

14.1 Speed of Sound, Frequency, and Wavelength

Section Learning Objectives

By the end of this section, you will be able to do the following:

- Relate the characteristics of waves to properties of sound waves
- Describe the speed of sound and how it changes in various media
- Relate the speed of sound to frequency and wavelength of a sound wave

Teacher Support

Teacher Support The learning objectives in this section will help your students master the following standards:

- (7) Science concepts. The student knows the characteristics and behavior of waves. The student is expected to:
 - (A) examine and describe oscillatory motion and wave propagation in various types of media;
 - (B) investigate and analyze characteristics of waves, including velocity, frequency, amplitude, and wavelength, and calculate using the relationship between wave speed, frequency, and wavelength;
 - (C) compare characteristics and behaviors of transverse waves, including electromagnetic waves and the electromagnetic spectrum, and characteristics and behaviors of longitudinal waves, including sound waves;
 - (F) describe the role of wave characteristics and behaviors in medical and industrial applications.

In addition, the High School Physics Laboratory Manual addresses content in this section in the lab titled: Waves, as well as the following standards:

- (7) Science concepts. The student knows the characteristics and behavior of waves. The student is expected to:
 - (B) investigate and analyze characteristics of waves, including velocity, frequency, amplitude, and wavelength, and calculate using the relationship between wave speed, frequency, and wavelength.

Section Key Terms

Teacher Support

Teacher Support [BL][OL] Review waves and types of waves—mechanical and non-mechanical, transverse and longitudinal, pulse and periodic. Review

properties of waves—amplitude, period, frequency, velocity and their inter-relations.

Properties of Sound Waves

Sound is a wave. More specifically, sound is defined to be a disturbance of matter that is transmitted from its source outward. A disturbance is anything that is moved from its state of equilibrium. Some sound waves can be characterized as periodic waves, which means that the atoms that make up the matter experience simple harmonic motion.

A vibrating string produces a sound wave as illustrated in Figure 14.2, Figure 14.3, and Figure 14.4. As the string oscillates back and forth, part of the string's energy goes into compressing and expanding the surrounding air. This creates slightly higher and lower pressures. The higher pressure... regions are compressions, and the low pressure regions are rarefactions. The pressure disturbance moves through the air as longitudinal waves with the same frequency as the string. Some of the energy is lost in the form of thermal energy transferred to the air. You may recall from the chapter on waves that areas of compression and rarefaction in longitudinal waves (such as sound) are analogous to crests and troughs in transverse waves.

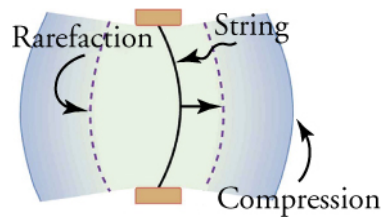


Figure 14.2 A vibrating string moving to the right compresses the air in front of it and expands the air behind it.

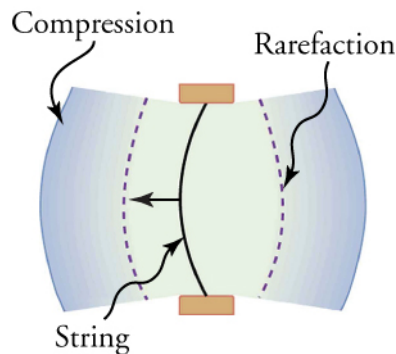


Figure 14.3 As the string moves to the left, it creates another compression and rarefaction as the particles on the right move away from the string.

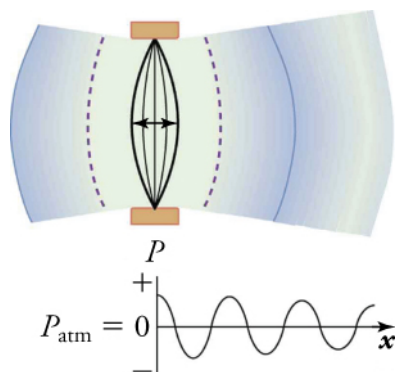


Figure 14.4 After many vibrations, there is a series of compressions and rarefactions that have been transmitted from the string as a sound wave. The graph shows gauge pressure (P_{gauge}) versus distance x from the source. Gauge pressure is the pressure relative to atmospheric pressure; it is positive for pressures above atmospheric pressure, and negative for pressures below it. For ordinary, everyday sounds, pressures vary only slightly from average atmospheric pressure.

The amplitude of a sound wave decreases with distance from its source, because the energy of the wave is spread over a larger and larger area. But some of the energy is also absorbed by objects, such as the eardrum in Figure 14.5, and some of the energy is converted to thermal energy in the air. Figure 14.4 shows a graph of gauge pressure versus distance from the vibrating string. From this figure, you can see that the compression of a longitudinal wave is analogous to the peak of a transverse wave, and the rarefaction of a longitudinal wave is analogous to the trough of a transverse wave. Just as a transverse wave alternates between peaks and troughs, a longitudinal wave alternates between compression and rarefaction.

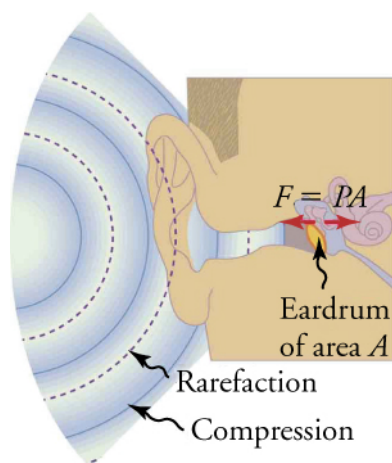


Figure 14.5 Sound wave compressions and rarefactions travel up the ear canal and force the eardrum to vibrate. There is a net force on the eardrum, since the sound wave pressures differ from the atmospheric pressure found behind the eardrum. A complicated mechanism converts the vibrations to nerve impulses, which are then interpreted by the brain.

The Speed of Sound

Teacher Support

Teacher Support [BL] Review the fact that sound is a mechanical wave and requires a medium through which it is transmitted.

[OL][AL] Ask students if they know the speed of sound and if not, ask them to take a guess. Ask them why the sound of thunder is heard much after the lightning is seen during storms. This phenomenon is also observed during a display of fireworks. Through this discussion, develop the concept that the speed of sound is finite and measurable and is much slower than that of light.

The speed of sound varies greatly depending upon the medium it is traveling through. The speed of sound in a medium is determined by a combination of the medium's rigidity (or compressibility in gases) and its density. The more rigid (or less compressible) the medium, the faster the speed of sound. The greater the density of a medium, the slower the speed of sound. The speed of sound in air is low, because air is compressible. Because liquids and solids are relatively rigid and very difficult to compress, the speed of sound in such media is generally greater than in gases. Table 14.1 shows the speed of sound in various media. Since temperature affects density, the speed of sound varies with the temperature of the medium through which it's traveling to some extent, especially for gases.

Teacher Support

Teacher Support

Misconception Alert

Students might be confused between rigidity and density and how they affect the speed of sound. The speed of sound is slower in denser media. Solids are denser than gases. However, they are also very rigid, and hence sound travels faster in solids. Stress on the fact that the speed of sound always depends on a *combination* of these two properties of any medium.

Table 14.1 Speed of Sound in Various Media

Teacher Support

Teacher Support [BL] Note that in the table, the speed of sound in very rigid materials such as glass, aluminum, and steel ... is quite high, whereas the speed in rubber, which is considerably less rigid, is quite low.

The Relationship Between the Speed of Sound and the Frequency and Wavelength of a Sound Wave



Figure 14.6 When fireworks explode in the sky, the light energy is perceived before the sound energy. Sound travels more slowly than light does. (Dominic Alves, Flickr)

Sound, like all waves, travels at certain speeds through different media and has the properties of frequency and wavelength. Sound travels much slower than light—you can observe this while watching a fireworks display (see Figure 14.6), since the flash of an explosion is seen before its sound is heard.

The relationship between the speed of sound, its frequency, and wavelength is the same as for all waves:

$$v = f\lambda,$$

14.1

where v is the speed of sound (in units of m/s), f is its frequency (in units of hertz), and λ is its wavelength (in units of meters). Recall that wavelength is defined as the distance between adjacent identical parts of a wave. The wavelength of a sound, therefore, is the distance between adjacent identical parts of a sound wave. Just as the distance between adjacent crests in a transverse wave is one wavelength, the distance between adjacent compressions in a sound wave is also one wavelength, as shown in Figure 14.7. The frequency of a sound wave is the same as that of the source. For example, a tuning fork vibrating at a given frequency would produce sound waves that oscillate at that same frequency. The frequency of a sound is the number of waves that pass a point per unit time.

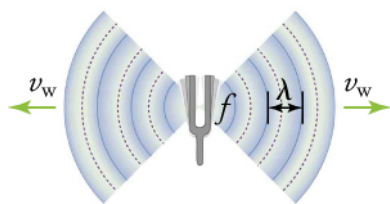


Figure 14.7 A sound wave emanates from a source vibrating at a frequency f , propagates at v , and has a wavelength λ .

Teacher Support

Teacher Support [BL][OL][AL] In musical instruments, shorter strings vibrate faster and hence produce sounds at higher pitches. Fret placements on instruments such as guitars, banjos, and mandolins, are mathematically determined to give the correct interval or change in pitch. When the string is pushed against the fret wire, the string is effectively shortened, changing its pitch. Ask students to experiment with strings of different lengths and observe how the pitch changes in each case.

One of the more important properties of sound is that its speed is nearly independent of frequency. If this were not the case, and high-frequency sounds traveled faster, for example, then the farther you were from a band in a football stadium, the more the sound from the low-pitch instruments would lag behind the high-pitch ones. But the music from all instruments arrives in cadence independent of distance, and so all frequencies must travel at nearly the same speed.

Recall that $v = f\lambda$, and in a given medium under fixed temperature and humidity, v is constant. Therefore, the relationship between f and λ is inverse: The higher the frequency, the shorter the wavelength of a sound wave.

Teacher Support

Teacher Support

Teacher Demonstration

Hold a meter stick flat on a desktop, with about 80 cm sticking out over the edge of the desk. Make the meter stick vibrate by pulling the tip down and releasing, while holding the meter stick tight to the desktop. While it is vibrating, move the stick back onto the desktop, shortening the part that is sticking out. Students will see the shortening of the vibrating part of the meter stick, and hear the pitch or number of vibrations go up—an increase in frequency.

The speed of sound can change when sound travels from one medium to another. However, the frequency usually remains the same because it is like a driven oscillation and maintains the frequency of the original source. If v changes and f remains the same, then the wavelength λ must change. Since $v = f\lambda$, the higher the speed of a sound, the greater its wavelength for a given frequency.

Teacher Support

Teacher Support [AL] Ask students to predict what would happen if the speeds of sound in air varied by frequency.

Virtual Physics

Sound [Click to view content](#)

This simulation lets you see sound waves. Adjust the frequency or amplitude (volume) and you can see and hear how the wave changes. Move the listener around and hear what she hears. Switch to the Two Source Interference tab or the Interference by Reflection tab to experiment with interference and reflection.

Tips For Success

Make sure to have audio enabled and set to Listener rather than Speaker, or else the sound will not vary as you move the listener around.

PhET Explorations: Sound. This simulation lets you see sound waves. Adjust the frequency or volume and you can see and hear how the wave changes. Move the listener around and hear what she hears.

[Click to view content](#)

In the first tab, Listen to a Single Source, move the listener as far away from the speaker as possible, and then change the frequency of the sound wave. You may have noticed that there is a delay between the time when you change the

setting and the time when you hear the sound get lower or higher in pitch. Why is this?

- a. Because, intensity of the sound wave changes with the frequency.
- b. Because, the speed of the sound wave changes when the frequency is changed.
- c. Because, loudness of the sound wave takes time to adjust after a change in frequency.
- d. Because it takes time for sound to reach the listener, so the listener perceives the new frequency of sound wave after a delay.

Is there a difference in the amount of delay depending on whether you make the frequency higher or lower? Why?

- a. Yes, the speed of propagation depends only on the frequency of the wave.
- b. Yes, the speed of propagation depends upon the wavelength of the wave, and wavelength changes as the frequency changes.
- c. No, the speed of propagation depends only on the wavelength of the wave.
- d. No, the speed of propagation is constant in a given medium; only the wavelength changes as the frequency changes.

Snap Lab

Voice as a Sound Wave In this lab you will observe the effects of blowing and speaking into a piece of paper in order to compare and contrast different sound waves.

- sheet of paper
- tape
- table

Instructions

Procedure

1. Suspend a sheet of paper so that the top edge of the paper is fixed and the bottom edge is free to move. You could tape the top edge of the paper to the edge of a table, for example.
2. Gently blow air near the edge of the bottom of the sheet and note how the sheet moves.
3. Speak softly and then louder such that the sounds hit the edge of the bottom of the paper, and note how the sheet moves.
4. Interpret the results.

Grasp Check

Which sound wave property increases when you are speaking more loudly than softly?

- a. amplitude of the wave
- b. frequency of the wave
- c. speed of the wave
- d. wavelength of the wave

Worked Example

What Are the Wavelengths of Audible Sounds? Calculate the wavelengths of sounds at the extremes of the audible range, 20 and 20,000 Hz, in conditions where sound travels at 348.7 m/s.

Strategy

To find wavelength from frequency, we can use $v = f\lambda$.

Solution

- (1) Identify the knowns. The values for v and f are given.
- (2) Solve the relationship between speed, frequency and wavelength for λ .

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

14.2

- (3) Enter the speed and the minimum frequency to give the maximum wavelength.

$$\lambda_{\max} = \frac{348.7 \text{ m/s}}{20 \text{ Hz}} = 17 \text{ m} \approx 20 \text{ m (1 sig. figure)}$$

14.3

- (4) Enter the speed and the maximum frequency to give the minimum wavelength.

$$\lambda_{\min} = \frac{348.7 \text{ m/s}}{20,000 \text{ Hz}} = 0.017 \text{ m} \approx 2 \text{ cm (1 sig. figure)}$$

14.4

Discussion

Because the product of f multiplied by λ equals a constant velocity in unchanging conditions, the smaller f is, the larger λ must be, and vice versa. Note that you can also easily rearrange the same formula to find frequency or velocity.

Practice Problems

1.

What is the speed of a sound wave with frequency 2000 Hz and wavelength 0.4 m?

- a. $5 \times 10^3 \text{ m/s}$
- b. $3.2 \times 10^2 \text{ m/s}$
- c. $2 \times 10^{-4} \text{ m/s}$
- d. $8 \times 10^2 \text{ m/s}$

2.

Dogs can hear frequencies of up to 45 kHz . What is the wavelength of a sound wave with this frequency traveling in air at 0°C ?

- a. $2.0 \times 10^7 \text{ m}$
- b. $1.5 \times 10^7 \text{ m}$
- c. $1.4 \times 10^2 \text{ m}$
- d. $7.4 \times 10^{-3} \text{ m}$

Links To Physics



Echolocation

Figure 14.8 A bat uses sound echoes to find its way about and to catch prey. The time for the echo to return is directly proportional to the distance.

Echolocation is the use of reflected sound waves to locate and identify objects. It is used by animals such as bats, dolphins and whales, and is also imitated by humans in SONAR—Sound Navigation and Ranging—and echolocation technology.

Bats, dolphins and whales use echolocation to navigate and find food in their environment. They locate an object (or obstacle) by emitting a sound and then sensing the reflected sound waves. Since the speed of sound in air is constant, the time it takes for the sound to travel to the object and back gives the animal a sense of the distance between itself and the object. This is called *ranging*. Figure 14.8 shows a bat using echolocation to sense distances.

Echolocating animals identify an object by comparing the relative intensity of the sound waves returning to each ear to figure out the angle at which the sound waves were reflected. This gives information about the direction, size and shape of the object. Since there is a slight distance in position between the two ears of an animal, the sound may return to one of the ears with a bit of a delay, which also provides information about the position of the object. For example, if a bear is directly to the right of a bat, the echo will return to the bat's left ear later than to its right ear. If, however, the bear is directly ahead of the bat, the echo would return to both ears at the same time. For an animal without a sense of sight such as a bat, it is important to know *where* other animals are as well as *what* they are; their survival depends on it.

Principles of echolocation have been used to develop a variety of useful sensing technologies. SONAR, is used by submarines to detect objects underwater and measure water depth. Unlike animal echolocation, which relies on only one transmitter (a mouth) and two receivers (ears), manmade SONAR uses many transmitters and beams to get a more accurate reading of the environment. Radar technologies use the echo of radio waves to locate clouds and storm systems in weather forecasting, and to locate aircraft for air traffic control. Some new cars use echolocation technology to sense obstacles around the car, and warn the driver who may be about to hit something (or even to automatically parallel park). Echolocation technologies and training systems are being developed to help visually impaired people navigate their everyday environments.

If a predator is directly to the left of a bat, how will the bat know?

- a. The echo would return to the left ear first.
- b. The echo would return to the right ear first.

Check Your Understanding

Teacher Support

Teacher Support Use these questions to assess student achievement of the section's Learning Objectives. If students are struggling with a specific objective, these questions will help identify which and direct students to the relevant content.

3.

What is a rarefaction?

- a. Rarefaction is the high-pressure region created in a medium when a longitudinal wave passes through it.
- b. Rarefaction is the low-pressure region created in a medium when a longitudinal wave passes through it.
- c. Rarefaction is the highest point of amplitude of a sound wave.
- d. Rarefaction is the lowest point of amplitude of a sound wave.

4.

What sort of motion do the particles of a medium experience when a sound wave passes through it?

- a. Simple harmonic motion
- b. Circular motion
- c. Random motion
- d. Translational motion

5.

What does the speed of sound depend on?

- a. The wavelength of the wave
- b. The size of the medium
- c. The frequency of the wave
- d. The properties of the medium

6.

What property of a gas would affect the speed of sound traveling through it?

- a. The volume of the gas
- b. The flammability of the gas
- c. The mass of the gas
- d. The compressibility of the gas