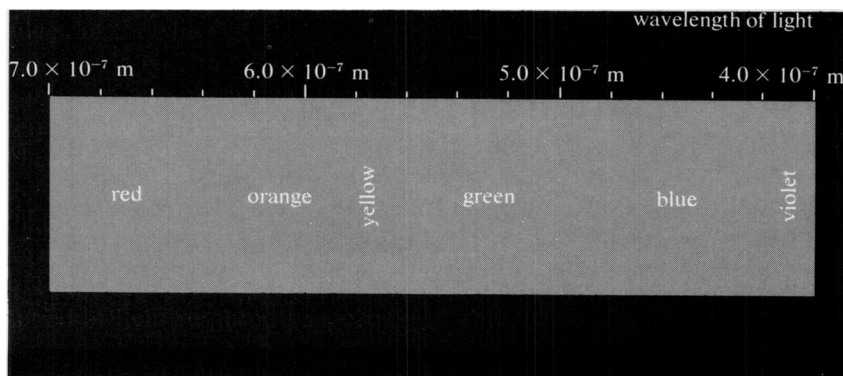


TABLE 7.5 WAVELENGTH AND COLOR OF LIGHT (APPROXIMATE)

Color	Wavelength range (m)
violet	$4.0 \text{ to } 4.2 \times 10^{-7}$
blue	$4.2 \text{ to } 4.9 \times 10^{-7}$
green	$4.9 \text{ to } 5.7 \times 10^{-7}$
yellow	$5.7 \text{ to } 5.8 \times 10^{-7}$
orange	$5.8 \text{ to } 6.4 \times 10^{-7}$
red	$6.4 \text{ to } 7.0 \times 10^{-7}$

Ole Roemer (1644-1710) was a prominent Danish scientist who served as a member of the French Academy and as the tutor of the son of King Louis XIV. With the revocation of the Edict of Nantes in 1681, Roemer, like Huygens and others prominent in the French Academy, fled France for the safety of Protestant Northern Europe.

Equation 7.4 (Roemer's measurement of the speed of light in 1676)

$$v_{\text{light}} = \frac{\Delta s}{\Delta t}$$

$$\Delta s = \text{diam., earth orbit} \\ = 3 \times 10^{11} \text{ m}$$

$$\Delta t = 22 \text{ min.} \\ = 1.3 \times 10^3 \text{ sec}$$

$$v_{\text{light}} = \frac{3 \times 10^{11} \text{ m}}{1.3 \times 10^3 \text{ sec}} \\ = 2.3 \times 10^8 \text{ m/sec}$$

Modern value:
 $v_{\text{light}} = 3.0 \times 10^8 \text{ m/sec}$

there is a refreshing lesson here; our eyes (and brains) indeed are capable of quite extraordinary feats as detectors of light, able to easily distinguish colors that have almost identical wavelengths (or slightly different mixtures of wavelengths). Modern spectrosopes and other instruments are extraordinarily good at spreading light out and detecting even the faintest components, but our eyes are also extremely capable. The human visual system (the eye and brain) is also capable of making extraordinarily fast judgments in real time; while the best optical instruments probably could match or exceed the human eye in the narrowly-defined task of distinguishing between slightly different wavelengths; there would be no contest with regard to speed.

We can also think of the differences among the various colors of light in terms of their frequencies. The frequency of visible light (calculated from $f = v/\lambda$) ranges from about 1.3 to 2.3×10^{15} ! This is an extraordinarily high frequency. The complex information about colors that can be conveyed by light is a example of the huge information-carrying ability of a wave with such a high frequency. It is indeed generally true that higher frequency waves can carry more information. Another example of this is in the capacity of fiber optic cables (which use light) to convey information, which far exceeds the capacity of coaxial cable or ordinary telephone wires (both of which use much lower-frequency waves in the radio range).

By using energy detectors other than the human eye it is possible to identify diffracted radiation of shorter and of longer wavelength than visible light. This radiation is called *ultraviolet* light and *infrared* light, respectively. In other words, the implicit operational definition for light, "radiation detected by the human eye," should be extended to forms of radiation that are not detected by the eye, but are functionally very similar to visible light.

The speed of light. Ancient philosophers speculated about the speed of light and variously held the opinion that light propagated with a finite speed and that it propagated instantaneously. Galileo made the first attempt to measure the speed of light by having two distant observers flash lanterns back and forth. The experiment failed because the time required by the light was much less than the reaction time of the participants.

Roemer's measurement. Ole Roemer made the first successful measurement of the speed of light in 1676. He studied the revolution of Jupiter's satellites (the four "Galilean moons," discovered by Galileo in 1610). Roemer noticed something strange: the moons' orbital periods all became gradually shorter while the earth was approaching Jupiter and longer while the earth was moving away from Jupiter. Roemer figured out that these changes must be due to the fact that light did not travel at infinite speed. In fact, light took some time to travel from Jupiter to the earth, and this delay would gradually become shorter (or longer) when the earth was approaching (or moving away from) Jupiter. Roemer measured the maximum time difference in the revolution periods to be 22 minutes (1.3×10^3 sec), during which time the light would

Jean Bernard Lion Foucault (1819-1868) studied medicine before changing to physics. In 1851 his celebrated Foucault pendulum experiment demonstrated the earth's rotation relative to the fixed stars. In later years, he invented the gyroscope and made a determination of the velocity of light by using a revolving mirror.

TABLE 7.6 SPEED OF LIGHT

Material	Speed (m/sec)
vacuum	3.0×10^8
air	3.0×10^8
glass	1.9×10^8
water	2.3×10^8

have to cross the earth's orbit, a distance that was then thought to be 3.0×10^{11} meters. Even though Roemer's result (Eq. 7.4) is considerably lower than the presently accepted value, it is a truly remarkable achievement because it occurred only a century after the planetary model for the solar system was introduced by Copernicus, only 66 years after Jupiter's moons were discovered by Galileo, and at a time when the diameter of the earth's orbit around the sun was not known accurately.

Foucault's measurement. Modern methods for measuring the speed of light basically make use of Galileo's concept but substitute a mirror rotating at a known high speed (Foucault's contribution) for the man flashing the lantern. The rotating mirror flashes a beam of light to a distant mirror, which returns the light with a delay equal to the time required for the light to travel to and from the distant mirror. Depending on the time delay, the rotating mirror has assumed a new position, which reflects the returning light to a detector. Because the mirror rotates at high speed, even the short travel time of the light flash finds the mirror in a measurably changed position. This change in the mirror's position is compared with the known speed of rotation to yield the travel time. The speed of light is then found by dividing the distance the light traveled by the time. (Table 7.6).

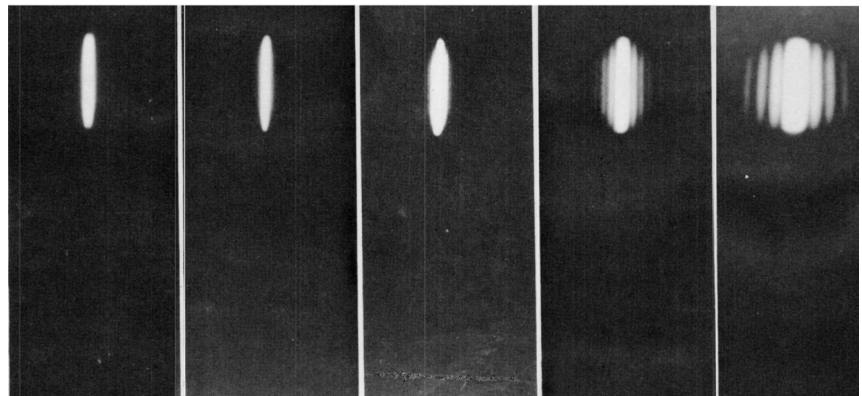
It is ironic that modern methods for measuring the dimensions of the solar system represent a reversal of Roemer's procedure. Now that the speed of light is known accurately from terrestrial measurements, the travel time of light to other planets is observed (as it was by Roemer) and the distance to them is calculated.

Speed of light in water. Foucault also measured light's speed in water and found that it travels considerably *slower* than in air. This behavior is contrary to the behavior of sound, which travels *faster* in dense materials than in air (Table 7.1). For this reason, as we explain below, Foucault's measurements of the speed of light were very significant in the history of the theory of light; Foucault's measurements provided a critical test for models of light and dramatized the inadequacy of the wave model. Later measurements confirmed Foucault's results for water and found that light also travels more slowly in glass than in air (Table 7.6).

The ray model and the wave model for light. The ray model described in Section 5.2 was based on a set of assumptions that were not further justified. It was sufficient that they were successful in explaining the observed properties of light, such as formation of shadows, operation of lenses, combination of colors, and so on. The model described but did not explain refraction (Fig. 5.16, Assumption 5) or the difference among monochromatic rays of various colors. Furthermore, it did not specify how a single ray might be separated from a light beam; that is, the ray was a formal concept in the model and did not have an operational definition.

Isolation of a light ray. Since the ray model says that light is composed of rays, you may well be curious to see a single such ray. Suppose we attempt to isolate a single ray as follows: We place an opaque shield in front of a light source and puncture it. Through the tiny hole, a

Figure 7.7 The attempts to isolate a single light ray by passing light through a narrow slit fail. The slit widths (in order from left to right) are 1.5, 0.7, 0.4, 0.2, and 0.1 millimeters, respectively.



slim beam of light passes. Now we make successively smaller and smaller punctures in the shield. The ray model predicts that we should get thinner and thinner shafts of light. However, the physical world doesn't always act the way we expect: Figure 7.7 shows what actually happens.

The light actually *spreads out* as the hole is reduced below a fraction of 1 millimeter in width (Fig. 7.7)! This behavior, especially the pattern of light and dark fringes in the photo with the narrowest slit (on the far right) is very mysterious; it doesn't fit at all naturally with the ray model. You may think that the spreading out of the light could be explained within the framework of the ray model by reflection or scattering of the light in some way from the edges of the slit; scientists, including Newton, indeed used the ray model to construct such explanations. However, any explanations based on the ray model simply cannot explain the pattern of dark and light fringes that appear as the slit gets narrow. In fact, the narrower the slit, the wider and more pronounced the fringes become, and there isn't any way to combine rays of light in such a way as to cancel themselves and thus produce a dark fringe.

On the other hand, this phenomena is very reminiscent of what we observed with waves in Chapter 6: waves naturally spread out or diffract when they pass through narrow openings (Section 6.4); furthermore, waves can easily cancel one another, as in destructive interference (Section 6.2, Fig. 6.11). In addition, the two-hole interference pattern (Figure 6.21) had certain locations where the waves always cancelled one another out; this would be a natural way to explain the dark fringes. Finally, Huygens' Principle (Section 6.3) applied to waves striking a diffraction grating (Section 6.4) predicted that, as the angle of diffraction changed, the waves cancelled and reinforced and cancelled and reinforced (Figure 6.24); this would seem likely to produce a pattern of dark and light fringes.

Limitation of the ray model. Evidently the ray model is limited. When experiments are pushed beyond the limits of this model, it breaks down. The wave model is suggested by the diffraction of the single slit (Fig. 7.7), and by the interference pattern seen through the handkerchief (Fig. 7.2). As we will show below, it is a better model for light than the ray model. In other words, light beams are better represented as packets of

Equation 6-14

angle of incidence θ_i

angle of reflection θ_R

$$\theta_i = \theta_R$$

Equation 6-17b

angle of refraction θ_r

speeds of light v_i, v_r

$$\frac{\sin \theta_i}{\sin \theta_r} = \frac{v_i}{v_r}$$

Equation 5-2

indices of refraction n_i, n_r

$$n_r \sin \theta_r = n_i \sin \theta_i$$

EXAMPLE 7.1

From Equation 5.2:

$$\frac{\sin \theta_i}{\sin \theta_r} = \frac{n_r}{n_i} \quad (1)$$

and from Equation 6.17(b)

$$\frac{\sin \theta_i}{\sin \theta_r} = \frac{v_i}{v_r} \quad (2)$$

Let the incident medium be air. Then $n_i = 1$ (from Table 5.1), and

$$v_i = v_{\text{air}}, \quad n_r = n_{\text{medium}}, \quad \text{and} \quad v_r = v_{\text{medium}}.$$

Putting together

Eqs. (1) and (2):

$$n_{\text{medium}} = \frac{v_{\text{air}}}{v_{\text{medium}}} \quad (2)$$

"Are not all Hypotheses erroneous, in which Light is supposed to consist in Pression or Motion, propagated through a fluid Medium?"

Isaac Newton
Opticks, 1704

light waves than as bundles of rays. The diffraction visible in Fig. 7.7 may be considered a consequence of the uncertainty principle for waves (Section 6.2). Attempts to localize the wave packet (that is, make it thinner from side to side) require a mixture of a broader range of wave numbers and wavelengths (that is, some of the light has a larger wavelength and thus spreads out sideways after leaving the slit). Within the limits of the uncertainty principle, or in the absence of diffraction, the ray model is satisfactory.

Adequacy of the wave model. Does the propagation of wave packets correctly explain Assumptions 1 to 5 (Fig. 5.16) about light rays? The answer is that it does, in view of Huygens' principle and the laws of reflection and refraction of waves (Eqs. 6.14 and 6.17b). The observed reflection and refraction of light corresponds directly with the observed behavior of water waves. In fact, the index of refraction of a material (Eq. 5.2) acquires a dramatic new significance in the wave model: it is the ratio of the speed of light waves in air to the speed of light waves in that medium (Example 7.1). With this new insight, a table of light speeds in various media can be constructed from that of indices of refraction (Table 5.1), with no measurement other than the speed of light in air (Table 7.5).

However, there is a contradiction lurking in the background: the speed of sound is *greater* in water and glass than in air, but the speed of light is *less* in water and glass than in air. This may seem like a small detail, and in the 1700s it was. But much later, in the late 1800s, after the wave model for light had become very well accepted, scientists recognized that this contrast between sound and light pointed to a very serious limitation of the wave model for light. In fact, scientists' attempts to use their experience with sound (and other) waves to identify the *medium* for light waves generated many other contradictions and problems that were only resolved with Einstein's revolutionary theory of relativity. We will explain this more fully below in Section 7.3.

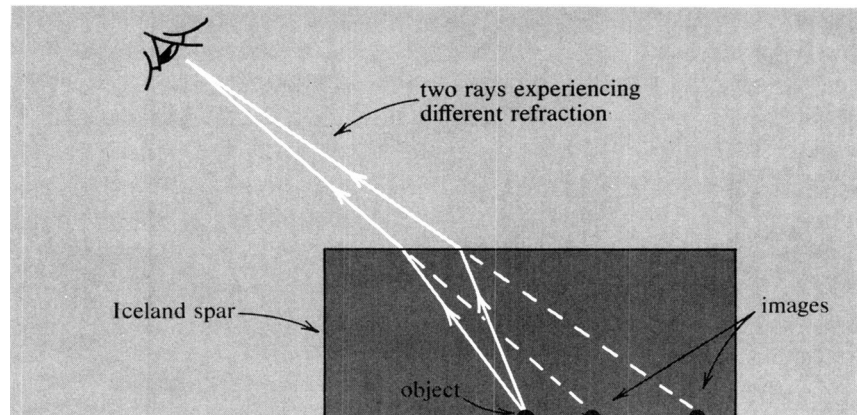
Early history of models for light. The role of Isaac Newton in the development of models for light makes a remarkable chapter in the history of science. It is clear from Newton's writings that he understood Huygens' wave theory and that he was informed, through his own experiments and those of others, of the properties of light known in his day. These properties included the speed of light as measured by Roemer, the diffraction of light by a thin slit, the interference of light to form colors by multiple reflection from thin films (for example, soap bubbles), the association of color with wavelength (ultraviolet the shortest and red the longest), as well as the phenomena on which Newton based his formulation of the ray model.

Newton's rejection of the wave model. Newton summarized all these data in a set of rhetorical questions that defined the wave model for light. Included in his reasoning was the existence of a medium (aether) whose properties he estimated by assuming that the light waves were pressure waves in aether analogous to sound waves in air. Newton gave three principal reasons for rejecting the wave model.

First, Newton expected that light waves would be diffracted more ex-

tensively than observations showed. He dismissed the diffraction that had been observed as being too small to arise from the interference of waves and ascribed it instead to a repulsive interaction with the edges

Figure 7.8 Double refraction of light by the mineral Iceland spar. Two images are seen. The distance between images depends on the viewing angle and the thickness of the mineral specimen.



of the slit.

Second, Newton found that the minerals Iceland spar and crystal quartz could split a light beam into two beams refracted through different angles (double refraction, Fig. 7.8). This was incompatible with Newton's concept of a wave unless the crystal itself were to modify the light wave. But one of Newton's fundamental assumptions was that the properties of light other than speed and direction were determined by the source and not by the media traversed.

Third, Newton rejected the aether concept because the very large speed of light required properties (extremely low inertia, strong interaction) that seemed unphysical. Furthermore, Newton was unable to find any reason for its existence other than that it could serve as a medium for the propagation of light.

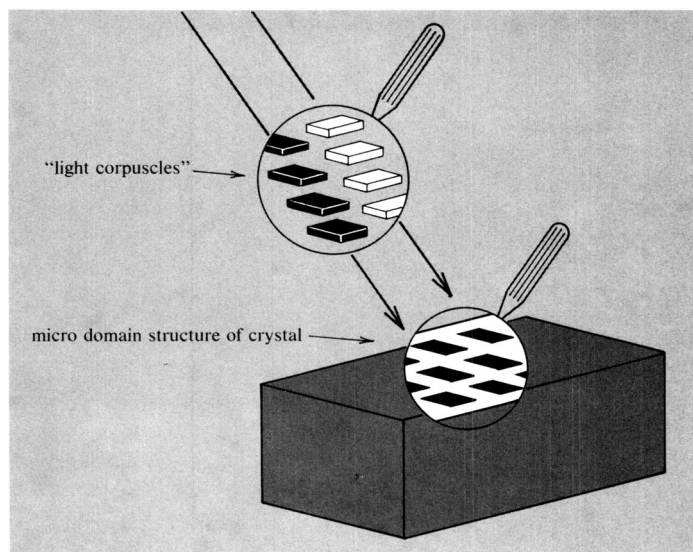
Newton's corpuscular model. Having thus demolished the wave model, Newton proposed his own. Upon his belief that light consisted of "very small Bodies," or corpuscles, Newton built the corpuscular model for light. Besides particle structure, other features of this model were an association of particle size with color, an interaction that accelerated and deflected corpuscles falling on a dense medium (refraction), and an MIP model for matter in which the light corpuscles were easily emitted and absorbed by matter particles. The corpuscular model for light rays answered Newton's three objections to the wave model. The corpuscles can interact-at-a-distance and be deflected, but are not diffracted. The double refraction by Iceland spar and quartz crystals was explained by ascribing a shape to the corpuscles; depending on how the corpuscles were aligned relative to the micro-domain structure of the crystals, they would be deflected through different angles (Fig. 7.9). And the aether was unnecessary.

These compelling arguments show how, in the formulation of scientific models, it is usually necessary to make a compromise: some parts are more satisfactory and other parts are less satisfactory. The greatest

*"Are not the rays of Light
very small Bodies emitted
from shining Substances? For
such Bodies will pass through
uniform Mediums in right
Lines...."*

Isaac Newton
Opticks, 1704

Figure 7.9 Working model for Iceland spar to illustrate Newton's interpretation of double refraction. Newton ascribed double refraction to the shape of the "light corpuscles," which could be oriented parallel or at right angles to structures in the crystal. (The details of this model were invented by the author.)



triumph of wave theory was the law of refraction, purchased at the cost of an aether. Partly because of his idea that refraction of rays was deflection of corpuscles, Newton was not willing to pay the price.

Huygens' preference for the wave model. Huygens, however, was willing to pay the price. He believed in the wave model for light. His reasoning overlaps Newton's but comes to different conclusions. He was aware of the very great speed of light, but felt that this was incompatible with particles of matter being shot from the source to the eye. Instead, a wave motion propagating through an intervening medium was the more attractive model to him. Huygens was aware also that rays of light could cross one another without disturbing each other. This observation led him to reject particles, which might collide, and made him favor waves that obey a superposition principle. In Huygens' theory, pulses reinforce one another at their common tangent line (Section 6.3). Huygens, unfortunately, did not know about the interference of wave trains and the resulting standing waves, nor about the double-slit interference pattern (Figure 6.21). These phenomena, which strongly confirmed the wave model, were discovered later and would have substantially bolstered Huygens' arguments.

Particle versus wave theory of refraction. Of the two men, Newton had the greater reputation, and his model was accepted by most of his contemporaries. A clear-cut detectable difference between the two models lay in their prediction of the speed of light in dense media like water and glass. According to Newton, the speed was *increased* by the attractive interaction that deflected (refracted) the corpuscles at the surface. According to Huygens, the observed refraction required a decrease in the speed of light (Table 5.1 and Example 7.1). As mentioned above, it was only much later, in the middle 1800s, that Foucault determined that light in fact traveled slower in water than in air. From the modern point of view, both models have weaknesses, but these were only resolved in the twentieth century, after development of the theory

Thomas Young (1773-1829) was an astonishingly versatile figure: physician, linguist, and scientist. While a medical student, Young made original studies of the eye and later developed the first version of the three-primary-color theory of vision. A large inheritance in 1797 enabled him to devote himself primarily to science. After becoming professor at the Royal Institute in 1801, he turned to physical optics and discovered that Newton's work was explainable in terms of waves. Young was also a pioneer in Egyptology and was among the first to try to decipher the Rosetta Stone.

"Those who are attached to the Newtonian Theory of light. . . would do well . . . to imagine anything like an explanation of these experiments derived from their own doctrines . . ."

Thomas Young
Philosophical Transactions,
1804

To Newton, the downfall of his corpuscular theory would not have been entirely unexpected. Unlike many of his predecessors and followers, Newton did not confuse theory with doctrine: "Tis true, that from my theory I argue the corporeity of light: but I do it without any absolute positiveness . . . I knew, that the properties, which I declared of light, were in some measure capable of being explicated not only by that, but by many other mechanical hypotheses."

of relativity and quantum mechanics. (A dual theory is now in use, with a wave packet (Section 6.2) playing a central role. Propagation of light is determined by the wave character of the packet, while emission and absorption are determined by the corpuscular aspect of the wave packet as a "chunk" of light.)

Discovery of interference. The next development in the physics of light took place 100 years after the time of Newton and Huygens. Thomas Young conducted experiments on the diffraction of light by two slits; he also observed the patterns we showed for water waves in Fig. 6.2, and he introduced the concepts of superposition and interference of waves in a series of three papers. The two-slit interference experiment was very much more suggestive than the much earlier single-slit diffraction experiments and served to revive the wave model for light. Curiously, Young felt compelled in his first publication to ascribe the original wave model for light more to Newton (who considered it in his treatise) than to Huygens. Young played down Newton's own complete rejection of the wave model.

Young went considerably further in his second and third papers, in which he described the conditions for constructive and destructive interference in terms of the wave path difference measured in "breadths" (wavelengths) of the supposed "undulations," (waves) which differed for different colors. Young was then no longer so respectful of Newton; he used Newton's data to illustrate his own ideas, and he completely rejected Newton's interpretation.

Acceptance of the wave model. The last blow to Newton's corpuscular model was delivered in the middle of the nineteenth century by Foucault's measurements of the speed of light in water. We have already reported that this speed was found to be less than the speed in air, as required by the wave model's explanation of refraction and in contradiction to Newton's prediction based on the corpuscular model. With this achievement, the wave model was unanimously accepted and physicists' attention could turn to new questions: What is the aether? What kind of waves are light waves? How is light emitted and absorbed by matter?

Emission, reflection, and absorption spectra. The emission of light by a hot source means that there is energy transfer from thermal energy of the glowing material to radiant energy of light, which travels to a distant energy receiver. The reverse energy transfer occurs when light is absorbed; then the radiant energy of the light is transferred to a form of energy in the receiver. This is usually thermal energy, but some of it may be chemical energy also (as in photosynthesis, photography, and sunburn).

Emission and absorption by gases. The diffraction grating has been used to decompose the light from many sources into its monochromatic parts. Once the wave nature of light was generally accepted, such studies were used to gain information about the light source itself. It was

Figure 7.10 Line emission spectra of gases.
(a) Hydrogen gas.
(b) Mercury gas.

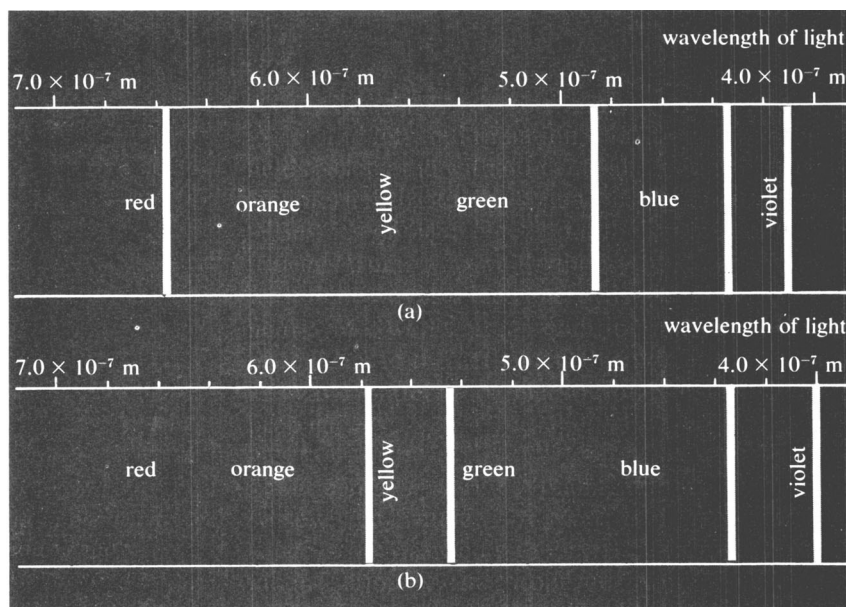


TABLE 7.7 EMISSION SPECTRAL LINES OF SELECTED ELEMENTS

Element	Wavelength
(m)	(m)
calcium	4.9×10^{-7}
	6.1×10^{-7}
	6.4×10^{-7}
copper	4.6×10^{-7}
helium	5.3×10^{-7}
mercury	4.4×10^{-7}
	5.5×10^{-7}
	5.8×10^{-7}
neon	5.4×10^{-7}
	6.4×10^{-7}
	6.5×10^{-7}
sodium	5.9×10^{-7}

found that many glowing gases emitted characteristic line spectra (Fig. 7.10). That is, the spectrum of light they produced did not include all colors, but only certain colors in very narrow bands of wavelengths called spectral lines. These emission line spectra are unique for each element and can be used for identification, just as fingerprints can be used to identify a person (Table 7.7).

Absorption of light by gases, like emission, is selective. That is, gases absorb light only at certain wavelengths or absorption lines. Most of the absorption lines have the same wavelength as emission lines and can be used to identify the presence of a chemical element (Fig. 7.11). Virtually all information about the chemical composition of the sun and stars comes from the analysis of spectral lines. Astronomers have now recorded and analyzed spectra from essentially all of the stars and other objects they have found in the sky; this huge body of evidence leads to a conclusion that may seem disappointing to sci-fi fans: the entire known universe is composed of the same chemical elements as the earth, though in different proportions than found on the earth.

Emission and absorption by solids. Glowing solids, such as light bulb filaments or hot coals, emit continuous spectra (Fig. 7.6). That is, all wavelengths are represented, and not only selected ones as in the

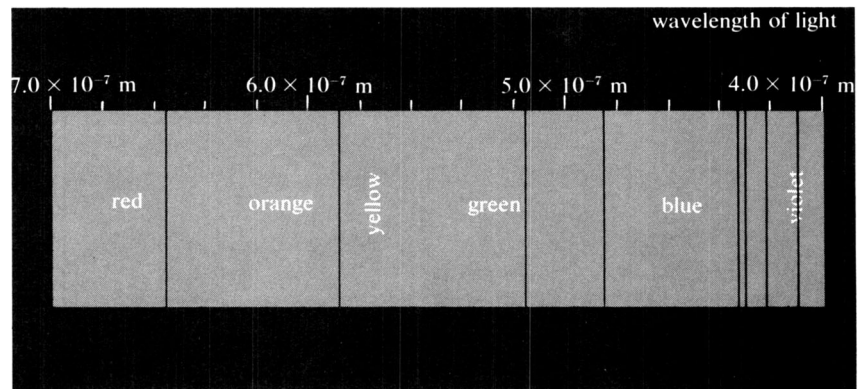


Figure 7.11 Light emitted by the sun. Dark lines (called Fraunhofer lines after their discoverer) are evidence of absorption of light by chemical elements in the gases at the surface of the sun.

line spectrum emitted by a glowing gas. By contrast with line spectra from gases, the continuous spectra from different glowing solid materials are very similar to one another and depend on the temperature but not on the composition of the material.

We have already described the selective reflection and absorption of light that is responsible for the relative brightness and the color of a reflecting surface (Section 5.2). By analyzing the reflected light with a diffraction grating, you can find out whether a color is pure (monochromatic) or mixed. By inference from the colors of the incident and reflected light, you can find which colors (wavelengths) are absorbed.

Micro-domain model for emission and absorption. Are the sources of light macro-domain systems? Since the wavelength of light is at the borderline of the two domains, the sources are in all likelihood very small by macro-domain standards. Another clue comes from the spectra of gases. According to the MIP model, the particles in gases are far apart and do not interact with one another appreciably. Since gases nevertheless emit and absorb light, the source must be a gas particle acting alone. Furthermore, since gases emit line spectra (isolated wavelengths and frequencies), you may conclude that a gas particle acts like a tuned system with several oscillators, one frequency corresponding to each spectral line emitted. In this interpretation of spectral lines, therefore, their frequency is a more significant property than their wavelength.

This model helps to explain why solid materials emit continuous spectra rather than line spectra. In the solid phase, the particles of the MIP model interact strongly with one another. The interaction shifts the frequencies of the individual oscillators so all possible frequencies are represented. Each of these oscillators emits light of its own frequency, but all oscillators together give rise to a continuous spectrum of light.

The frequency of an oscillator responsible for the emission of light

Equation 7.5

speed of light $= v$

wavelength $= \lambda$

frequency $= f$

$$f = \frac{v}{\lambda} = \frac{3 \times 10^8 \text{ m/sec}}{5.9 \times 10^{-7} \text{ m}} \\ = 5 \times 10^{14} \text{ /sec}$$

James Clerk Maxwell (1831-1879) was born into a wealthy Scottish family in Edinburgh. After education at Edinburgh and Cambridge, Maxwell was Professor of Physics at Marischal College, Aberdeen, and Kings College, London. He published important papers in 1859-1860 on Saturn's rings and on the kinetic theory of gases. His greatest work, however, was in electromagnetism. Adopting Faraday's theory of fields, Maxwell set out to establish a unified mathematical description of electric and magnetic phenomena. Maxwell's findings, published in 1865 and 1873, are a landmark in theoretical physics.

can be calculated from the known speed of light and the measured wavelength of one spectral line. To take an example, the frequency of sodium light is found to have a value of enormous magnitude (Eq. 7.5). Since the wavelengths of all visible light do not differ greatly, the frequencies of all the oscillators in the particle model are of similar magnitude. What could be oscillating with such high frequency?

7.3 The electromagnetic theory of light

As we explained in the previous section, the model of light as displacement waves propagating in the aether was generally accepted by the middle of the nineteenth century. In spite of the satisfactory state of affairs, however, there were loose ends yet to be explained. These problems had been pointed out by Newton in his critique of the wave model: no independent evidence of the aether's existence and no mechanism for the emission and absorption of light. Soon, however, there were several developments that led ultimately to a brilliant confirmation of the wave model's applicability to the propagation of light; however, they also required considerable adjustment in the models that scientists had for light waves, and indeed for other physical phenomena.

Maxwell's theory. The first step was a theoretical synthesis, by J. Clerk Maxwell, of the discoveries regarding electric fields, magnetic fields, the magnetic effects of electric currents, and the electric effects of moving magnets, which had been made during the preceding decades. Maxwell came to the conclusion that rapidly vibrating electric charges would generate electric and magnetic fields whose intensity exhibits wavelike patterns, much as a vibrating violin string generates air pressure variations that exhibit wave patterns (Section 7.1).

Maxwell called his waves electromagnetic waves. He viewed them as oscillatory displacements of the aether, again in analogy to sound

Figure 7.12 Electric and magnetic fields in an electromagnetic wave.

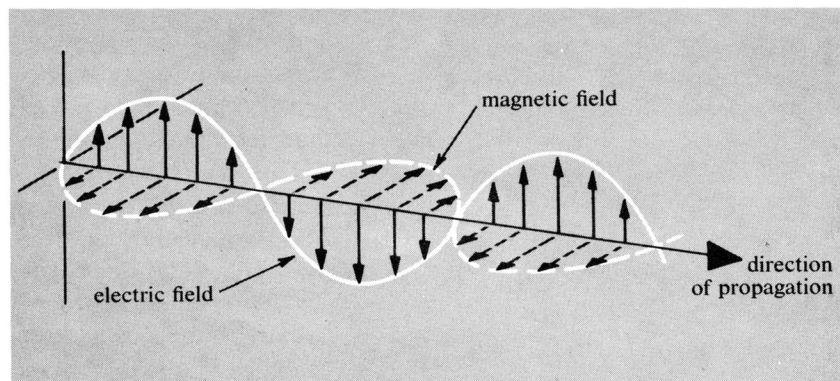
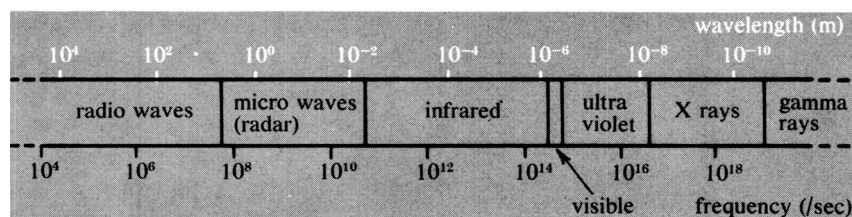


Figure 7.13 The electromagnetic spectrum



"The ... difficulties ... which are involved in the assumption of particles acting at a distance ... are such as to prevent me from considering this theory as an ultimate one ... I have therefore preferred to seek an explanation of the facts in another direction. ... The theory I propose may ... be called a theory of the Electromagnetic Field, because it has to do with the space in the neighbourhood of the electric or magnetic bodies."

James Clerk Maxwell
Philosophical Transactions,
1865

waves or water waves. A diagram indicating the electric and magnetic field patterns in such a wave is shown in Fig. 7.12. The electric and magnetic fields are at right angles to each other. At any particular point in space, the intensity of the fields oscillates in magnitude and/or direction with the frequency of the source. The entire pattern shown moves in the direction of propagation with the speed of light.

Maxwell's calculation indicated that the waves would propagate in aether with a speed of 3×10^8 meters per second. This speed was, to everyone's amazement, just equal to the speed of light measured a few years earlier (Table 7.6). Light waves were therefore identified as electromagnetic waves with a wavelength of about 5×10^{-7} meters. The frequency of these waves is related to their wavelength through the same equation that applies to sound and other waves ($v = f\lambda$, Eq. 7.5); the frequency of light waves, however, is enormously high compared to that of sound waves. Maxwell's theory demonstrated conclusively that electric charges were the source of the vibrating electric and magnetic fields; thus these charges would have to exist within any object that is a source of light, and in order to generate light, they would have to be able to vibrate at the high frequencies of light waves. Furthermore, if the electric charges vibrate (oscillate) at such a high frequency, they must have an extremely small inertia and be subject to very strong interaction compared to the oscillators that are responsible for generating sound waves. This requirement will turn out to be extremely important in the search for understanding of the structure and constituents of matter.

The characteristic spectra of gases exhibit sharp frequencies and are evidence that gases contain "tuned" electrically charged systems capable of oscillating at well-defined high frequencies. In Chapter 8 we will explore the sources of light waves, which are now identified with the atoms and molecules composing all matter.

The electromagnetic spectrum. Maxwell's theory suggested strongly that electromagnetic waves should exist with frequencies different from those of light. One only had to arrange for electric charges to vibrate at a lower frequency. Heinrich Hertz (1857-1894) succeeded in generating waves with a wavelength of a few centimeters (rather than the 5×10^{-7} m wavelength of light) by making sparks in simple electric circuits, and Marconi (1874-1937) turned this discovery to practical use in his invention of the wireless telegraph (radio). Many other forms of electromagnetic (E-M) radiation have since been discovered. Such E-M waves are extremely useful; for example, radio and radar waves can transmit information over great distances, and x-rays and infrared can create images of objects that are otherwise invisible. The entire frequency range is called the electromagnetic spectrum (Fig. 7.13). It includes not

"It appears therefore that certain phenomena in electricity and magnetism lead to the same conclusion as those of optics, namely, that there is an aethereal medium pervading all bodies, and modified only in degree by their presence ..."

James Clerk Maxwell
Philosophical Transactions,
1865

Albert Einstein (1879-1955), perhaps the greatest theoretical physicist since Isaac Newton, was born in Ulm, Germany and educated in Munich and Switzerland. After graduation he could not obtain a university teaching position and had to accept the obscurity of a minor post at the Berne Patent Office. This obscurity ended dramatically in 1905 when Einstein published five important papers, including two that shook the scientific world to its foundations – one on the photoelectric effect, and the other on the special theory of relativity. In 1933, Einstein resigned as Director of the Kaiser Wilhelm Institute of Physics in Berlin as a protest against Hitler's fascist policies. He emigrated to the United States, where he spent the rest of his life working at the Institute for Advanced Study in Princeton.

only visible light and radio waves, but also X-rays, ultraviolet and infrared radiation, radar, and even the electric and magnetic fields associated with 60-cycle alternating house current (Section 12.4). Visible light actually spans only a minute portion of the spectrum.

Besides giving a clue about the sources of light and vastly expanding the spectrum, Maxwell's theory made it possible to associate energy with light waves, since energy is associated with electric and magnetic fields. Maxwell's great contribution, however, also called attention once again to the aether, the medium in which light waves, now viewed as wave patterns of electric and magnetic fields, were believed to propagate.

The aether mystery. You might think that the existence of the aether, so severely criticized by Newton, was now firmly established with the success of Maxwell's theory. Far from it! Now that aether had to be taken seriously, its properties were investigated more thoroughly.

The first question was asked by Maxwell himself: What about the motion of the aether? Clearly, he reasoned, light waves traveling at a certain speed relative to the aether would be observed to travel at a different speed relative to objects moving with respect to the aether. Nobody knew, of course, what objects moved with respect to the aether, but the planets' relative orbital motion at different rates made it impossible for the aether to be at rest with respect to all of them at the same time.

Many experiments were carried out to detect motion of the earth relative to the aether by comparing the speed of light measured under many different conditions: parallel to the earth's orbital motion around the sun, perpendicular to this motion, inside rapidly moving liquids, light generated on earth and coming from moving sources, and so on. The results were negative; the speed of light gave no evidence that the earth moved relative to the aether. Was the earth, then, really at rest in the aether, while the entire universe moved around the earth? More than 300 years after Copernicus this was not an acceptable hypothesis.

There were other mysteries about the aether; we pointed out above, in Section 7.2, that the behavior of light and sound was not consistent: light traveled slower in denser materials (water and glass) than air but sound traveled faster in such materials. This apparent contradiction raised doubts about the similarities between the medium for sound and the aether. Such concerns became more serious when scientists started actively investigating the properties of the aether, using Maxwell's theory of electromagnetism. For sound (and other waves), the faster the speed of the wave, the lower the inertia and the higher the interaction among the oscillators of the medium. However, applying this kind of thinking to light and its extremely high speed meant that the aether would have to be made up of oscillators with contradictory properties: an inertia that was much, much lower, yet a strength of interaction that was much, much stronger, than in any existing substance!

The theory of relativity. Attempts to resolve these contradictions made little progress until Albert Einstein, early in the twentieth century,

approached the subject from a new, apparently unrelated, direction; Einstein seriously pursued the problem of how the interaction of electrically charged bodies and the light waves they generate would appear to two observers in relative motion. In particular, how would a light wave in vacuum appear to an observer who moves alongside it, with the same speed? Maxwell's theory excluded the possibility of a stationary light pulse.

Einstein took the viewpoint that the interaction of two electrically charged objects should depend only on their motion relative to one another and not on their common motion relative to some outside reference frame. To reconcile this requirement with the known laws governing electric and magnetic interactions, Einstein found it necessary to abandon the aether and to modify the commonsense concepts of space and time.

At the basis of Einstein's reasoning was an operational approach to the methods by which observers in relative motion can communicate their

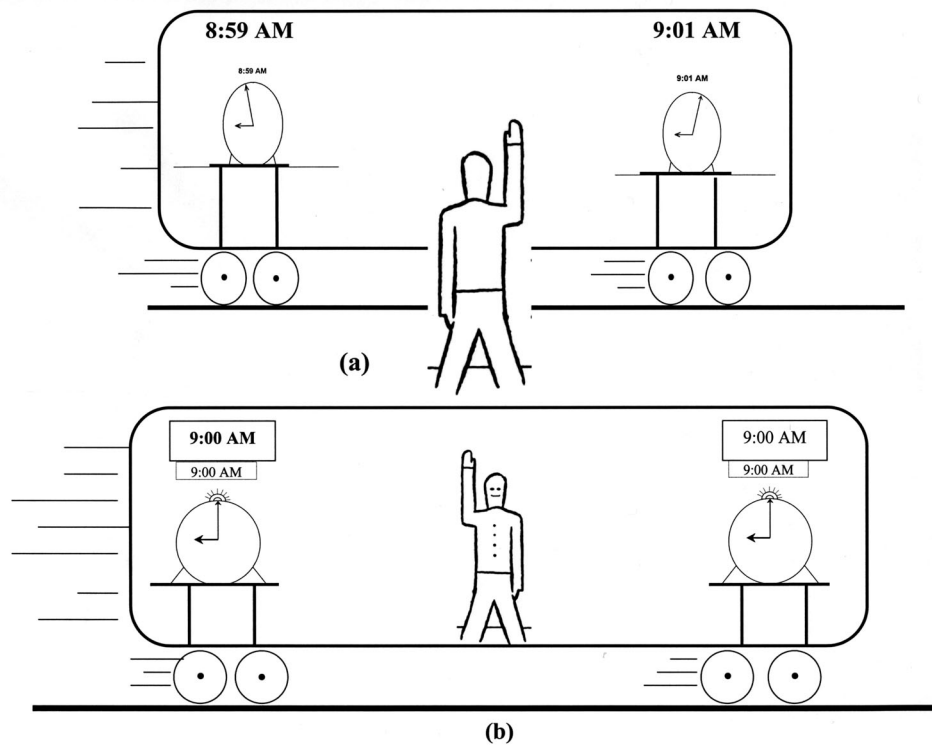


Figure 7.14 Two clocks on a train, as observed by two observers in relative motion. The effect is vastly exaggerated and would not be observable in a train.

(a) To the observer opposite the car's center, but off the train, the clock at the rear of the train would appear to be running two minutes behind the clock at the front of the train.

(b) To the observer at the car's center on the train, the two clocks would appear perfectly synchronized.

This paradoxical behavior is the direct result of the assumption that the speed of light is the same for all observers, which also seems to contradict our experience but is extremely well documented. It would seem difficult to build a reliable theory of physics based on such anti-intuitive ideas, but Einstein did exactly that. His theory of relativity provides a solid basis of understanding for all situations in which velocities near the velocity of light are involved.

Einstein's disruption of the old Newtonian scheme inspired J. C. Squire to add to Alexander Pope's couplet:

*"Nature and Nature's Laws
lay hid in night.
God said, Let Newton be,
and all was light."*

one of his own:

*"It did not last: the Devil
howling, 'Ho,
Let Einstein be,' restored the
status quo."*

observations to one another. Instead of assuming that this could be done, as had Galileo and Newton, he described how observers must use light signals (the fastest known method of communication over a distance) to standardize their instruments for measuring distances, time intervals, and so on. Built into the scheme were the experimental results, which indicated that the observed speed of light was not influenced by motion of neither the light source nor the light detector.

Einstein's results, embodied in his theory of relativity, have substantially influenced both science and philosophy. Einstein demonstrated that several of our apparently "intuitive" ideas about the physical world had to be discarded. The theory of relativity was both consistent and comprehensive, and it required us to accept several new ways of thinking that seemed to conflict with intuition: First, two events that are simultaneous for one observer are not simultaneous for a second observer in motion relative to the first (Fig. 7.14). Second, if observer A is moving with respect to observer B and they both measure the length of a given object and the duration of a given event, (using standard rulers and clocks moving with them), they will *not* find the same results. Third, an automobile moving at exactly 75 miles per hour passing another at exactly 55 miles per hour is not traveling at exactly 20 miles per hour relative to the second car (Section 2.2), though the difference is insignificant for such slowly moving objects. Finally, the answer to Einstein's original question about the observer "catching up" with the light wave in vacuum is deceptively simple: the properties of space and time are such that this can never happen!

Summary

Sound and light are intermediaries in interaction-at-a-distance between a source and a receiver. The modern understanding of both phenomena is achieved with the help of a wave model.

Sound waves are pressure waves in solids, liquids, or gases. Associated with the pressure variations are displacements of micro-domain particles making up the material. The tone or pitch of sound is associated with the wave frequency, the intensity with the wave amplitude. The speed of sound in air is 344 meters per second.

The human ear can detect sound waves whose frequencies fall between about 20 vibrations per second and 20,000 vibrations per second, with most speech using waves from 200 to 2000 per second. The wavelength of sound waves in speech, therefore, is comparable in size to the human body and to many environmental objects in the macro domain. These sound waves are so strongly diffracted by objects of this size that no sharp acoustic images can be formed.

Light waves are electromagnetic waves that propagate in vacuum and in various media. Visible light is only a very narrow portion of the electromagnetic spectrum, which also includes radio, microwaves (radar), infrared, ultraviolet, X-ray, and nuclear radiation. The color of light is associated with the wave frequency, the intensity with the wave amplitude. The speed of electromagnetic waves in vacuum is 3×10^8 meters per second.

The wavelength of visible light in air is very small, about 5×10^{-7} meters. Evidence of the wave nature of light is therefore difficult to obtain through experiments in the macro domain. The ray model describes light very well until it interacts with objects at the lower limit of the macro domain. Then the effects of diffraction and interference can be observed and the inadequacies of the ray model are revealed.

As a matter of fact, light spans the micro, macro, and cosmic domains. The speed of light is so great that it traverses the cosmic distance from the earth to the moon in about 1 second. The wavelength of light is in the micro domain. And the light rays (pencils of light) that make possible human vision are in the macro domain. No wonder that so much controversy surrounded the models for light! For this very reason, however, light has been a powerful tool in the study of systems in the micro and cosmic domains.

One of the most revolutionary consequences of the electromagnetic theory, as applied by Einstein, was to eliminate the need for the existence of the aether. Light waves propagate in vacuum, without a medium. There is no medium, therefore, that could serve as a special reference frame for measurements of the speed of light. The startling consequences of this conclusion have changed our view of space and time.

List of new terms

octave	shock waves	infrared
ultrasonics	spectrum	double refraction
sonar	absorption	line spectrum
sub-audible waves	emission	electromagnetic waves
seismic waves	ultraviolet	aether
theory of relativity		

List of symbols

v	wave speed	Δs	distance traversed
λ	wavelength	Δt	time interval
f	frequency	d	distance between grating slits
c	speed of light in vacuum	l, L	distances in experimental arrangements
θ	angle		
n	index of refraction		

Problems

- Prepare several more or less well-tuned systems that act as sound sources (rubber band, stretched wire, air in a bottle, glass of water) and experiment to produce musical notes with them.
 - Describe how you can change the pitch of the note (i.e., tune the system) in terms of the wave model for sound.
 - Relate the pitch of the sound to the wave speed in the medium and the dimensions of the tuned system.
- Mersenne's shorter brass wire was 22 centimeters long (Section 7.1). Estimate the wave speed on the wire in his experiment. (Note: the

speed of a mechanical wave on a wire is usually *not* equal to the speed of a sound wave in the wire material. Mechanical waves of the wire as a whole involve macro-domain displacements; whereas sound waves in the material, set up, for example, by scraping the wire with a file, involve micro-domain displacements of the many interacting particles making up the wire.)

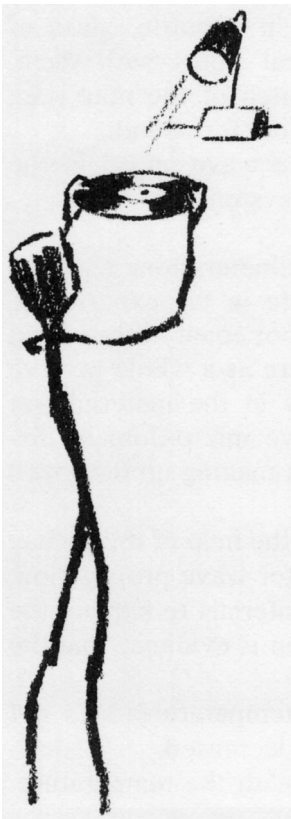


Diagram for Problem 12

3. Explain the following three statements with the help of the gasbag model for sound waves and the conditions for wave propagation. If necessary, make hypotheses about the materials to explain the observations. (Note: a successful explanation is evidence that the hypothesis is valid.)
 - (a) The speed of sound in air at room temperature does not change if the air pressure is increased or decreased.
 - (b) The speed of sound in air increases with the temperature. At the boiling temperature of water it is 386 meters per second.
 - (c) The speed of sound in carbon dioxide is less, and in hydrogen gas is more, than in air at the same temperature.
4. Complete the wavelength column in Table 7.2.
5. Calculate the frequencies and wavelengths of the highest and lowest notes on an 88-key piano.
6. An organ pipe that plays a B note is filled with hydrogen gas. What note will it play then?
7. Look for "sound shadows" produced by buildings or other large obstacles. Describe the relative position of the sound, source, obstacles, and receiver for a significant shadowing to be observable. (Note: you may use your ear as receiver, but you will need a reliable and cooperative sound source, such as a friend with a musical instrument.)
8. Explain the operation of sonar with respect to the following. (a) What size underwater objects can be reliably detected by sonar of 20,000 vibrations per second? Justify your estimate. (b) The echo from an underwater object is received 5 seconds after the sonar pulse was emitted. How distant is the object?
9. Find the wavelength of bat "sonar" pulses. (frequency about 10^5 /sec)
10. (a) Estimate the wavelength of seismic waves.
 - (b) Would you recommend that geologists use a ray model or a wave model for seismic waves? Explain your answer and any limitations it may have.
11. Use a fine, regularly woven fabric to measure the wavelength of light approximately (Figs. 7.2, 7.3, Problem 5.9).
12. Look at the glancing reflection of a bright, medium-distant light source in a phonograph record, compact disc (CD) or digital videodisc (DVD). (See figure at left.)
 - (a) Describe your observations and explain them in terms of the wave theory of light.
 - (b) Make appropriate measurements and calculate the approximate spacing of the tracks on the record, CD, or DVD.

Problems 13-16. To observe interference of light, you will need a narrow light source and one or more very thin slits. The simple slit holder shown in Fig. 7.15 below gives satisfactory results. A "source slit" aimed at a lamp acts as a narrow light source. A diffraction grating, a single slit, or a double slit can be attached to the opening in near your eye so as to view the light from the source slit.

Figure 7.15 (to right) Slit holder and slits for Problems 13-16. The slits shown in the detailed drawings above and below the slit holder may be attached to the slit holder or may be built on separate pieces of cardboard that are attached to the slit holder with paper clips.

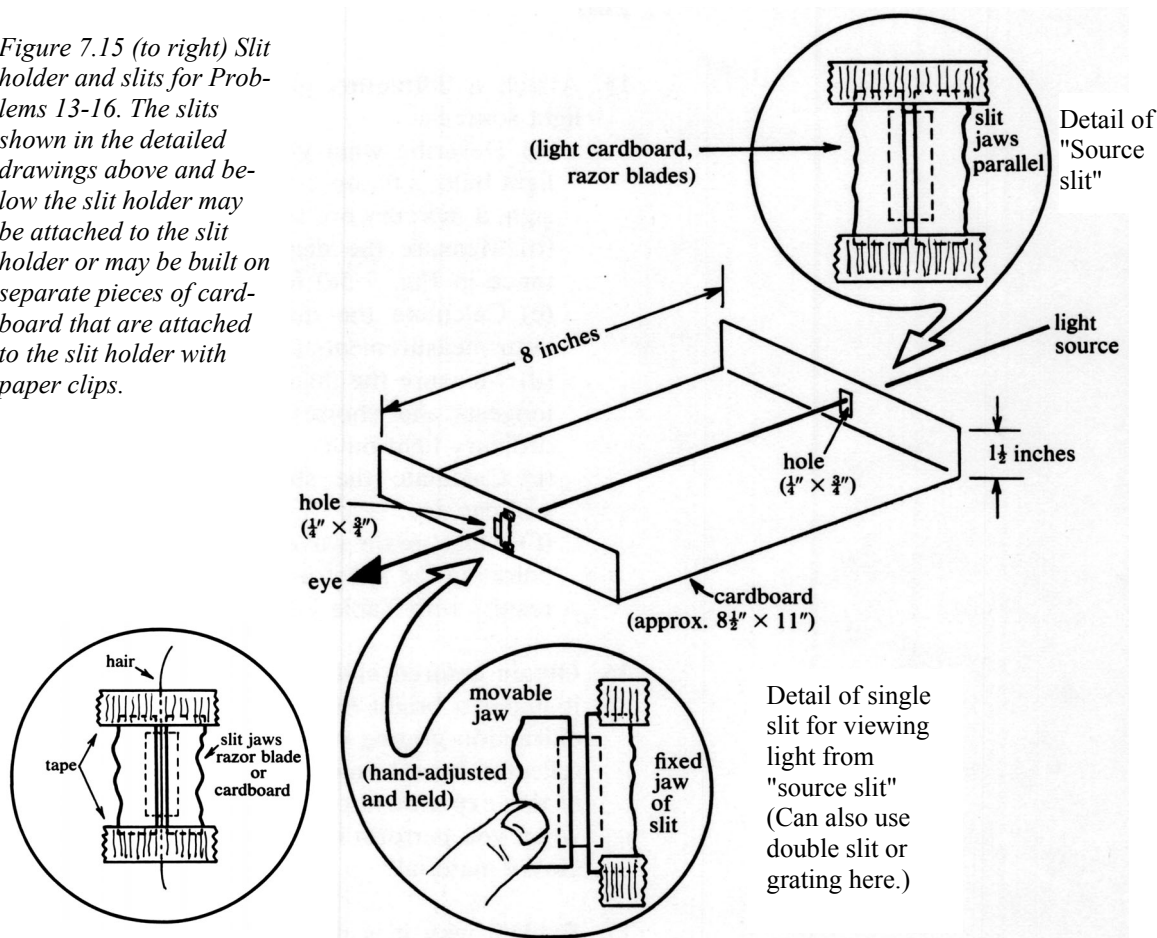


Figure 7.16 (above) Construction of a double slit. The slits should be as narrow as possible, with a hair centered in a cardboard slit (Fig. 7.15) to make it into a double slit. Keep the slit jaws parallel. You may need to work with a magnifier

13. Make a variable-width slit (Fig. 7.15) and attach it to the slit holder. Look at the light bulb through the holder and observe the single-slit diffraction pattern. Describe the colors, the number of bright fringes, and the spacing of the fringes while you vary the slit width.
14. Make a double slit (Fig. 7.16) and attach it to the slit holder. Look at a light bulb through the holder and observe the double-slit diffraction pattern.
 - (a) Describe your observations (color, number of bright fringes, position of dark fringes).
 - (b) Measure the position of the dark fringes and the slit dimensions as well as you can. Use these to calculate (roughly) the wavelength of light (Section 6.4, Problem 6.12).

15. Attach a plastic diffraction grating to the holder and look at various light sources.
 - (a) Describe what you observe when you look at an ordinary light bulb, a fluorescent bulb, a red "neon" sign, a green "neon" sign, a mercury arc lamp and a sodium vapor lamp. Sodium vapor lamps are often used in street lights because of their high efficiency; their light is very strongly yellow and seems harsh.
 - (b) Measure the displacement of the diffraction images (distance labeled "l" in Fig. 7.5a) for the spectral lines of one element.
 - (c) Calculate the distance between slits in the grating from your measurements using Eq. 7.3 and the known wavelength of the light from that element (see Table 7.7).
 - (d) Measure the displacement of the diffraction images for the longest- and shortest-wavelength light you can see from an ordinary light bulb.
 - (e) Calculate the shortest and longest wavelengths of light you can see.
 - (f) Measure the wavelengths of the various colors as you see them in the spectrum of an ordinary light bulb. Compare your results with Table 7.5.
16. Obtain colored cloth or paper (preferably not glossy) and place it under a bright lamp. Look at this colored material through a diffraction grating on your slit holder (Fig. 7.15). Describe the light that is reflected by the material. (You may wish to compare the result of this experiment carried out in bright sunlight with that obtained when you perform it under artificial light.) Why should you avoid glossy material?
17. Explain why it is more accurate to say that the color of light is associated with its frequency rather than with its wavelength.
18. Describe your evaluation of the disagreement between Huygens and Newton. Optional: Do additional reading on the subject.
19. (a) Calculate the wavelength range of the standard AM broadcast band (frequency 5.6–1600 kHz, 1 kHz = 1,000 /sec)
- (b) Calculate the wavelength range of FM broadcasts. (frequency 88–106 MHz, 1 MHz = 1,000,000 /sec)
- (c) Explain why hilly terrain interferes with FM broadcast reception much more seriously than with AM radio reception.
20. Identify one or more explanations or discussions in this chapter that you find inadequate. Describe the general reasons for your dissatisfaction (conclusions contradict your ideas, or steps in the reasoning have been omitted; words or phrases are meaningless; equations are hard to follow; and so on) and pinpoint your criticism as well as you can.

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